STRUCTURAL RESILIENCY THROUGH SUSTAINABILITY

M. Marsh\textsuperscript{1} and J. Nelson\textsuperscript{2}

ABSTRACT

Architects, engineers, and builders can all agree that buildings need to be resilient, but not everyone would agree that the way to accomplish this is through sustainable design.

While resilience is defined as toughness or structural elasticity—the ability to recover and “bounce back”, sustainability encompasses three concepts: maintain, support, and endure. Therefore, while seeking a solution for resilient structures, designers have been unintentionally seeking a more sustainable solution. By implementing “smart” sustainable solutions during the design of a project, structural engineers can create a more resilient structure, environment, and community.

This paper provides alternative structural solutions through the selection and comparison of sustainable and resilient material modifications pertaining to concrete, masonry, and timber. When buildings are designed to maintain, support, and endure, the ability to “bounce back” and recover is inherent. Many sustainable material modifications lead to a more durable and efficient finished product and consequently, more resilient buildings, environments and communities. For example, replacing a percentage of portland cement with fly ash or slag reduces the amount of CO\textsubscript{2} and is environmentally beneficial. Additionally, incorporating fly ash or slag can improve workability and durability of the concrete design mix. Improved workability results in a higher quality finished product whereas enhanced durability prolongs a building’s lifespan and increases structural resilience.

While the concrete industry is making changes to the mix design, the wood industry is making changes to the essence of the material itself. Rather than growing a tree with the intent of

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using it for sawn lumber, manufacturers and industry leaders see the entire tree as a raw material that can be reconstituted into engineered wood products. Engineered wood products have been growing in popularity due to the efficiency, practicality, and availability of the product. By manipulating and reorganizing the wood fibers, manufacturers create a more consistent material with enhanced structural properties, contributing to a more resilient structure.

This document is presented in a concise format, simplifying its usability for design professionals. Advantages and possible concerns are discussed for each material modification. These discussions include interdisciplinary effects of the modifications, such as necessary coordination between disciplines and alterations to construction practices. Incorporating these alternate materials will allow structural engineers to play an active role in the sustainable and resilient design of a building. Understanding and using the three main concepts of sustainability — maintain, endure, and support — will enhance the design and resiliency of a structure.
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ABSTRACT

Architects, engineers, and builders work together to create a built environment that is both sustainable and resilient. Often these are viewed as two similar but separate goals. A simpler approach is to create buildings that are resilient by utilizing sustainable design practices. While resilience is defined as toughness or structural elasticity—the ability to recover and “bounce back”, sustainability can be described by three concepts: maintain, support, and endure. Therefore, while seeking a solution for resilient structures, designers have been unintentionally seeking a more sustainable solution.

This paper provides alternative structural solutions through the selection and comparison of sustainable and resilient material modifications pertaining to concrete, masonry, and timber. Many sustainable material modifications lead to a more durable and efficient finished product and consequently, more resilient buildings and communities. For example, replacing a percentage of portland cement with fly ash or slag reduces the amount of CO\textsubscript{2} emissions. Additionally, incorporating fly ash or slag can improve workability and durability of the concrete design mix. Improved workability results in a higher quality finished product whereas enhanced durability prolongs a building’s lifespan and increases structural resilience.

This document is concise and easy to use for designers. Advantages and possible concerns are discussed for each material modification. By incorporating alternate building materials, structural engineers have the ability to play an active role in the sustainable and resilient design of a structure.

Introduction

Architects, engineers, and builders can all agree that buildings need to be resilient, but not everyone would agree that the way to accomplish this is through sustainable design. While resilience is defined as toughness or structural elasticity—the ability to recover and bounce back \cite{14}, sustainability alludes to longevity and renewability with a definition that stems from the idea that

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designers can implement techniques that help the present while maintaining the goals and needs of the future [13]. The parallel between the two is distinct and encompasses three concepts: maintain, support, and endure. Therefore, while seeking a solution for resilient structures, designers have been unintentionally seeking a more sustainable solution. By implementing “smart” sustainable solutions during the design of a project, structural engineers can create a more resilient structure, environment, and community.

