Structural Engineering Strategies Towards Sustainable Design

Grace S. Kang, SE, LEED AP; Alan Kren, SE, LEED AP, Past Co-Chairs
SEAONC Sustainable Design Committee
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Structural engineering “best practices” incorporates strategies that embrace the tenets of sustainable design. Sustainable design is not a novelty; it is a mainstream approach that reflects good design. Federal, state, and local governmental agencies, public and private building owners, and the general public have established and expect their buildings to incorporate sustainable design practices. Responding to the public’s needs makes good business sense.

The intent of this presentation is to inform the structural engineer of the significance of sustainable design and increase awareness of considerations associated with it. Each of the following issues is presented in cursory form as is appropriate for this type of survey presentation: the global perspective, impacts and responses, materials, resource conservation in design and construction, structural systems and performance based engineering, and collaboration opportunities with other design professions.

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Global Perspective

Human activity continues to impact the earth’s atmosphere in ways that are expected to modify the climate [IPCC]. The main greenhouse gases are carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (N$_2$O), and specialist chemicals (halogenated compounds). Of these gases, the greatest contributor to climate change is CO$_2$ [IEA]. Of CO$_2$ emissions, 30% to 50% is produced by the construction and operation of buildings. Cement production, for example, produced about 8% of the total CO$_2$ emissions in 2000 [EPA].

A global increase in temperatures disrupts large-scale climatic patterns, and the patterns of human activity will change. Snow cover on mountains has decreased, and broad regions have irregular rates of precipitation and temperature fluctuation [IPCC]. Global sea levels have increased. The increase in summer drying of continental interiors and the associated risk of drought are likely.
Carbon dioxide is persistent and irrecoverable once in the atmosphere. After 100 years, 37% of CO₂ released today will remain. After 200 years, 14% will remain [CSCC]. The current level of greenhouse gases and rate of emissions is a long-term issue that extends beyond the generation of people producing the gases. For every building under construction today, the emissions associated with the manufacturing and assembly will remain as a burden through the life span of the children born at this same time. Even with a rapid change in the current use of fossil fuels and the reduction of new greenhouse gases, the decrease in the CO₂ concentrations would not be rapid. After stabilization of CO₂ levels, temperature and sea level increases are likely to last for several centuries [IPCC].

**Impacts and Responses**

The benefits of sustainable design are summarized in the triple bottom line: environmental stewardship, social responsibility, and economic viability. Environmental cultivation is in the form of controlling waste and limiting emissions. Social benefits of sustainably designed buildings are being documented. The advent of the LEED rating system provides some guidance in sustainable design features. And the small, cost premium associated with sustainable buildings, generally less than 3% of construction costs, compared to the potential large operational savings, has the attention of many building owners [DL, 2004].

**ENVIRONMENTAL IMPACT**

As reported in the 2004 California Statewide Waste Characterization Study, construction and demolition accounted for almost 22% of the total waste stream in 2003, up from 12% in 1999.

<table>
<thead>
<tr>
<th></th>
<th>1979</th>
<th>1995</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor space (million sq. ft)</td>
<td>43.546</td>
<td>58.772</td>
<td>35</td>
</tr>
<tr>
<td>Energy Consumption (trillion Btu)</td>
<td>4,965</td>
<td>5,321</td>
<td>7.2</td>
</tr>
<tr>
<td>Energy-Related Emissions (million metric tons of carbon)</td>
<td>164.2</td>
<td>178.7</td>
<td>8.8</td>
</tr>
<tr>
<td>Electricity Consumption (trillion Btu -- site energy)</td>
<td>1,908</td>
<td>2,608</td>
<td>36.6</td>
</tr>
<tr>
<td>Electricity-Related Emissions (million metric tons of carbon)</td>
<td>111.7</td>
<td>125.6</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Source: Battle and Burns

The United States Green Building Council (USGBC) reports that in addition to the trends shown above, buildings account for 49% of sulfur dioxide emissions, 25% of nitrous oxide emissions, and 10% of particulate emissions all of which damage urban air quality.

