# Serviceability and Safety: Core Aspects of Sustainable Structures

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Synopsis: Serviceability, safety, and resilience are core components of a sustainable structure. This paper will discuss the key issues related to economic, social, and environmental factors. Structural efficiency plays an important role in reducing material usage while maintaining the necessary serviceability (including durability) of a structure. Resilience against both manmade events (such as terrorist attacks) and forces of nature (such as tsunamis, hurricanes, tornados, and flooding) has come to the forefront in recent years since longevity of a structure is central to sustainability. Wrapped into each of these decisions related to serviceability and safety/resilience are the potential environmental concerns related to choice of materials. Each of these topics is discussed within the context of concrete structures.

**Keywords**: sustainability, green, resilience, safety, environment

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## INTRODUCTION

### Sustainability Defined

While there are many interpretations of the meaning of the term "sustainability," the most commonly accepted definition is from the Bruntland Commission report (1987): "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This framework is not limited to only green or environmental aspects. Sustainable designs include economic, social, and environmental considerations.

## SUSTAINABLE ASPECTS

### Environmental

Environmental issues related to sustainable building design and construction can be grouped in various ways. Fig. 1 illustrates a grouping that aligns with LEED (Leadership in Energy and Environmental Design) for building construction.


*Fig. 1—One representation of the environmentally related components for buildings (Schokker, 2010).*

*Materials*—The use of perceived green materials is one of the most common examples cited in sustainability discussions. Materials such as bamboo and cork are touted for their rapid growth that makes their use potentially sustainable. The most sustainable material is one that is never used at all (by reducing material needs). In concrete, material reduction can be achieved by structural efficiency through use of higher strength concrete, prestressing, and many other design choices. Supplementary cementitious materials also can reduce the use of natural resources necessary to make cement. If material reduction is not possible or is limited, the next best alternative is to reuse materials. When a structure or structural components can be repaired or retrofitted, this is typically a far more sustainable option than demolition followed by new construction. With the large building inventory already in place, retrofit/repair is growing and is expected to continue to increase (Bureau of Labor Statistics, 2010). Components such as panels, pavers, block, and other materials can also be removed intact from one site and reused on another with few changes made to the component itself.

Recycling typically is mentioned when environmental concerns are discussed. Reduction and reuse are preferable to recycling, but recycling can have a major contribution to sustainability. Recycling materials not only keeps them from going into landfills, but also can reduce the amount of new material needed. During demolition of a concrete structure, the steel reinforcement can be recycled as well as the concrete itself. The concrete can be crushed to form recycled concrete aggregate for use in new concrete. ACI Committee 555 has a report that provides details on the use of recycled aggregate (2001). Waste products such as tire, glass, fibers, and many others have also found a home in some concrete applications. Waste packaging from the construction site should be recycled (and ideally, packaging is minimized in the first place).

*Site Selection*—Site selection considerations include location to services and preservation of green space. Clean-up of Brownfield sites for use as sites for new construction is particularly encouraged over use of new land. Building footprints and traditional paving with concrete or asphalt should be minimized. The effects of paving can be reduced through use of permeable concrete or interlocking permeable concrete pavers.

*Water*—Water is a resource that continues to be strained more each year throughout the world. As part of the building industry we can contribute in two major areas: stormwater management and reduction of water use. Permeable concrete and paver systems provide access for runoff to get back to the aquifers directly while filtering out debris. These systems can provide a holding area for water during heavy rain events that allows the water to slowly filtrate into the soil. Concrete cisterns can be used to collect and store water for other uses on-site. Green roofs can provide multiple benefits including additional green space, stormwater filtration and quantity management, and a reduction in the heat island effect.

*Air Quality*—Ventilation, mold control, and the use of low emitting (low volatile organic [VOC] compound) materials is critical for maintaining good air quality in buildings. Carpet, paint, sealants, stains and other finishes must be carefully controlled to maintain air quality. Concrete adapts well as a bare finish and aesthetics can be enhanced through use of pigments, form liners and stamping. Concrete also resists mold growth.

*Energy*—Energy use can be divided into embodied energy and operational energy. Embodied energy includes all of the energy used in the materials and construction of the physical building. The manufacture and transport of materials is a part of the embodied energy. Operational energy is the energy needed to heat, cool, light, and operate a building. The operational energy is typically significantly larger than the embodied energy and this gap increases as the service life of the building increases. However, as we move toward use of renewable energy and more efficient systems for heating/cooling and lighting, the operational energy decreases.