Although tying sustainability and resiliency together is hardly a recent conceptual discovery, many industry professionals have struggled with the transition from theory to practice. This paper provides alternative structural solutions through the selection and comparison of sustainable and resilient material modifications pertaining to concrete, masonry, and timber. When buildings are designed to maintain, support, and endure, the ability to bounce back and recover is inherent. Many sustainable material modifications lead to a more durable and efficient finished product and consequently, more resilient buildings, environments and communities.

This paper is presented in a concise format, simplifying its usability for design professionals. Advantages and possible concerns are discussed for each material modification. These discussions include interdisciplinary effects of the modifications, such as necessary coordination between disciplines and alterations to construction practices. Incorporating these alternate materials will allow structural engineers to play an active role in the sustainable and resilient design. Understanding and using the three common elements of design – maintain, endure, and support – will enhance the overall sustainability and resiliency of a structure.

Concrete

A resilient design elicits toughness; therefore, many designers instinctively turn to concrete as the building material of choice. Among other positive characteristics, concrete is preferred for its durability, availability and desirable structural properties. Because a concrete design mix is dependent upon different ingredients and their respective quantities, there are many opportunities to not only create a more resilient structure with a higher strength final product, but a more sustainable structure with a smaller carbon footprint. Due to the detrimental environmental impact of CO₂ emissions during cement production, one of the most common sustainable solutions in concrete design is to seek out cement substitutes.

Cement substitutes can partially or completely replace ordinary portland cement. Research shows that there are many options, each with its own advantages and disadvantages. What most design professionals don’t realize about cement substitutes is that they often result in a less permeable, more durable, and higher quality finished product, thus making it the easy choice for a resilient and sustainable structural design. More predominant cement substitutes include fly ash (HVFA), slag, silica fume, Solidia Cement™, and CeraTech Ekkomaxx™ Cement [1]. Interestingly, the same approach and material modification can also be applied to concrete masonry units (CMU blocks).

Cement Substitutes

Fly ash, slag, and silica fume are commonly used cement substitutes since each material is
produced as a by-product of other manufacturing processes. These by-products are carbon-neutral, widely available, and can reduce the amount of water required for the concrete design mix, therefore further decreasing the material’s overall environmental impact. Each substitute can only replace a certain percentage of portland cement before affecting structural integrity. Consequently, care must be taken during the design phase to achieve both a resilient and sustainable structure, requiring designers to get involved in the details and specifications of each building material. Some benefits of using fly ash, slag, or silica fume to replace ordinary portland cement (other than a decrease in CO$_2$ emissions) include minimal cost impact, improved workability and durability, and a higher-quality finished product. It has also been found that there is no change in plastic shrinkage or abrasion resistance when compared to a standard concrete mix [1]. Enhanced durability and abrasion resistance means less damage, therefore less repair and an increase in the overall resiliency of a structure.

**Fly Ash and Slag**

As a by-product of coal combustion in electric power plants and a co-product of steel production respectively, fly ash and slag are widely available. When added to a concrete mix, ground, granulated blast furnace slag (commonly referred to as “slag”) is known to prevent an early rise in temperature for large concrete pours, thus reducing cracking. Using slag as a cement substitute has also been shown to increase resistance to chemicals found in groundwater and harsh environments, therefore improving overall durability and resilience [2]. Each substitute can replace 15-70% of portland cement; however, a fly ash concentration greater than 40% is generally referred to as high-volume fly ash or HVFA. Aside from lowering the amount of cement required and therefore reducing CO$_2$ emissions, a concrete design mix that uses HVFA also requires a lower water-to-cement ratio when compared to a conventional design mix. Whereas a standard concrete mix has a water-to-cement ratio of about 0.5, a HVFA design will have a ratio of about 0.37 to 0.40. There are other advantages when using fly ash or slag as a cement substitute. For example, concrete that incorporates fly ash or slag into the design mix will typically result in a net cost savings, depending on product availability and location.