SOCIAL IMPACT

Sustainable buildings can provide health benefits to the building occupants. In the 1970s and 1980s, a series of incidences known as sick building syndrome (SBS) propelled the sustainable movement forward. Building inhabitants were suffering from respiratory illnesses, asthma, and chronic headaches as a result for poor air circulation and insufficient lighting. A study performed at the Lawrence Berkeley National Laboratory estimated that improved indoor air quality may produce savings and productivity gains of “$6-14 billion from reduced respiratory disease, $1-$4 billion from reduced allergies and asthma, $10-$30 billion from other SBS related causes, and $20-$160 billion from direct improvements in worker performance that are unrelated to health.” [BDC] In a smaller study performed with 21,000 students in schools located in Orange County, Seattle, and Fort Collins, it was determined that students performed better in schools with natural day lighting. Orange County students progressed 20% faster on math tests and 26% faster on reading tests, while Seattle and Fort Collins students improved test scores between 7%-18% [BDC].

ECONOMIC IMPACT

According to the DOE, the initial cost premium associated with sustainable buildings is small compared to the operational savings that can be incurred during a building’s lifetime. Energy savings through the use of day-lighting, natural ventilation, and photovoltaic power generation have been shown to reduce operation costs in a range of 20%-50% [FEMP]. For example, in 1996 the City of San Diego renovated the Ridgehaven Building, a 73,000 sq. ft office for the San Diego Environmental Services Department. The renovation cost approximately $37 per sq. ft to complete. As a result, the building now provides an annual utility savings of $70,000 or $1 per sq. ft [CIWMB]. The Naval Base Building 850 in Port Hueneme, CA, was constructed using sustainable principles and is estimated to save “64% in lighting, 67% in heating, and 43% in cooling expenses each year [FEMP].” The net increase in initial cost of a building in order to make it sustainable depends on the degree of sustainability measures implemented and how synergistic those measures are. The table below shows the net increase in initial cost as a function of the building’s LEED rating. The data includes the analysis of 33 LEED registered projects consisting of 25 office buildings and 8 schools [BDC].

Average Green Cost Premium for LEED Buildings

<table>
<thead>
<tr>
<th>LEED Rating (No. of projects)</th>
<th>Green Cost Premium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certified (8)</td>
<td>0.66%</td>
</tr>
<tr>
<td>Silver (16)</td>
<td>2.11%</td>
</tr>
<tr>
<td>Gold (6)</td>
<td>1.82%</td>
</tr>
<tr>
<td>Platinum (1)</td>
<td>6.50%</td>
</tr>
<tr>
<td>Average (33)</td>
<td>1.84%</td>
</tr>
</tbody>
</table>

On average, an increase in cost of 1%-2% occurred. However, the single Platinum rated building included in the study had a net cost increase of 6.5%. Careful balancing of design, program, and project quality components can offset the initial cost increases.
USGBC & THE LEED RATING SYSTEM

The US Green Building Council (USGBC), founded in 1993, is a coalition of leaders across the building industry working to advance buildings that are environmentally responsible, profitable and healthy places to live and work. USGBC has developed the Leadership in Energy and Environmental Design (LEED) rating system which is a voluntary, consensus-based national standard for developing high-performance, sustainable buildings. LEED provides a ratings framework for assessing building performance and meeting sustainability goals. It emphasizes strategies for sustainable site development, water savings, energy efficiency materials selection and indoor environmental quality. The first LEED system (LEED-NC) was developed in 2000 for new commercial construction and major renovation projects and is currently in Version 2.2. Other LEED systems for housing, commercial buildings, and existing buildings are at various stages of development.

As of late 2006, there are over 500 certified LEED projects, with over 400 of them in the LEED-NC category. There are four project certification categories: certified, silver, gold, and platinum. The rankings are dependent on how many “points” are implemented in the project.

