Spring 2022

A Comparison of Common Structural Materials

Molly Green
msg82@uakron.edu

A COMPARISON OF COMMON STRUCTURAL MATERIALS

The University of Akron
Department of Civil Engineering
Molly Green

Table of Contents

List of Figures

Introduction

This report will compare and contrast the three most common structural materials: steel, concrete, and lumber. All have their own benefits and downfalls, and structural engineers must know them all in order to ensure a structure performs well. This report will expand on the material properties, the design process, the cost of materials, and the environmental impact.

Due to the wide variety of options within each kind of material, clarification is necessary. The type of steel that is referenced is ASTM A992 because it is the most common type for columns and beams. There are many different kinds of concrete as well (lightweight, high-performance, ultra-high performance), but this report will focus on normal weight. The wood species referenced are spruce, pine, and fir. Most data will be an approximate average of the three unless noted otherwise.

Material Properties

Mechanical Properties

Performance in Compression or Tension

Compression and tension are the two most common forces that structural members are subjected to. Compression can be described as a pushing force, and, conversely, tension can be described as a pulling force. The force they exert is described in pounds in the English system and Newtons in the metric system. It is important to note that the loads being applied to structural members are not what is compression or tension. The loads can be described based on whether they are a point load or distributed load or if they are an axial load or a lateral load. Compression and tension are how the structural member reacts to that load. For example, if a structural member has ropes tied to each end and those ropes are pulled – this would be an axial load – then that structural member is in tension. This situation would be described as a tensile force being applied. This distinction is important in order to understand how different materials respond to these forces. Another important distinction to make is that a structural member experiencing bending is actually a structural member experiencing tension and compression. If a typical beam (or other similar structural member) has a force applied and begins to bend, the sections above and below its neutral axis will respond differently. The section above the neutral axis and closer to the force will begin to compress as the material is forced in on itself. The section below the neutral axis will stretch as the material is pulled apart. See figure 1 below.

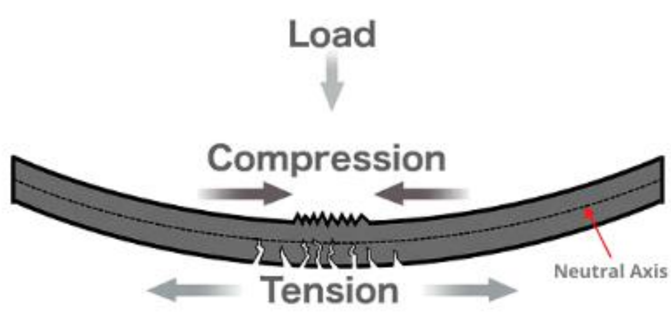

Figure 1: Beam experiencing tension and compression while bending

Steel is strong in both tension and compression. Its ultimate compressive strength is 35,000 psi and its ultimate tensile strength is 65,000 psi. An arguably more important value for steel than its ultimate strength is its yield strength. Since steel has a high modulus of elasticity of 29,000,000 psi, it can be subjected to a certain level of forces while maintaining its full strength and recovering from any deformation. This cap of how much force can be applied it its yield strength. Once the force applied exceeds this value, steel will begin to permanently deform. Steel's yield strength is 50,000 psi.

Concrete is known for being strong in compression, but weak in tension. It typically has a compressive strength of 2500 – 4000 psi. Its tensile strength is significantly less at about 300 – 600 psi. This weakness when subjected to tension is why concrete needs steel reinforcing bars. Concrete does have an ultimate strength and yield strength like steel does, but they are much closer in value. Since concrete's modulus of elasticity is only 4,000,000 psi, there is a more narrow window of forces concrete can take before it fails completely.

How lumber behaves in tension or compression depends on the direction of the load with respect to the direction of the grain. Figure 2 below shows the different directions a load can be applied to a standard piece of lumber.

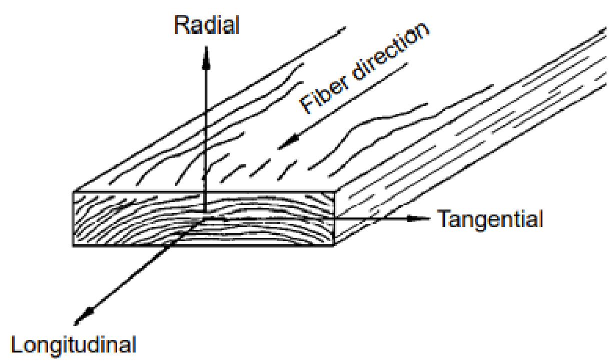

Figure 2: The three directions loads can be applied to lumber

For simplicity, the radial and tangential directions will be referred to as perpendicular to grain and any values referenced as such will be an average of radial and tangential values. Lumber, compared to concrete and especially steel, has a low modulus of elasticity of 1,600,000 psi. As stated before, this means lumber cannot deform much before it fails completely. Lumber has a compressive strength parallel to grain of 6,000 psi and perpendicular to grain of 700 psi. It has a tensile strength perpendicular to grain of 400 psi. There is a lack of data about tensile strength parallel to grain, since it is an uncommon way of loading wood, so it has been excluded.