While there are many perks to using fly ash and slag as cement substitutes, there are some disadvantages. When using HVFA, other specifications must be modified to maintain a high-quality finished product. For example, because the design mix requires less water, good gradation of the aggregate is recommended (aggregates of $\frac{1}{2}”$ to $\frac{3}{8}”$ in size) [1]. Finishing the concrete surface is slightly more difficult with a set time reduced from 8 to 6 hours. Curing time is typically longer than 7 days, which can be an issue in cold weather conditions and may require additional formwork maintenance during this time period. Additionally, a HVFA concrete design mix may be less desirable for thicker sections due to the fact that the design compressive strength, $f’_c$, is reached in 56 days vs. a standard 28 days. Whereas this may be problematic for most projects, a resilient design emphasizes long-term objectives regardless of short-term inconveniences.

**Silica Fume**

The third commonly used cement substitute is silica fume: an ultrafine material that forms as a result of silicon and ferrosilicon alloy production. Due to its highly reactive properties and small particle size (1/100$^{th}$ the size of a cement particle), silica fume greatly reduces permeability and can increase concrete’s compressive strength, $f’_c$, up to 10,000psi [3]. For this reason, it is often
used in lightweight or high-performance concrete to improve compressive strength values. As with all cement substitutes, there are some limitations. Currently silica fume is used to replace no more than 12% of portland cement because of an increased water demand. Furthermore, it requires the use of a superplasticizer to prevent the concrete mix from drying quickly and consequently, a skilled contractor to create a high-quality final product [3]. Lastly, the use of silica fume can result in a more brittle final product. Although using silica fume has advantages and disadvantages, it can contribute to a more resilient and resolute structure. With only a minor change to a design mix, structural engineers are able to obtain concrete compressive strengths that were relatively unattainable until recently. Higher compressive strength values can lead to structural resiliency and sustainability due to its direct correlation to an increase in member capacity. Therefore, designers have the opportunity to create a more unyielding structure with the same amount of material or a more efficient structure with less material. The use of silica fume illustrates the need for professionals to take a holistic approach by weighing the advantages and disadvantages of a new material when designing with resiliency and sustainability in mind.

### Cement Replacements

Lastly, the use of more innovative cement products such as Solidia Cement™ and CeraTech Ekkomaxx™ Cement will improve structural sustainability and resiliency. While most cement substitutes discussed thus far are only able to replace a certain percentage of portland cement, advances in technology have inspired a new wave of cement products. Solidia Cement™ and CeraTech Ekkomaxx™ Cement are products that aim to replace 100% of portland cement used in concrete design. While there are other innovative products seeking to entirely replace portland cement, Solidia Cement and CeraTech Ekkomaxx™ Cement are at the forefront of sustainable change in the concrete industry.

Developed by Solidia Technologies® in 2013, raw ingredients typically found in portland cement are combined using different ratios and fired at a lower temperature. Interestingly, this unique process results in a 30% reduction of CO₂ emissions and uses up to 80% less water during production [4]. Solidia Cement™ has a number of beneficial characteristics. When used in precast applications where concrete is manufactured off-site, cure time has been reduced to 1 day vs. the 28 day standard. Similar to fly ash and slag, the final product is less permeable and ultimately, more durable and tougher than a standard design mix [3]. In addition to a reduction in CO₂ emissions from its unique manufacturing process, one of the greatest sustainable benefits of Solidia Cement™ is that it is CO₂-cured meaning that carbon dioxide is sequestered during the curing process [4].