OTHER RATING SYSTEMS

Another sustainable design rating system is Green Globes [GBI], developed in Canada and adopted in the US in 2004. Green Globes awards points for categories including project management, site, energy, water, resources, building materials, solid waste, emissions, effluents, and the indoor environment.

Building for Environmental and Economic Sustainability [BEES] measures the environmental performance of building products by using a life-cycle assessment approach. BEES is different than LEED and Green Globe in that it provides information on the environmental performance of building products, as opposed to rating a building or development.

GREEN BUILDING OWNER CLIENTS

There is increasing interest from public and private sector owners towards the sustainable design, and they are requesting sustainable buildings from the design team. The US Army, U.S. Environmental Agency, and NASA are among those who have adopted US Green Building Council’s LEED standard for their new buildings. GSA, the largest civilian landlord in United States, requires that all new GSA building projects be LEED certified, and a Silver LEED rating is encouraged.

In California there are many municipalities who require LEED certification on their newly constructed buildings. In 2001, the City of San Jose passed a law that requires the use of the LEED standard on all municipal buildings larger than 10,000 sq. ft. Since 2002, the City of Los Angeles requires that all municipally funded buildings larger than 7,500 sq. ft be LEED certified. Also in 2002, the San Diego City Council decided that municipal buildings should achieve a LEED silver rating. The City of San Francisco adopted a green building ordinance which requires that all city-owned facilities at least meet a LEED silver level. Pleasanton’s “Commercial and Civic Green Building Ordinance” requires city projects to meet LEED-certified status. San Mateo County requires the county’s new building construction of at least 5,000 sq. ft. to be LEED certified [BDC].

The private sector is following the public sector. Ford, Sprint, Steelcase, PNC Financial Services, and Toyota are among the first major corporations that embraced LEED and sustainable design. Ford has built several buildings in recent years that are LEED certified. Steelcase’s Wood Product plant in West Michigan is the largest building ever to be certified under the LEED Pilot Program. Toyota, manufacturer of hybrid cars, has a California Sales Headquarters with LEED Gold rating.

Materials

Structural materials provide the structural engineer with real opportunities to contribute to a project’s sustainability. The structural engineer, in using the traditional criteria for material selection such as economy and appropriateness to project structural requirements, has already been an active participant in sustainable design. The structural engineer can further contribute to the overall sustainability of a project by considering and exploiting the efficiency, availability, recycled content, reuse, and impact a material has on the environment. Consideration of benefits and disadvantages of some of the major building materials
such as concrete, masonry, steel, and timber, are briefly outlined.

CONCRETE

Concrete consists primarily of cement paste binder and aggregate. While concrete is an essential and structural material, cement production contributes approximately 1.5% of annual U.S. carbon dioxide emissions [PCA], and as much as 7% of world wide annual emissions [Mehta, 1998]. Cement production produces approximately one pound of CO\(_2\) for each pound of cement. [Mehta, 2001]. The process of converting calcium carbonate into calcium oxide can be written as 

\[
\text{CaCO}_3 + \text{Heat} \rightarrow \text{CaO} + \text{CO}_2.
\]

Both the chemical reaction and the combustion of fossil fuels to drive the reaction produce carbon dioxide as a by-product. Reducing the amount of cement used in concrete will reduce carbon dioxide emissions.

The amount of cement in concrete can be reduced by substituting fly ash or ground granulated blast furnace slag, or slag for short, for cement. Fly ash is a by-product of the combustion of coal in electric power generating plants, and slag is made from iron blast-furnace slag. Fly ash has less embodied energy than Portland cement. Designers in Canada have used large volumes of fly ash in their concrete, replacing up to 80% by weight of the cement with fly ash. The Portland Cement Association recommends against such high replacement rates as such high percentages of fly ash reduces the amount of cement and thereby reduces the concrete’s alkalinity which is critical in protecting reinforcing steel from corrosion [PCA, 2005]. More typically, fly ash replaces cement at 15% to 25% by weight, and slag replaces cement at 15% to 40% by weight, with little effect on concrete mix design, placement, curing, and finishing. The Portland Cement Associations recommended replacement by weight percentages are listed in the table below [PCA, 2005].