Resistance to Shear

Shear is another very common force that is often applied to structural members. A shear force is a combination of two forces offset slightly from one another and acting in opposite directions. This results in a small section of the structural member being pushed in two different directions. Figure 3 below illustrates this. An example of when shear forces are applied in structures are at the bolted connections between a beam and a column. Bolts are pushed one way from the load of the beam, then another way from the resistance to that load from the column.

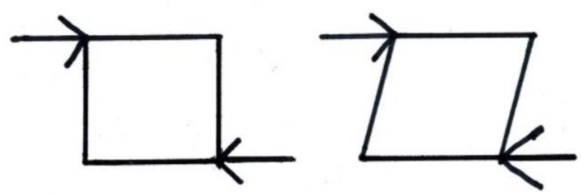

Figure 3: An example of shear force

Steel has a shear strength of 50,000 psi. Concrete is weaker than steel with a shear strength of 900 psi. Lumber's shear strength parallel to grain is 1,200 psi. Not much data exists about wood's shear strength perpendicular to grain, but some data suggests it is about 2.5-3 times the shear strength parallel to grain. Steel is clearly the best choice to resist shear forces, with concrete and lumber being not too different from one another.

Durability

Resistance to Chemical Changes

There are a few notable types of chemical changes that can harm the performance of structural materials. Fire, decay, and corrosion will be explained, but there is also exposure to miscellaneous chemicals in the environment. This is a vast topic due to the enormous number of chemicals, either natural or man-made, that structures can be exposed to. While this specific issue will not be addressed, it represents the complexity of protecting against chemical change. Engineers must be aware of the environment surrounding the structure, along with any chemicals that will be housed in the structure.

Fire is one of the most common concerns in the construction industry. There are a wide variety of ways to help keep fire contained, but some materials are inherently more susceptible to damage than others. Steel and concrete are classified as noncombustible. This means that they will not actually catch on fire – so the main concern for these materials is how the high temperatures will decrease structural capacity. Figure 4 below is an example of how a fire did not turn steel to ash, but instead caused it to warp. As far as resistance to the incredibly high temperatures from a fire, concrete is better than steel. For steel, there are options for protection such as intumescent coatings, gypsum, spray-applied fire-resistive material, and masonry. For concrete, there are not many options. In fact, it is actually another type of coating that can go around steel for fire resistance. Lumber is the outlier in fire resistance. Since it is combustible – meaning it will actually catch on fire – it needs more protection. The exact chemicals applied varies by manufacturer, but they will all end up being completely infused into the wood using a high-pressure system. Once the chemicals are infused, they can help the lumber resist igniting and, if they do ignite, slow how fast the fire burns through. Lumber can never be made fully noncombustible like steel and concrete though, so it is unlikely to be used if there is a risk of a large fire like in factories, warehouses, etc.

Figure 4: Steel warped after being exposed to high temperatures from a fire

Decay is an issue that only lumber experiences. It is caused by fungi. Certain types of fungi metabolize the cellulose fraction of the wood, which is the part that gives lumber its strength. To add to the difficulty, decay is nearly impossible to detect until it is too late. Just a slight increase from 5% to 10% loss in weight can result in an increase from 20% to 80% loss in toughness, impact bending resistance, and more. The best method of combatting decay is simply inspecting regularly and, when necessary, discarding every piece of lumber that has been affected.

A major change that steel undergoes is corrosion. Corrosion is the destruction of a material due to a reaction between its surface material and factors such as moisture and oxygen. The risk of corrosion varies depending on where the steel is located. For example, a bridge in salt water exposed to stagnant moisture will have a higher risk of corrosion than a beam on the interior of high-rise building. For lower risks of corrosion, selecting the right kind of steel can be enough defense. For higher risks of corrosion, something more protective is needed. Examples include galvanizing, a polysiloxane coating, an epoxy coating, and an acrylic coating. In almost all instances, steel will need at least some protection against corrosion and it must be taken into account during the design process.

Resistance to Physical Damage

Physical damage does not have as many opportunities to become a problem as chemical changes. Chemical changes happen in a variety of ways due to a variety of factors while physical damage does not. Physical damage occurs in two ways. The first is when the material itself fails and the second is when an outside force causes damage. However, while it may not be the most complex issue, physical damage can mean complete and immediate failure.

Cracking is how a material shows it is starting to be loaded beyond its capacity. It is one of concrete's biggest issues that engineers must account for. An important note is that some cracking in concrete is acceptable and structural engineers plan on it happening. As stated before, concrete does not handle tension well and in instances of it being to subjected to slightly too much tension – like in the bottom portion of a beam – the concrete will crack. As long as there is steel reinforcing in that bottom portion and the cracks are not too large, the beam will remain structurally sound. An acceptable crack width can range from 0.016 in. in dry air conditions to 0.004 in. in water retaining structures. Once the cracks extend beyond this acceptable range, repairs are necessary. A typical repair is an epoxy injection. These injections are a relatively quick and simple fix; however, if the concrete is cracking due to being significantly overloaded or another complex condition, the epoxy will not help and the concrete will crack in another location. Lumber is similar to concrete in that smaller cracks are often acceptable, but repairs must take place once they become too large. Repairs for lumber involve gluing nails or bolts into holes that run perpendicular to the grain or attaching high-strength patches to the side of the member. Steel is different from concrete and lumber in that any cracking symbolizing failure. Steel has such a high modulus of elasticity that it should be able to bend a significant amount before it breaks. Cracking can mean different things for different materials, but they warrant consistent attention regardless of the size.