Concrete contributes significantly to the embodied energy of a building in a large part due to the manufacture of cement. The cement contribution to energy use can be reduced through more efficient kilns, use of waste products or by-products for fuel, or substitution of a percentage of the cement with supplementary cementitious materials in the final concrete mixture.

When considering the overall energy impact of a structure, the area where concrete stands out is in its ability to reduce the operational energy of a building. Concrete has the advantage of high thermal mass that can effectively reduce energy needs by lowering peak energy needs and shifting the time of maximum demand (thus moving demand to off peak times). Fig. 2 illustrates this effect. When combined with an effective insulating layer (such as in precast sandwich panels) with little thermal bridging, concrete can provide the tight envelope that is crucial for significantly lowering energy demand.

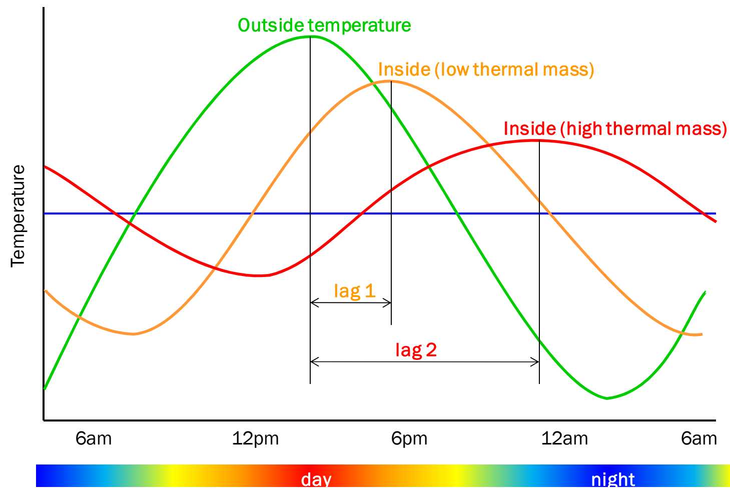


*Fig. 2—The effect of thermal mass on moderating and shifting interior temperatures (Schokker, 2010).*

**Social**

The social aspects surrounding a building's design, construction, and use form one of the three pillars of sustainability. This includes humanitarian issues as well as workplace related human factors such as building acoustics, aesthetics, and daylighting. The heat island effect is also included in this category for this discussion, but (like other topics) could also be in one of the other categories.

Community issues such as use of the local workforce or influence on local industry are integral to a building's sustainability. A building that doesn't become a part of the community (socially, economically, or otherwise) has little chance of lasting long-term. Our building infrastructure needs must be focused on service lives measured in centuries, not decades. The specifics of durability, safety and serviceability are covered in detail in later sections.

Studies in human factors combine the aspects of the workplace, people, and management. A building must provide a workplace that allows occupants to be productive. This includes comfort in temperature, day lighting, sound, and aesthetics. Temperature regulating effects were discussed in the previous section related to thermal mass. Effective day lighting for the work environment can be provided through the combination of exterior windows, selective shading from direct sunlight in work areas, and use of light colored finishes (such as concrete or light colored painted surfaces). For acoustic considerations, concrete is effective in reflecting sound, making it a good choice for reducing sound transfer between rooms. Furnishings and people contribute to the sound absorption that is needed within a room than concrete does not provide. Aesthetics can often be considered "a matter of taste," but concrete has long established itself as a choice that combines flexibility of shape, color, and texture that is popular with architects, engineers, and the public.

**Economic**

The economic pillar of sustainability is focused on both direct and indirect monetary costs. In a building structure, this includes the upfront cost as well as life-cycle costs. The concrete industry has long worked toward providing economic options for structures. Since durability is forefront in the benefits of concrete structures, life-cycle cost is particularly important to understanding the overall building cost. The energy benefits discussed in previous sections combined with the length of service life provided by a durable structure are the biggest impacts on reducing overall costs.

## SAFETY AND SERVICEABILITY

**Functional Resilience**

"Functional resilience" has developed as the term in the sustainable building industry that encompasses the safety, durability, disaster resistance, adaptability, and other aspects that relate to creating a structure that sustains the unpredictable environment that it will see over potentially a century or more of use. A building with renewable energy, reused or recycled materials, wonderful day lighting and air quality that is demolished by a hurricane after a few years of service is not a sustainable building. Functional resilience must be fully integrated into sustainable buildings and concrete has a strong record in this area.

*Fire*—Concrete is inherently fire resistant and has no additional requirements for fire protection for most applications, so material and money can be saved. Concrete walls and other members provide not only fire resistance, but also can play a crucial role in fire containment and in keeping routes of egress clear. This provides a substantial safety increase for occupants.