<table>
<thead>
<tr>
<th>Product</th>
<th>PCA/ACI Recommended Replacement by Weight</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly Ash Class C</td>
<td>15% - 40%</td>
<td>Pozzolanic and cementitious properties - Generally available on East Coast and Midwest - Not allowed in California hospitals or public schools [CBC]</td>
</tr>
<tr>
<td>Fly Ash Class F</td>
<td>15% - 25%</td>
<td>Pozzolanic properties - Generally available on West Coast, allowed in California hospitals and public schools [CBC]</td>
</tr>
<tr>
<td>Slag</td>
<td>30% - 40% Typ.</td>
<td></td>
</tr>
</tbody>
</table>

Considerations when using fly ash at 15% to 25% replacement and for slag at 30% to 40% replacement for cement in concrete are the following:

- Minimal cost impact
- Improved workability
- Less bleeding
- Improved finishability
- Improved pumpability
- No change in plastic shrinkage
- No change in abrasion resistance

High Volume Fly Ash (HVFA) concrete mixes replace cement binder with fly ash at rates of 50% to 55% by weight. These mixes have been developed in recent years and have the advantage of reducing cement requirements while producing concrete with low permeability and lower heat of hydration. HVFA mixes require low water content and well graded aggregate; water-to-cementitious material ratios are usually on the order of 0.37 to 0.40 and “transitional” aggregates in the ½” to 3/8” size are used to provide good gradation. Low water content is achieved in part by using high range water reducing admixtures; proper curing is essential due to the low water content in the mix.
Finishing HVFA slabs can be a challenge as set time is usually retarded from six to eight hours, and the concrete can be stickier than conventional mixes. Strength gain is also slower in HVFA concrete than in conventional concrete though slower strength gain results in lower heat of hydration, making HVFA desirable for mat foundations or other thick section placements. Design compressive strength should be specified at 56 days, as opposed to 28 days, in recognition of the slower rate of strength gain.

HFVA and high slag replacement concrete can be most easily used in foundations and slabs-on-grade that do not require a finished surface. If HFVA is used, pre-construction conferences and mockups to familiarize concerned parties with the particulars of the material can be helpful. The source of fly ash or slag at exposed to view concrete should be constant throughout the project to avoid potential color variations. Concrete containing slag may show mottled green or blue-green areas for a few days after forms are stripped. Commonly termed “greening”, this discoloration disappears when the concrete is exposed to direct sunlight and air. Greening does not affect concrete properties but can be quite disconcerting if unexpected.

Ternary concrete mixes replace cement with a blend of fly ash and slag. 40% to 60% of the cement is typically replaced, with fly ash replacing approximately 20% of the cement and slag replacing the remaining portion. Ternary mixes with up to 70% replacement have been successfully used in California. Ternary mixes have the advantage of having set times and rate of strength gain similar to those of concrete with normal volume (20% or less) fly ash replacement.

Another sustainable approach when using concrete is to include recycled aggregate, which is generated as follows:

1) Breaking up and removing the old concrete.
2) Crushing this old concrete in primary and secondary crushers.
3) Removing reinforcing steel and other embedded products.
4) Grading and washing the aggregate.
5) Stockpiling the types of aggregate.