Steel and concrete are incredibly strong so extreme forces must be applied in order to damage them. Lumber, on the other hand, is relatively soft and so it is more easily harmed. Insects are one of these forces that would not do any damage to steel or concrete, but can destroy Lumber. Termites are a notorious problem for wood, but different kinds of beetles, ants, and bees can also cause a lot of damage. Some insects can even make their damage hard to detect. Powderpost beetle larvae burrow into wood through very small holes then proceed to destroy the interior. This leaves behind a seemingly intact piece of wood with virtually no strength. Figure 5 below shows the damage powderpost beetle larvae can do. Note how the destruction is seen only once the outer layer is peeled off. Unfortunately, there is no way of knowing lumber has been damaged until the outside has been affected or until the member begins to fail. There are a variety of coatings that can be put on lumber to deter any insects from doing damage, but there are limitations. If an insect has already managed to get inside, a coating can do nothing to get rid of it. Additional forms of insecticides must be used then. Insects have the ability to destroy wooden structures so a great deal of thought must go into protection.

Figure 5: The damage powderpost beetle larvae can do to wood

Design

Selection of Material

The decision of what a structure is made of is not usually done by the structural engineer. Typically, the architect works with the owner to decide what would look best and fit the budget. This typically is not as problem as structural engineers have access to a wide variety of solutions to address any problems. However, there may be instances in which an engineer does not believe a design will work well or at least will not be efficient, and offer their input about making a change. For example, an architect may want large open spaces without columns and they chose to use lumber. An engineer could point out that the spans are likely to be too large for lumber and steel would make a better choice. From there the architect could accept the change or redesign.

There is a pattern of what materials are used most often for certain structures. Houses, for example, are almost always made of lumber. The structure typically is not subjected to any enormous loads and the layout is quite straightforward. For houses and other smaller, simple structures, lumber is a common choice. Once some complexity or size is introduced, then steel and concrete begin to be considered. Technically, a combination of the two materials like concrete columns and steel beams is allowed, but it is uncommon. For cutting-edge, modern designs like the Walt Disney Concert Hall, pictured in figure 6 below, steel is the optimum choice given its strong yet lightweight properties. For large buildings without any complexity, steel or concrete perform the same. Hotels, office buildings, factories, and other similar buildings fall into this category. When designing structures like these, the owner must voice their priorities about cost, construction time, etc. to help make the decision about which material to use. An important note about the selection of materials is that concrete will always be used because that is what foundations are made of. Some materials are more common for different structures than others, but steel, concrete, and lumber are all quality options that will perform well.

Figure 6: Using steel allows the Walt Disney Concert Hall to achieve this beautiful design

Design Process

Modern computer programs make design a simpler process than one might think. SAP2000, Enercalc, RAM Structural System, WoodWorks, and more are common tools that allow structural engineers to design single members or even entire structures. Figure 7 below shows the variety of designs that Enercalc alone can calculate. The information that is typically inputted into these programs is loads, span length, section shape (for steel), soil characteristics, along with other miscellaneous information depending on what is being designed. The engineer using these programs must of course have an understanding of what the program is doing and about what outcome it should produce in order to catch any possible mistakes.