Alternatively, CeraTech Ekkomaxx™ Cement is a cement design mixture containing approximately 95% fly ash and 5% proprietary liquid additives [5]. CeraTech’s proprietary cement design has paved the way for a more sustainable future with its near zero-carbon footprint product. It has also been shown that CeraTech’s mix design uses 95% less virgin resources and 50% less water [5]. Aside from its’ environmental benefits, CeraTech’s Ekkomaxx™ Cement concrete has also been shown to increase durability and product lifespan when compared to ordinary portland cement concrete [6]. The product has completed the first environmental product declaration (EPD) for a non-portland cement [7]. CeraTech’s Ekkomaxx™ Cement concrete has been certified for use in construction applications [6] and has been accepted by industry codes such as the American
Concrete Institute (ACI) [15], International Code Council (ICC) and the United States Green Building Council (USGBC)[16].

Cement substitutes, whether partially or completely replacing ordinary portland cement, have common advantages of increased durability, reduced permeability, and reduced CO₂ emissions. By enhancing the structural system’s durability, a building is likely to have a longer life-span, thus verifying one of the core concepts in sustainable and resilient design: *endure*. Concrete structures are known to curb adverse effects of destructive agents such as floods, fires and other harsh environments, but increasing the material’s durability can further improve upon its inherent resiliency. Similarly, by reducing permeability, the finished concrete product is less susceptible to harmful environments and therefore embodies the second concept of sustainable design: *maintain*. Lastly, engineers have the ability to *support* the natural environment by dramatically reducing CO₂ production and even sequestering it from the atmosphere. While targeting cement design and production is the most effective way to reduce environmental impacts of the concrete industry, professionals can recognize the long-term benefits of more resilient structures and ultimately, a more resilient community.

**Self-Compacting Concrete & Controlled Permeability Formwork**

If cement substitutes are not locally available nor viable for a project, designers can also investigate the use of self-compacting concrete (SCC) and controlled permeability formwork (CPF) [8]. While this is a strategy that requires additional coordination between the engineer and project contractor, resiliency and sustainability can improve by altering construction practices rather than material composition.

Self-compacting concrete, initially developed in Japan, involves a new production and casting process where manual compaction is prohibited; therefore, SCC is free of local variations in permeability caused by traditional construction practices. The difference in finished surface quality between SCC and conventional concrete (CC) is clear in Fig. 1. SCC uses mineral additions that are finer than cement and enables hydration to a denser mix, therefore reducing the water-to-cement ratio from 0.5 to 0.4. As with self-compacting concrete, controlled permeability formwork (CPF) is used to improve the concrete surface zone.

![Figure 1: (Left) Surface quality comparison of SCC and conventional concrete shows distinct differences in permeability or porosity of the finished product. (Right) Schematic diagram for controlled permeability formwork illustrating the extraction of excess water and air. [8].](image)
CPF uses a textile liner to allow air bubbles and surplus water to escape while retaining the binder particles in the mix as shown in Fig. 1 [8]. Using SCC and CPF together has been shown to improve durability-related parameters by 40-50% and create a more homogeneous product [8].

Additional benefits when using SCC with CPF include comparable specific gravity values and slightly higher compressive strength (f'c) values when compared to conventional concrete. By using SCC with CPF during construction, the quality of concrete cover is improved, creating a higher resistance to aggressive deterioration agents [8]. In summary, using these two products together reduces permeability, enhances strength, and improves durability of the final product which ultimately lengthens a building’s life span and increase the structure’s resiliency [8]. As shown with cement substitutes, these positive characteristics support the pillars of a sustainable and resilient design solution: maintain, endure and support.

Timber

Timber is a biodegradable, non-toxic, renewable, recyclable, and reusable material. Being one of the most common building materials in residential and low-rise construction, timber is an obvious sustainable material choice, but is it a resilient one? Having the ability to “bounce back” implies a structure that maintains its integrity while enduring natural, probabilistic events in the future. A resilient and sustainable structure must support itself before, during, and after a given event with moderate, but controlled damage.