It is important to prevent other products from contaminating the final product. Recycled aggregate is mainly used in pavement reconstruction and can be used as the only source of aggregate or a partial replacement of aggregate. It generally has a higher adsorption and lower specific gravity than new, conventional aggregate, resulting from the high adsorption of porous mortar and hardened cement paste. This increased adsorption requires more water in the concrete mix to achieve the same workability and slump as with conventional aggregate. It is important to check the sulfate and chloride content of recycled aggregate before using it to avoid harmful chemical reactions. The durability, carbonation, permeability, resistance to freeze-thaw action, and even compressive strength of concrete made with recycled aggregate should be checked with project performance objectives. Additionally, drying shrinkage and creep may increase by up to 100%. There is potential for alkali-silica-reaction in recycled aggregate concrete. It is important to make trial batches of recycled aggregate concrete to determine its properties and proper mixture proportions. A potential hazard with using recycled concrete is the variability in the properties of the old concrete that may in turn affect the properties of the new concrete. In order to avoid this, it is necessary to frequently monitor the properties of the old concrete and adjust the mixture proportions as needed. At this time, concrete batch plants do not have dependable sources of readily available recycled aggregate, nor can they depend on constancy of material properties. The structural engineer should carefully research these aspects of recycled aggregate before specifying it in a mix design.

Specifications should be tailored to address exposed structure, typically when the concrete is used as thermal mass, as discussed later in “Synergies”. ACI 303.1-97, “Standard Specification for Cast-In-Place Architectural Concrete, American Concrete Institute, 1997”, includes provisions for Architecturally Exposed Concrete that addresses quality and uniformity of finish. Specifications can also include mock-ups of exposed concrete or CMU elements; mock-ups should be left on site for reference and comparison to finished work until the structural work is complete. Completed work at an existing building can serve as a reference sample allowing contractors to view the anticipated level of finish prior to bid. Input from the Architect is typically required in order to correctly specify the level of desired finish.
MASONRY

The use of concrete masonry has many sustainable benefits throughout the life of the structure. It is often obtained from local suppliers, and its thermal mass can be used for night time heat purge. Unlike light framed construction, masonry remains warm or cool long after the heat or air-conditioning has shut off, reducing heating and cooling loads and moderating indoor temperature swings year-round. Masonry also offers improved indoor environmental quality by eliminating plaster or paint if an architectural finish is desired. The use of masonry construction also reduces the potential for mold growth because masonry does not provide a ready food source for mold [NCMA]. Additional benefits are gained by specifying lightweight or aerated concrete masonry units whenever feasible. These units decrease resource depletion, reduce transportation energy impact, and increase concrete unit masonry wall insulation values.

Masonry construction also benefits from the specification of recycled content including fly ash, slag cement, silica fume and recycled or salvaged aggregates, for all the same reasons cited for concrete in the previous section [www.greenbuilder.com]. The use of fly ash is no longer limited to the masonry units themselves. In 1999, fly ash was added to the approved material list for grout within ASTM C476-99 “Standard Specification for Grout for Masonry”. There is, however, a maximum permissible amount of 40% when used with Portland cement [IMI]. Because fly ash results in less bleed water, grout with high fly ash content may have difficulty bonding to the CMU face shells. Therefore it is recommended that fly ash be used in limited quantities for grout, well below the maximum specified by ASTM C476-99.

In addition to traditional concrete and clay masonry units, there are many alternative forms of masonry available today. Adobe is an especially environmentally friendly masonry product, using less than one-sixth the production energy of concrete block [Karolides]. Interlocking concrete masonry units for landscape retaining walls do not require mortar and are easy to disassemble and reuse or recycle. Use of salvaged marble reduces demand on non-renewable virgin resources. Other salvaged materials such as brick and stone are readily available.

STEEL

Steel is the most recycled material used in modern building construction. In 2005 alone, almost 76 million tons of steel were recycled which corresponds to a recycling rate of 75.7% [www.recycle-steel.org]. This is an increase of 5% from 2004 and the highest steel recycling rate ever recorded in the United States. Steel in all forms including cans, automobile parts and structural shapes is continually salvaged by various mills throughout the country and can be made into new steel products of any form through one of two new technologies: the electric arc furnace (EAF) and the basic oxygen furnace (BOF).