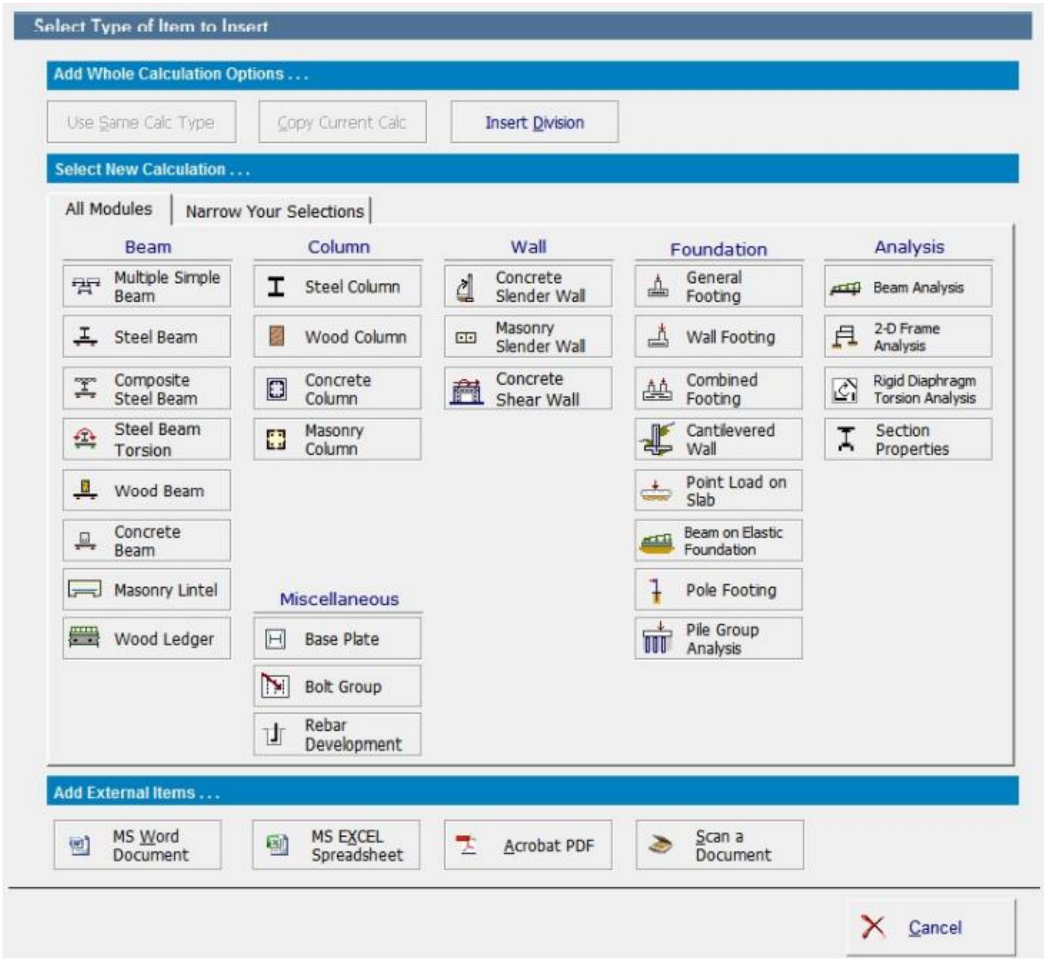

Figure 7: A screenshot of the calculations Enercalc can do

Once the members are designed, connections and foundations follow. Connections have become quite standardized. Structural engineers typically pick from welds, bolts, and nails/screws then specify from there. Manufacturer information and design manuals give guidance about what sizes of connections to use. Foundations are the final major step to a design and they can also be done using a computer program. The engineer just has to input the loads and choose what type of foundation they want.

The existence of these modern-day tools has dramatically simplified the design process such that no one material is harder to design with than others.

Cost

Manufacturing Process

Steel

Simply, steel is about 98% iron and 2% carbon. Obtaining each of these materials is an advanced process in it of itself. The iron mining process starts with using explosives to break taconite, a very hard rock containing iron ore, into many pieces. Next, the taconite pieces are scooped up and put into large dump trucks, then taken to a processing plant. Once at the processing plant, the taconite is crushed until it is about one centimeter across. Next, it is mixed with water and ground in a mill until it is a powder. Converting the taconite from a piece of rock to a powder is a way to ensure that only the iron gets extracted. Magnets are used to separate the iron and having the material broken up like that helps. The final step is the iron powder is rolled with clay to make marble-sized balls. These balls get dried then heated to form taconite pellets. Taconite pellets are what is melted down into steel. The carbon process is similar to iron, but there are some key differences. Instead of coming from taconite, carbon comes from coal. Also, instead of the coal getting turned into a powder, it is directly heated up to cook off the volatile matter and produce a block of concentrated carbon. Both of these processes are laborious, time-consuming, and require a large investment to get up and running.

The process of actually making the steel can begin now that the essential materials have been acquired. There are two options for the first step in steelmaking: basic oxygen furnace and electric arc furnace. The electric arc furnace is the more modern process and now accounts for 70% of the steel production in the United States, so it is the process that will be described here. The basic oxygen furnace works differently, but the end result will be similar. In the first step of steelmaking, iron and carbon, along with any other materials that are desired, are put in the electric arc furnace. This furnace heats up by utilizing electric arcs that are delivered via graphite electrodes. The materials are then melted. The steel is tapped into a ladle and goes to the next step while the slag is poured off to be heated again. The next step comes in many forms, but the main goal is to purify the liquid steel. Unwanted materials can have a bad effect on the quality of steel. The process used are refining, vacuum degassing, argon oxygen decarburization, or using the ladle metallurgy furnace. The end result is a liquid steel that is ready to be cast – this is the third step. From here, the steel is cast into whatever shape the customer wants. These shapes include slabs, thin slabs, strips, billets, blooms, near net shapes, and ingot castings. The final step of steelmaking is the shaping and treating of the steel. Structural steel shapes can be made by hot or cold rolling or by welding plates together.

Variations can be made to the typical steel makeup by adding more carbon or by introducing other elements. Nickel or manganese are two common elements added – they specifically help prevent the steel from becoming too brittle while it is being welded. Other options include aluminum, titanium, and lead. The addition of different elements depends on the end use for the steel.

The entire manufacturing process for steel is complex. There are many moving parts, expensive equipment, intricate chemistry, and a need for the end result to be perfect. Structural steel cannot be made incorrectly or people can get hurt. This all results in a premium price.

Concrete

Concrete is primarily a mixture of cement, aggregates, and water. Water is relatively straightforward to obtain, so cement and aggregate are the two ingredients that make up the majority of concrete's cost.