*Wind and Water*—Heavy rainfall events, wind storms, hurricanes and tornados can leave structures devastated. Concrete structures perform well under these conditions due to their ability to resist high winds. The concrete can also remain uncompromised even after submersion in water for extended periods of time. While mold and rot are a concern with many materials, concrete resists both and thus not only positions a structure to go quickly back into service, but also reduces health concerns related to the removal of molded or rotted materials. Fig. 3 shows a concrete house after hurricane Katrina. The high water mark on the house was 28 feet (8.5 m) above the base of the structure and the house was the only one left standing in the neighborhood. Fig. 4 shows a board impaled in a concrete wall after a tornado in Georgia. Concrete walls can be very effective in protecting occupants from flying debris.

*Fig. 3—This concrete house (under construction during hurricane Katrina) was the only house left standing in the neighborhood (photo courtesy of John Fleck, FEMA)*

*Earthquakes*—Earthquakes can produce extreme loads on a structure, and specialized building design procedures are used to achieve a building that can withstand the forces. Seismic design includes provisions for ductile performance and separation of participating versus non-participating structural elements. Various materials can be used for building systems that will minimize structural damage and protect occupants. Many types of concrete systems can be used and innovations continue in this area to achieve more ductile and robust structures. Earthquakes can also trigger fires and tsunamis, so concrete's ability to resist water and fire damage also factors in to the safety for occupants during earthquakes.

*Blast and Impact*—Design for blast and impact loads has become more prevalent in the past decade as concerns rise about potential terrorist attacks. Mass concrete is a popular choice for barriers to resist blast and impact. Properly detailed concrete elements can effectively resist blast load damage as well as reduce the potential for shrapnel from failed portions of the structure. The "United Facilities Criteria: Structures to Resist the Effects of Accidental Explosions" gives details on blast resistant design (U.S. Department of Defense, 2008). Concrete spalls on the interior side of walls can also be resisted through the use of innovative fibers particularly for this purpose (Coughlin et al, 2010).

*Fig. 4—During a tornado in Georgia, this awning was ripped apart and board was impaled into an adjacent concrete wall (inset) (photo courtesy of Mike Moore, FEMA)*

*Pests*—Pests such as termites can heavily damage wood structures in short periods of time. Damage to a wood structure's framing can occur without outward visual indications if siding or other cladding covers the wood. Termites and other pests cannot feed on concrete.

*Durability*—Long-term durability and corrosion resistance is critical to serviceability. Concrete has a long track record of proven durability in structures dating from ancient times. It also provides a high pH environment to protect the steel reinforcement used in structural concrete. Proper design (mix design, structural design, detailing) and construction (placement, quality control, curing, etc) are the key to getting a durable concrete structure.

**Building Codes**

Building codes are based on providing health and safety to occupants. Green rating (certification) systems such as LEED (Leadership in Energy and Environmental Design) have provided the basis for increased awareness of the design, construction, maintenance and operations of sustainable buildings. However, these rating/certification systems are not codes and are not written in mandatory language. They also have not adequately address the functional resilience aspect that is integral to true sustainability.

Green codes are being developed at levels from local jurisdictions up to international levels and are beginning to recognize the importance of functional resilience. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has published Standard 189.1, *Standard for the Design of High-Performance Green Buildings except low-Rise Residential Buildings (2009).* The *International Green Construction Code* (IGCC) is currently under development with the second public release out for comment. The code is anticipated to be published in early 2012.

## SUMMARY

As the concrete industry moves toward designing, constructing, and maintaining more sustainable structures, we must incorporate functional resilience at the core. Safety and serviceability are fundamental for any structure. When spending considerable effort and money for sustainable buildings, the safety and serviceability must also take a step up to account for extreme events and previously unforeseen catastrophes.

## REFERENCES

ACI Committee 555, 2001, *Removal and Reuse of Hardened Concrete (ACI 55R-01),* American Concrete Institute, Farmington Hills, MI, 26 pp.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2009, ANSI/ASHRAE Standard 189.1-2009, Standard for the Design of High-Perforamnce Green Buildings, Atlanta, GA, 122 pp.

Bruntland, G., ed., 1987, *Our Common Future: The World Commission on Environment and Development,* Oxford University Press, Oxford, UK, 374 pp.

Bureau of Labor Statistics, *Career Guide to Industries, 2010-11 Edition*, www.bis.gov/ovo/cg/cgs003.htm (accessed August 2011).