The primary method used in the production of structural shapes and bars is the EAF which uses 95-100% [www.aisc.org] old steel to make new. With this process, producers of structural steel are able to achieve up to 97.5% recycled content for beams and plates, 65% [www.recycle-steel.org] for reinforcing bars and 66% [www.aiacolorado.org] for steel deck. Total recycled content varies from mill to mill. Steel for products such as soup cans, pails, drums and automotive fenders is produced using the BOF process which uses 25-35% [www.aisc.org] old steel to make new.

Given the nature of the structural steel manufacturing process (EAF), it is intrinsically unnecessary to specify that steel of a minimum percent recycled content be used on a given project, and doing so may trigger a reactionary and unnecessary increase in bid prices. Furthermore, since all steel is produced using recycled materials, geographical limitations are of minimal concern in the procurement of recycled steel.

Should there be a desire to salvage and reuse entire pieces of steel from one structure in another, consideration should be given to steel type and grade, accurately determining member size, previous use including loading, environmental exposure, and surface preparation, in order to ensure adequate assessment of the member’s structural integrity. For instance, residual stresses due to previous welding may be of particular relevance.

In addition to the recyclability and percent recycled content of the materials used in building construction, the deconstructability of a building can be considered when evaluating its sustainability. For instance, using
all-bolted connections in the structural framing system is one method for facilitating ease of deconstruction. As another example, the use of butted steel deck under concrete fill as opposed to lapped and welded metal deck also aids in deconstruction.

WOOD

Of the many material choices designers have at their disposal, timber at first glance may appear the least sustainable. Discussions of timber harvesting conjure images of clear cutting and global deforestation. However, timber holds the distinction of being the only conventional building material that is renewable. Additionally, it is biodegradable, non-toxic, energy efficient, recyclable, and reusable. With more than one-quarter of the world’s consumption of wood used in building products such as lumber, plywood, veneer, and particleboard [Lenssen and Roodman], a shift in the way structural engineers utilize timber could have far reaching ecological effects. The three primary areas the structural engineer can promote the sustainable use of wood are: efficient framing, alternative products, and sustainable material suppliers.

Conventional wood framing practice can be re-examined so that it is more efficient and less wasteful. Rethinking the way we detail light framed wood construction can significantly reduce a project’s wood waste. Consideration of efficient design strategies includes laying out the building so that dimensions are multiples of two feet to accommodate board and plywood sheets’ typical sizes, placing joists and studs at 24 inches on center, designing window headers to actual structural requirements, and using double 2x lumber instead of 4x where possible [San Mateo County’s RecycleWorks Program]. For efficient resource use of solid sawn lumber, the structural engineer can specify the most efficient grade of lumber to suit the purpose. These strategies need to be carefully balanced with the project structural demands, durability objectives, and design fee. For example, sheathing materials that can span 24 inches must be used, and the contractor must be prepared to use varying sized headers. The designer may want to elevate framing layouts to illustrate layout efficiency, something generally not done in document preparation and that could impact the design budget.

There are a number of alternatives to new solid sawn lumber available to the structural engineer. Reclaimed lumber can be used since it performs comparably to new lumber, provided that is properly inspected by a grading agency in accordance with American Lumber Standards Committee grading rules. The engineer should consider what effects past use might have on the wood, such as cyclic loading if wood members were used for bridges. Where uncertainty exists a testing program should be undertaken to verify wood properties.

Engineered wood products use timber in an efficient manner and thereby reduce the demand for large solid sawn pieces of virgin timber. As old growth forests have diminished, the giant mature trees have all but vanished as a lumber resource. Today the building industry is limited to younger, smaller trees that yield smaller pieces of lumber. By using these trees that are too small for sawn lumber, engineered lumber is a product that is available in larger sizes, is stronger, and can be more economical than traditional sawn lumber. As with all pre-engineered products, the appropriate use of engineered lumber should be considered for the specific project requirements.