The aggregates in concrete can vary widely in shape and type depending on the final use for that concrete mix. Both coarse and fine aggregates are used with gravel being a very common coarse aggregate and sand being a very common fine aggregate. If the aggregates are natural, they are likely gravel and sand that came from being dug from a pit or body of water. If natural aggregates are not available or not desired, crushed stone is a common alternative. Crushed stone can come from a variety of sources from bedrock to cobbles. Regardless of the source though, the crushed stone is crushed into a more manageable size before it goes through its final processing. All aggregates will go through the same or similar final processing. The first step is to crush the aggregates into their desired final size. There are a variety of crushers that can be used. The next step is to sort the aggregates. The final crushing process can produce excess aggregate that are not the desired size. Essentially, large sieves are used to sort what is wanted and what is not. The final step is washing the aggregates. Another byproduct of crushing is dust can accumulate on the surface. This dust makes it difficult for the cement (or any other binder, like asphalt) to bind to the aggregates. It must be removed before the aggregates can be used. Once this is completed, the aggregates are ready for use. A large part of the cost of aggregates is the cost of transporting them. In order to save a great amount of money, it is recommended that the aggregates are sourced locally. Quarries are quite common so this is feasible for most projects.

Cement is a powder that, when mixed with water, forms a paste-like substance. This paste-like substance binds all of the aggregate in concrete together, then hardens. The first step in making cement is to quarry limestone and clay. These materials are crushed in a series of crushers. The first reduces the sizes to about six inches across, then the second reduces it further to about three inches across. Other materials can be quarried and crushed, but few are as common as limestone and clay. The next step is the crushed rock is combined with iron ore, fly ash, and more, then ground, mixed, and put in a kiln. The kiln's purpose is to evaporate off unwanted materials to form a substance called clinker. Clinker is gray and about the size of marbles. Once it cools after exiting the kiln, it is ground then mixed with a small amount of gypsum and limestone. This final product is cement. Since cement is the most expensive ingredient in concrete, there are alternatives. Fly ash, ground granulated blast-furnace slag, and silica fume have cementitious properties, but cost much less than actual cement. These ingredients cannot be used instead of cement though – they can only make up a certain percent of the cementitious material in a concrete mix.

There are also ingredients known as admixtures that can be put in a concrete mixture. Admixtures are the best way of manipulating the characteristics of concrete without changing fundamental aspects like the water to cement ratio. Admixtures can make a concrete cure more quickly or more slowly, make a concrete thinner or thicker without changing the water content, make a concrete stronger or lighter, and more.

Combining the water, aggregates, cement, and possibly admixtures is usually completed at a plant that is nearby the construction site. The process of mixing the concrete and even of determining what exactly will go in each mix is a relatively simple task for the contractors. They often have a variety of mixes already designed to meet a variety of needs in order to cut down on costs. The concrete only needs to be mixed, put into the trucks, and taken to the construction site. Concrete has a much simpler manufacturing process than steel and that is reflected in its price.

Lumber

While wood is a natural material, it still undergoes processing before it is ready to use. After waiting anywhere from 10 to 50 years for the tree to grow, it is felled and processed. Depending on which harvesting system is being used, the trees can be only topped and delimbed at the harvesting location or they can be nearly entirely processed while there. An entire processing involves topping, delimbing, cutting into logs, and debarking. Wherever the processing takes place, the next steps are the same. The logs are stored in water until they are ready to be cut. They enter the mill by conveyor belt, are debarked if they have not yet been, then cut to length. From there, making lumber simply involves sawing the logs into their desired dimensions. For the construction of many smaller structures, this lumber would be enough. However, larger structures require more complex structural members. Some other products made from wood include veneer (thin sheets of wood typically 0.5 – 1.0 mm) and laminated wood (parallel lumber boards glued together). Veneer can be processed even further to produce different kinds of structural lumber. Laminated veneer lumber and parallel strand lumber are examples of structural lumbers that are made from laminated veneer. These kinds of lumbers are exceptionally strong. All lumber products go through the same finishing treatments. First, they are dried by air drying, kiln drying, or other methods. This step is crucial to prepare the wood for further treatments. Next, the lumber is preserved by using oils or chemicals. These preservatives can help make the wood fire-resistant or help protect against fungi, bacteria, insects, and more. The lumber manufacturing process is largely simpler than steel and mildly simpler than concrete. However, because it is a natural resource that takes decades to produce, the cost is affected by more than the finishing steps.

Worldwide and Local Markets

A very large effect on the price of a material is where that material is from. For example, as of February 2022, a standard steel plate from the United States costs $2,031 per metric ton while from China it costs $699. Similarly, for hot-rolled bands and cold-rolled coils, they cost $1,487 per metric ton and $1,877 per metric ton, respectively, from the United States and $678 per metric ton and $764 per metric ton, respectively, from China. Western Europe and the World Export Market fall in between these two extreme regions with their hot-rolled bands costing $1,110 per metric ton and $920 per metric ton, respectively. While the United States produces an enormous amount of steel, it imports it as well. The price of steel is influenced the most by worldwide markets.