Coughlin, A.M.; Musselman, E.S.; Schokker, A.J.; and Linzell, D.L., 2010, "Behavior of Portable Fiber Reinforced Concrete Barriers Subject to Blasts from Contact Charges," *International Journal of Impact Engineering,* Vol. 37, Issue 5, pp. 521-529.

Schokker, A.J., 2010, *The Sustainable Concrete Guide: Strategies and Examples,* U.S. Green Concrete Council, Farmington Hills, MI, 86 pp.

U.S. Department of Defense, 2008, *Unified Facilities Criteria: Structures to Resist the Effects of Accidental Explosions,* UFC 3-340-02, Department of Defense, Arlington, VA, 1943 pp.

**SP-284 — 2**

# Impact of Adjacent Lane Traffic on the Serviceability of Concrete Bridge Decks

**Nakin Suksawang and Hani Nassif**

Synopsis: On major highways, bridge deck replacement often involves a diversion of traffic by shifting the travel lane adjacent to the repaired roadway. Thus, any traffic vibration or differential deflection, induced transversely due to truck traffic in the adjacent lanes, can affect the fresh concrete. Although there is very little evidence that traffic vibration in the adjacent lanes has affected the serviceability of concrete bridges in the past, more recently there have been some concerns about pouring high-performance concrete (HPC) in adjacent lanes because transverse cracking has been observed on newly repaired bridge decks. This paper examines the impact of traffic diversions and deflections that are induced transversely by truck traffic in adjacent lanes on the serviceability of bridge decks. In addition to field monitoring and laboratory testing, finite element analyses were used to simulate various bridge deck systems, traffic patterns, and truck loads to determine their effects on the serviceability of bridge decks. Results indicated that traffic loads and patterns can adversely affect the serviceability of concrete bridge decks. The results revealed that specific modifications to construction procedures and materials can significantly reduce the degree of transverse cracking in bridge decks.

**Keywords**: Bridge Deck; Finite Element Analysis; Traffic Vibration; Cracking; Serviceability.

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## INTRODUCTION

Concrete durability is one of the major concerns for many State Departments of Transportation (DOT), as well as other Transportation Authorities and the Federal Highway Administration (FHWA). One method of improving the durability and performance of concrete is to add pozzolans (such as silica fume, fly ash, and slag) to concrete mixtures. This led to the development of high-performance concrete (HPC), which is being currently implemented and used by many States in transportation structures with an emphasis on bridge decks. However, HPC requires applying proper placing and curing practices in order to minimize shrinkage effects. With the frequent use of HPC in applications such as bridge decks, many questions were raised regarding its long-term performance as well as early-age behavior. Moreover, many resources are allocated for implementing and producing HPC for its enhanced impermeability performance against chloride attacks and resistance to abrasion. However, with early-age cracking, the enhanced durability aspects start diminishing with time. Therefore, there is a need to understand the early age behavior of HPC under various adverse loading and placing conditions as well as its shrinkage behavior and potential for cracking under restrained conditions.

The effect of vibration (e.g., due to blasting, jarring, pile driving, and moving traffic) on fresh concrete has been a topic of concern for many years. One of the earliest research efforts to study the impact of vibration on fresh concrete was conducted by Abram in 1919. He performed a laboratory experiment to simulate various vibration frequencies on fresh concrete and their impact on the concrete strength, which proved to have little detrimental effect on concrete. It took another five decades for another research study (Whiffen and Leonard, 1971) to be conducted on the effect of vibration, but this time mainly focusing on bridges, particularly bridge deck widening. Additional, similar research studies followed (Furr and Fouad, 1982; Harsh and Darwin, 1983, 1986; Manning, 1981; Dunham et al., 2007; Issa et al., 2000), including a National Cooperative Highway Research Program (NCHRP) Synthesis (Arnold, 1980) to study the impact of adjacent traffic on bridge widening. Various parameters, including concrete slump, covers, water content, water-to-cement (w/c) ratio, and rebar size, were considered in many of these studies. The compressive, tensile, and bond strengths were the primary properties that were used to evaluate the influence of adjacent traffic, but other measurements, including deflection and visual inspection of bridges and cores were also used. More detailed summaries of these research studies can be found in Issa (1999) and the ACI Committee 345 (2005) report on "Guide for Widening Highway Bridges." Overall, all studies indicated that damage due to traffic-induced vibration is very rare and can be controlled by: i) use of moderate slump of 2 to 3 in. (50 to 75 mm); ii) good reinforcing details; and iii) good forming details. Despite all these research studies, one of the limitations is they do not address high-performance concrete (HPC). Unlike ordinary-performance concrete (OPC), HPC requires various chemical admixtures to alter its placeability and setting time. As a result, some of these effects may lead