The Federal Green Construction Guide for Specifiers [WBDG]] warns that engineered wood products might be more difficult to recycle than standard, solid sawn lumber due to the binders used in the manufacture of the engineered wood product. Additionally, it also suggests avoiding products manufactured with urea formaldehyde resin used as a binder. Formaldehyde is known to be a potential carcinogen to both workers and occupants since it can off-gas for years. There are two kinds of formaldehyde resin: phenol and urea. Phenol formaldehyde off-gasses less and for shorter periods of time. Products typically used in non-structural applications such as particleboard used as underlayment and for cabinets, usually contain urea-formaldehyde. Manufactured products typically used in structural applications use an exterior adhesive that usually contains phenol-, not urea-formaldehyde. Other structural manufactured products that contain phenol formaldehyde include plywood, oriented-strand board (OSB) panels, glued-laminated lumber, laminated and parallel strand lumber, and laminated veneer lumber. Despite these considerations, engineered lumber represents an efficient usage of natural resources and pre- and post-consumer recycled content.

Pressure-treated wood using with CCA (chromated copper arsenic) or ACA (ammoniacal copper arsenate) is
classified as hazardous waste by the EPA, and is no longer produced for residential and commercial use. An alternative treatment uses ACQ (ammonium/copper/quaternary ammonia) which does not contain arsenic or chromium, according to the “Federal Green Construction Guide for Specifiers”. ACQ is more corrosive to steel than CCA and ACA, requiring that fasteners have heavier galvanized coatings than for CCA and ACA, or are made of stainless steel.

Another effective way to incorporate sustainable design in wood design is to specify the use of Forest Stewardship Council (FSC) certified lumber. FSC is the only third-party non-profit organization that certifies sustainably harvested wood from environmentally responsibly managed forests. In practical terms, it means that the FSC defines industry standards for forestry that are environmentally responsible, socially beneficial, and economically viable. Non-sustainable harvesting of wood can produce soil erosion, pollutant runoff, increased levels of atmospheric carbon dioxide, global warming, and habitat loss [FSC]. Additionally, the support of non-sustainable wood promotes illegal logging which is quickly becoming an international crisis [www.illegal-logging.info/]. There has been progress gaining recognition in the industry, though less than 5% of all wood products in the country are now FSC-certified [Stewart]. While there are other competing standards for the certification of sustainably harvested lumber, the FSC system is the only one recognized by the USGBC as meeting the standards of the green building community.

Resource Conservation

Resource conservation can be considered in all stages of a project. These considerations include, but are not limited to material use, material source, construction process, and the end of a building’s useful life. Material, design and construction decisions have an enormous impact on the sustainability of buildings. The structural engineer has the opportunity to weigh these decisions with respect to the beauty, efficiency, function, constructability and budget of a building project.

DESIGN

During the design phase of a project, the structural engineer can affect the sustainability of a project through 1) the choice of locally available resources, 2) the recyclability and reusability of materials and systems, 3) the efficiency of structural systems, and 4) informed choices about demolition and preservation.

Resource location is a determining factor in material choice. Local resources minimize the use of fossil fuels in truck transportation and potentially increase the efficiency of the building process. The structural engineer should be aware of locally available materials, and make efforts to design using these materials. These materials would ideally be both harvested and manufactured in the local area. During construction, using local materials can result in shorter lead times, which can simplify logistics and speed up the construction process. The designers of the White Rock Operations Center in British Columbia set a goal to procure materials from manufacturers within a 500-mile radius of the site. The end result was that 31% of the building materials were obtained within this radius, and of these materials, 75% was harvested locally [O’Conner, 2005]. Choices concerning labor resources should be made similarly, though in fact the structural engineer often has little influence in contractor selection. For many of the same reasons as with material selection, a project’s overall sustainability will benefit when contractors and labor pools are in close proximity to the project location. Similar to procuring materials from manufacturers within a local radius, a goal should be also made to work with contractors and subcontractors within a certain radius (for example, 50 miles). Advantages of this include expertise on the local climate of the labor market, knowledge of local suppliers and manufacturers, and minimization of fossil fuels in daily transportation to the site. All these decisions about local materials and labor must be balanced with decisions of availability, cost, scheduling and appropriateness for the project as a whole.