Concrete and lumber are typically sourced locally around the project. There are significantly more quarries and forests all over the United States than steel mills, so the construction industry capitalizes and saves money where it can. The cement in concrete may be produced far away, but it is simple to transport. In 2020 in the United States, the average price per cubic yard of concrete was $125, equaling about $63 per ton. This is approximately 6% of the cost of steel for the same weight of material. Lumber is different because it is a natural resource that takes decades to produce – the cost is affected by more than the finishing steps. In 2021, the average price per 1,000 board feet was $1,000. This equals approximately $800 per ton for spruce, pine, and fir trees.

Other Cost-Affecting Factors

When comparing the cost of materials strictly by their cost per ton, there are other variables that get ignored. This ignorance risks making one material seems vastly superior to others when it is not.

There are plenty of drawbacks about structural materials that a cheap price cannot outweigh. One major downside of concrete is that it must cure. First, formwork has to be installed. Then, concrete is poured and cures for 28 days. This amount of time allows the concrete to gain its strength. A second downside of concrete is that it needs steel reinforcing. So even if concrete prices are low, the project budget will be affected by the steel market. A drawback for steel is transportation costs. Steel often must travel far to get to a construction site and it does so on big, expensive trucks.

While materials have their disadvantages, they have their advantages as well. Steel and wooden structures save money on their foundations versus concrete structures because their lightweight properties mean less dead load. They also can be constructed faster than concrete structures because they do not require curing. An advantage concrete has is it does not require extensive maintenance. As long as any defects are caught early on, they will not cost much to repair.

Environmental Impact

Manufacturing Process

The emissions produced during the manufacturing process of structural materials is a great cause for concern amongst environmental protection groups. Structural materials themselves do not produce any pollution after they are made (even though they can be made into things like engines or factories that do produce pollution) so the only place to critique them is in how they are made. As previously discussed, the manufacturing for steel, concrete, and lumber are vastly unique. They all use different materials, tools, and equipment. The material whose manufacturing process is regarded as most environmentally-friendly is wood. All the while the trees are growing, they help reduce the amount of carbon dioxide in the atmosphere. Once the time for felling and processing the trees comes, heavy machinery is used but it is smaller than what is used for aggregate and mineral mining. Many forestry operations used simple chainsaws, bulldozers, and semi-trucks. The manufacturing of steel and concrete have a significantly more detrimental impact on the environment. Concrete production is estimated to be 4-8% of the world's carbon dioxide emissions. Steel production is estimated to be 8% of the world's carbon dioxide emissions. Manufacturing these two materials is decidedly bad for the environment.

Longevity

Once materials are purchased and a structure is built, there is the question of how long it will last. If something must be repaired or rebuilt every few years, it may have been a better choice to just use a material that will last longer. As described in the previous sections, steel and concrete will last the longest due to lumber being susceptible to so many forms of damage. However, when taken care of properly, all of these materials can last for a very long time. Modern steel and concrete buildings are often quoted as lasting 50-100 years. Modern wooden houses are quoted to last 100-150 years. An interesting note here is that ancient concrete structures still exist. The Roman Colosseum was built with a concrete not too dissimilar from what is used today and it is 2,000 years old. Time will tell if any modern concrete structures will last that long, but if they do, then certainly the environmental impact from constructing them will be made worth it.

Recyclability

How easily a material can be recycled is a very attractive attribute. A common misconception is that most, if not all, of the cardboard, paper, glass, and plastic that people put in their recycling bins gets recycled. In reality, only a small portion gets recycled and the rest is put in a landfill. Recycling companies need the materials to be in pristine condition since any remaining substances like food particles or adhesives can cause their machinery to break. This same idea applies to steel, concrete, and wood. Steel is the most recycled material of the three. 98% of structural steel and 72% of reinforcing bars are recovered at the end of its useful life to be recycled. All of that scrap collected goes into making more steel. Structural steel today is made of 93% recycled materials. Some structural members like beams and columns can even be removed from a building and refabricated for use in new structures without being melted down. Concrete is recycled at a significantly lower rate – only 30%. Recycled concrete is typically turned into an aggregate base, but it could also be turned into new Portland cement concrete. Due to restrictions in concrete mix design, only up to 30% of natural crushed coarse aggregates can be replaced with recycled crushed aggregates. Wood is recycled the least. While the percentage of recycled wood has increased steadily over the last few decades, it hovers at about 20% today. Wood is very difficult to recycle since coatings, paints, and stains are considered contaminants and yet are so common. The most recyclable material of these three is steel.

Conclusion

Material properties vary widely between steel, concrete, and lumber. Steel is known for its ability to withstand enormous amounts of both tension and compression. Concrete lacks tensile resistance, thus it has the need for steel reinforcement, but excels when subjects to compression. Lumber's strength depends on how it is loaded in relation to its grain, but can perform respectably in tension and compression. Steel is also the best choice for resistance to shear forces. Fire harms steel, concrete, and lumber, though concrete has the least need for any additional coatings to protect it. Corrosion is an issue exclusive to steel, and decay is an issue exclusive to lumber. A variety of chemical changes can impact structures, but these three are the most straightforward. All structural materials can crack when loaded beyond capacity, but minimal cracking in concrete and lumber is actually acceptable. Lumber has a unique issue in that it can be destroyed by insects. Knowing these specific material properties can help structural engineers determine which materials work best in different situations.