As the timber industry progresses towards a more sustainable future, it has been unintentionally creating a more resilient one. Engineered wood products have progressed beyond the limitations of naturally occurring inconsistencies and are made by manipulating wood fibers to create a more homogeneous material. With an elevated level of control in the final product, designers have more confidence in structural performance. Engineered wood products such as glued laminated timbers (glulam), structural composite lumber (SCL), prefabricated wood I-joists, and cross-laminated timber (CLT) have become the most influential sustainable solutions in timber construction and can now be admired for their contribution to resilient design. Unlike the implementation of cement substitutes, engineered wood products address resiliency and sustainability on a macroscopic level. By using a sustainable product in a wider array of applications, designers have the ability to create not only structures that perform elastically and recover quickly following catastrophic events, but more resilient environments and communities. Engineered wood products allow for efficient material use since smaller trees and underutilized species can be used to manufacture these products [9]. All aforementioned engineered wood products have been adopted by the National Design Specifications for Wood Construction (NDS), making design and application relatively simple for engineers.

Glued Laminated Timber – Glulam

Composed of different layers or laminates of dimensional lumber, glulams have no upper limit for the width or depth of their section. This is not only a design advantage for engineers, but also a sustainability advantage for manufacturers. Whereas the maximum cross-sectional area for sawn lumber is limited to the size of a tree, glued laminated timber can be made from smaller, commonly available sizes [10]. Additionally, they can be manufactured to accommodate a wide variety of
shapes and configurations such as curves and can span longer distances when compared to sawn lumber. Glulam beams are preferred for their aesthetically pleasing character and are often left exposed, eliminating the need for a dropped ceiling and therefore, reducing the amount of materials required. In addition to any architectural benefits, glued laminated timbers use wood efficiently by placing higher graded species at the outer edges where stresses are at a maximum. While this is a structural and sustainable benefit, problems can arise if holes are needed for MEP systems. Although technically feasible, engineers typically avoid large openings in glulam beams, resulting in the potential for an increase in floor-to-floor height. An increase in floor-to-floor height will consequently increase all other elements of the building (structure, cladding, MEP systems, etc…). Proper coordination between the design and construction team can potentially reduce this complication resulting in an overall sustainable building.

**Structural Composite Lumber**

Structural composite lumber covers a myriad of engineered wood products including from weakest to strongest: laminated strand lumber (LSL), laminated veneer lumber (LVL), and parallel strand lumber (PSL). Oriented strand lumber (OSL/OSB) is also included as part of the structural composite lumber family. SCL products can be compartmentalized based on the two primary manufacturing processes: stranding (LSL & OSL/OSB) and rotary peeling (LVL & PSL). The stranding process used to make oriented strand board (OSB) allows for manufacturers to use more of the log than with rotary peeling [10]. Generally, structural composite lumber products can replace sawn lumber for structural members such as beams, joists, and even columns. Some benefits of using SCL include availability of longer lengths/spans and larger cross-sections as well as improved material consistency throughout the member [11]. As manufacturers attempt to create a more isotropic material, drilling holes becomes less problematic. Additionally, by minimizing natural inconsistencies, straighter members are manufactured, resulting in less complications and changes on site; therefore, less material waste and a reduced project schedule will ultimately create a more sustainable design, environmentally, socially, and economically. Structural composite lumber is a more uniform material that gives designers more confidence and therefore, greater predictability in structural performance. With greater predictability, engineers have a better understanding of how the structure will perform during a given event allowing for the development of more specific resiliency objectives. There are few disadvantages when specifying SCL products. Limited availability may be problematic due to added shipping costs or may even delay the project schedule in times of high demand.