Designing structures has been dramatically simplified by modern-day computer programs to the point that no specific material is most difficult to design with. Programs like Enercalc and SAP2000 allow a structural engineer to input the necessary parameters and get back the ideal member or even whole structure. When it comes initially choosing the material that will be used the engineer does not usually have much say, but they are given the opportunity to voice any concerns they see.

The prices of these materials are affected by numerous factors. The manufacturing process of steel and concrete are significantly more involved than for lumber; however, trees can take decades to grow. Where a material comes from also affects the price. Steel is produced worldwide and it typically most expensive when coming from the United States. Concrete and lumber are produced locally given the readily-available quarries and forests all over the country. Other miscellaneous factors should be kept in mind when figuring the price, but a general rule is that steel will cost the most per ton.

The environmental impact of structural materials must be considered. Not only do owners appreciate being able to say their investment is environmentally-friendly, but it is also an engineer's duty to do what is good. The manufacturing process for steel and concrete are great causes for concern considering they contribute to about 15% of the world's carbon dioxide emissions combined. Lumber production is considerably more environmentally-friendly in comparison. When considering if the excessive pollution may be worth it for the extended longevity of the structure, evidence suggests that any material can last around 100 years if properly maintained. Recyclability is one perspective in which steel is the most environmentally-friendly. The vast majority of steel gets recycled while concrete and lumber do not. In some instances, the environment is the least of the construction industry's concern, but it should be at least considered.

There is no clearly superior structural material. Steel, concrete, and lumber all have their own advantages and disadvantages. Ultimately, every project is unique and once details are presented, a choice can be made.

References

AISC. (n.d.). *Structural Steel Construction Costs*. Retrieved from American Institute of Steel Construction: https://www.aisc.org/why-steel/resources/construction-costs/

AISC. (n.d.). *Structural Steel Finishes, Coatings, and Fire Protection*. Retrieved from American Institute of Steel Construction: https://www.aisc.org/why-steel/resources/fire-protection/

AISC. (n.d.). *Structural Steel Sustainability*. Retrieved from American Institute of Steel Construction: https://www.aisc.org/why-steel/sustainability/

AIST. (n.d.). *Steel Production*. Retrieved from American Iron and Steel Institute: https://www.steel.org/steel-technology/steel-production/

Allen, E. (2016, February 12). *8 Steel Buildings That Are Incredible Examples of Modern Architecture*. Retrieved from Architectural Digest: https://www.architecturaldigest.com/gallery/steel-buildings

AMPP. (n.d.). *Corrosion Prevention and Protection Methods for Structural Steel*. Retrieved from AMPP: https://sspc.org/learning_center/corrosion-prevention-and-protection-methods-for-structural-steel/

APA. (n.d.). *Structural Composite Lumber (SCL)*. Retrieved from APA: https://www.apawood.org/structural-composite-lumber

Britannica. (n.d.). *Steel*. Retrieved from Britannica: https://www.britannica.com/technology/steel/Testing-of-properties

Britannica. (n.d.). *Wood*. Retrieved from Britannica: https://www.britannica.com/science/wood-plant-tissue/Harvesting-of-wood

Brooks, M. D. (2010). *Structural Engineering Library.* Corona del Mar: ENERCALC, INC.

Champion Termite & Pest Control. (n.d.). *Facts About Powederpost Beetles*. Retrieved from Champion Termite & Pest Control: https://www.championtermiteandpestcontrol.com/facts-about-powder-post-beetles/

Civil Lead. (n.d.). *Tension Vs Compression - Difference Between Tension & Compression*. Retrieved from Civil Lead: https://www.civillead.com/tension-vs-compression/

ConcreteNetwork.com. (2021, December 22). *Concrete Price Considerations - Cost of Concrete*. Retrieved from ConcreteNetwork.com: https://www.concretenetwork.com/concrete-prices.html

ConcreteNetwork.com. (n.d.). *Structural Concrete Repairs*. Retrieved from ConcreteNetwork.com: https://www.concretenetwork.com/concrete-repair/structure.html

Cook, B. (2018, November 8). *Manufactured wood products are renewable and environmentally friendly*. Retrieved from MSU Extension Forestry: https://www.canr.msu.edu/news/manufactured-wood-products-are-renewable-and-environmentally-friendly

Curtis Lumber & Plywood. (2019, August 30). *The Complete Guide To Fire Retardant Wood*. Retrieved from Curtis Lumber & Plywood: https://www.clp-inc.com/complete-guide-fire-retardant-wood/

Davies, J. (2022, April 1). *Is Wood Recyclable?* Retrieved from beeco: https://www.beeco.green/facts/is-wood-recyclable/

Designing Buildings. (2021, January 22). *Shear strength*. Retrieved from Designing Buildings: https://www.designingbuildings.co.uk/wiki/Shear_strength

EPA. (2018). *Wood: Material-Specific Data*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/wood-material-specific-data

Gerres, T., Lehne, J., Mete, G., Schenk, S., & Swalec, C. (2021, June 10). *Green steel production: How G7 countries can help change the global landscape*. Retrieved from Leadit: https://www.industrytransition.org/insights/g7-green-steel-production/#:~:text=From%20major%20infrastructure%20to%20buildings,8%25%20of%20global%20CO2%20emissions.