**Structural Wood I-Beams**

Structural I-beams were initially developed to allow for larger interior spaces and therefore longer spans. They were known to create “silent floors” because of a reduction in shrinkage, squeaking, and overall deflections [11]. While the design has changed over time, modern configurations use laminated veneer lumber (LVL) flanges with an OSB web. Structural I-beams use an efficient structural shape to create a light-weight and stable product with longer lengths and more opening options when compared to traditional sawn lumber. As with other engineered wood products, structural I-beams can be designed and tailored to the expected forces in a member [11]. Similar to SCL, structural wood I-beams increase a designer’s confidence and predictability of structural performance. Now with less material required to support the same demands, engineers are adopting
a sustainable approach. With greater predictability, engineers can progressively improve resilient design strategies.

**Cross-Laminated Timber**

One of the more recently available engineered wood is cross-laminated timber. CLT is manufactured by stacking layers of lumber board, typically sawn lumber or SCL, rotating each layer 90 degrees and gluing them together for a final product. CLT has been successfully used in Europe since the 1990s and has become recently available in North America [12]. Cross-laminated timber is a versatile product that can be used for both lateral and vertical load resisting systems and is also known for its rapid installation, minimal waste, and energy efficient sustainable qualities. To further improve installation times, reduce project schedule and overall impact of the structure, manufacturers can precut openings or notches and may include lift straps for placement when on-site storage capacity is limited [12]. While light frame wood construction is still considered to be the most economical wood system for low-rise projects, CLT is competitive for a variety of building types. It has been shown to have good ductile behavior and provide energy dissipation, implying a level of resiliency as well. As with all engineered wood products, advantages always come with disadvantages. Although the use of cross-laminated timber (CLT) is currently limited based on availability and economic viability, there is motivation to further investigate its structural behavior for greater predictability and resiliency.

**Conclusion**

While sustainability and resiliency may initially seem to be conflicting concepts, designers and engineers should recognize that these concepts are complementary to one another and share common goals. Sustainability stems from the idea of sustainable development which was originally described as the ability to “meet the needs of the present without compromising the ability of future generations to meet their own needs” [13]. Similarly, resilient design elicits toughness and elasticity – maintaining the ability to recover quickly following shocks or stresses [14]. It is clear that the future demands sustainable and resilient designs in order to create a strong and thriving society; therefore, the classic definition of sustainability should be also viewed as an achievable definition of resiliency. Resiliency and sustainability share three common threads: to maintain, support, and endure. Whether this pertains more closely to structural integrity or environmental stability, a community’s ability to “bounce back” after a catastrophic event is rooted in these three concepts.

To increase sustainability and improve resiliency, the concrete and masonry industries are changing material ingredients while the timber industry is making changes to the way wood products are manufactured and used in design. Whether taking an approach at the microscopic level such as defining a change in material composition or macroscopic level such as creating a resilient community, resiliency and sustainability are mutually related goals. The key is defining resiliency and sustainability objectives early on in the design phase to create opportunity for change in the future.

Implementing sustainable and resilient design concepts is about understanding when and how to use them. “Smart” solutions require design professionals to constantly seek growth and
Develop their professional skills in order to promote a more resilient and resolute community. Architects, mechanical engineers, civil engineers and builders continue finding ways to implement sustainability and resiliency into their design approach.

Structural engineers also have the opportunity to be at the forefront of these changes. A transition in structural design to include sustainability and resiliency goals doesn’t need to wait for direction from established avenues such as LEED, Green Globes, and Envision. It can begin with structural engineers finding opportunities within their individual projects and communicating those successful changes to the profession. Acceptance of these additional goals will require educating officials, building professionals, and the public as to their value. Understanding the added benefits of sustainable and resilient designs will allow the structure to be evaluated over its’ lifespan rather than simply the upfront cost.

Structural concepts have the potential to contribute not only to a design that can endure unforeseen catastrophes, but also to a design that supports and maintains people and their communities. As illustrated in this paper, sustainability and resiliency share common goals. Structural engineers and designers have an ability that is also an obligation to continue to advance the industry in ways that are socially, economically, and environmentally advantageous.

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