Government of Canada. (2022). *Current lumber, pulp and panel prices*. Retrieved from Government of Canada: https://www.nrcan.gc.ca/our-natural-resources/domestic-and-international-markets/current-lumber-pulp-panel-prices/13309

Green, D. W. (2001). Wood: Strength and Stiffness. In *Encyclopedia of Materials: Science and Technology* (pp. 9732-9736). Elsevier Science Ltd.

Green, D. W., Winandy, J. E., & Kretschmann, D. E. (1999). Chapter 4 - Mechanical Properties of Wood. In F. P. Laboratory, *Wood handbook - Wood as an engineering material.* Madison, WI: Department of Agriculture, Forest Service, Forest Products Laboratory.

Hance Construction, Inc. (2020, July 20). *Butler Building Renovation and Durability of Steel*. Retrieved from Hance Construction, Inc.: https://www.hanceconstruction.com/news/blog/butler-building-renovation-and-durability-of-steel#:~:text=Steel%20buildings%20face%20fewer%20issues,from%2050%20to%20100%20years.

Hubbe, M. A. (2017). *To Repair or Not Repair Cracked Wood*. Retrieved from NC State University BioResources: https://bioresources.cnr.ncsu.edu/resources/to-repair-or-not-to-repair-cracked-wood/

Izbicki, T., McDonald, D. B., Mendoza, J. E., & Turner, J. B. (2015). *Fire Resistance of Reinforced Concrete Buildings.* Schaumburt: Concrete Reinforcing Steel Institute.

Keulemans, G. (2016, June 17). *The problem with reinforced concrete*. Retrieved from UNSW Sydney Newsroom: https://newsroom.unsw.edu.au/news/art-architecture-design/problem-reinforced-concrete

Meyer, C. (n.d.). *Concrete Materials and Sustainable Development in the United States.* Columbia University.

Minnesota Iron. (n.d.). *Iron Mining Process*. Retrieved from Minnesota Iron: https://minnesotairon.org/education/iron-mining-process/

NAHB. (2022). *Framing Lumber Prices*. Retrieved from National Association of Home Builders: https://www.nahb.org/news-and-economics/housing-economics/national-statistics/framing-lumber-prices

NAHB Research Center, Inc. (2002). *Steel vs. Wood Cost Comparison.* U.S. Department of Housing and Urban Development.

PCA. (n.d.). *Aggregates*. Retrieved from PCA America's Cement Manufacturers: https://www.cement.org/cement-concrete/concrete-materials/aggregates

PCA. (n.d.). *Cement and Concrete Sustainability*. Retrieved from PCA America's Cement Manufacturers: https://www.cement.org/sustainability

PCA. (n.d.). *How Cement is Made*. Retrieved from PCA America's Cement Manufacturers: https://www.cement.org/cement-concrete/how-cement-is-made

PCA. (n.d.). *Recycled Aggregates*. Retrieved from PCA America's Cement Manufacturers: https://www.cement.org/learn/concrete-technology/concrete-design-production/recycled-aggregates

Quraini, M. (2020, June 5). *How does Structural Steel Fail Due to Fire Exposure? How to Protect it?* Retrieved from PassiFire: https://www.passifire-sa.com/hp/how-does-structural-steel-fail-due-to-fire-exposure-how-to-protect-it/

Southern Forest Products Association. (n.d.). *Wood & The Environment*. Retrieved from Southern Forest Products Association: https://sfpa.org/lumber-info/wood-the-environment/#:~:text=Wood%20may%20be%20the%20most,United%20States%20than%20is%20harvested.

SteelBenchmarker. (2022). *SteelBenchmarker Report #384.* Price Assessment Providers.

The Engineering Toolbox. (2004). *Wood - Densities of Various Species*. Retrieved from The Engineering Toolbox: https://www.engineeringtoolbox.com/wood-density-d_40.html

The Engineering Toolbox. (2008). *Concrete Properties*. Retrieved from The Engineering Toolbox: https://www.engineeringtoolbox.com/concrete-properties-d_1223.html

The Engineering Toolbox. (2011). *Wood, Panel and Structural Timber Products - Mechanical Properties*. Retrieved from The Engineering Toolbox: https://www.engineeringtoolbox.com/timber-mechanical-properties-d_1789.html

The Engineering Toolbox. (n.d.). *Young's Modulus, Tensile Strength and Yield Strength Values for some Materials*. Retrieved from The Engineering Toolbox: https://www.engineeringtoolbox.com/young-modulus-d_417.html

Watts, J. (2019, February 25). *Concrete: the most destructive material on Earth*. Retrieved from The Guardian: https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth

Zahner. (n.d.). *Discover the Sustainable Characteristics of Metal*. Retrieved from Zahner: https://www.azahner.com/blog/metal-sustainability/

Zoruba, S., & Grubb, K. A. (2003). *Do you 992?* Modern Steel Construction.