The choice of the structural system during the design phase is another factor that affects the sustainability of a project. For both the gravity and lateral force resisting systems, the engineer has a choice of materials, which include wood, concrete, and steel. Often, the use of different materials to optimize the performance of each is the best solution. For example, steel cables can be extremely efficient tension members of a wood truss. Wood truss members can be supported by concrete walls and open web steel joists can be supported by wood shear walls. Taking advantage of the inherent properties of the material can result in a reduction of the amount of
material. Detailing can be done on a similar level, as there are many types of prefabricated steel connectors for wood members available. Lateral force-resisting systems have similar concerns. Various systems are appropriate for different scales, loads, functions, architectural requirements, and seismic performance levels. The efficiency and sustainability of the material chosen for the system, the various types of systems available for a given material, and the desired performance level must be determined. Some factors that affect material choice include weight per square foot, reusability, recyclability, deconstruction, and CO₂ emissions associated with the production and installation of the material, as well as all the traditional factors such as cost and performance. For each material, the material usage will also vary greatly depending on the lateral system; for example, steel moment frames could easily weigh twice as much as steel braced frames on a weight per square foot basis. A lateral system designed for a higher level than basic code requirements may cost more initially. However, during a seismic event, the structure will likely perform better and could save materials and labor by minimizing repairs, or in the worse case, avoiding demolition. In addition, time and cost savings can also be achieved since the building will be less disrupted for repair or rebuilding after an earthquake.

In order to fully consider sustainability in the building design process, options other than demolition at the end of a building’s useful life should be considered in design. Though an owner or architect would primarily make this decision, the engineer can facilitate this process by providing options for adaptability of the structure for other uses or deconstruction. The condition of the structure is often not the determining factor for when a building is no longer useful. Adapting a building for other uses will conserve resources associated with demolition and reconstruction and also eliminate construction waste. Examples of adaptability include the conversion of warehouses to residential lofts and industrial buildings to recreational facilities. To ensure that a structure can last into future building uses, it must be designed for durability in a seismic environment or any other natural hazards to which it may be subjected. The structural engineer’s choice of structural systems during the design phase also affects how a building can be adapted for a future use. Buildings often change use over their lifetime, and therefore require reconfiguration of partition walls, openings, etc. For example, designing a building with exterior perimeter structure, such as a perimeter moment frame, and interior partitions allows the building to easily change configuration. Deliberate placement of structure can integrate with the mechanical systems, openings for light and natural ventilation, all which allow for an energy efficient building even with changes of occupants and uses over time.

In seismic regions, a building may not be readily adaptable due to seismic deficiencies. However, the benefits of adaptability are the same as those associated with seismic rehabilitation of a structure. Savings can be found in resource conservation and preservation of the historic fabric of the structure.

When adaptability is not an option, deconstruction is the next best alternative to demolition. The goals of deconstruction are not only to design for ease of disassembling the structure but also for the members to be reused in other structures. Generally, the principles are similar to those for constructability of a structure. Design practices that lend themselves to disassembly include the use of bolted connections in steel structures, pre-cast members in concrete construction, and prefabricated shear walls and metal fasteners in wood construction. Some of these principles may not be appropriate in high seismic areas, but may be appropriate to implement in low to moderate seismic environments. Modifying and reusing members consumes less energy than recycling. Lastly, recycling is still an option if the building or member cannot be reused. Recycled steel only consumes one quarter the energy it takes to produce virgin steel [Pulaski].

**CONSTRUCTION**

Decisions that the structural engineer makes during the design phase affect resource conservation during the construction process and the end of a building’s useful life. In order to be better informed about the decisions affecting sustainability, the structural engineer and the entire design team can benefit from a contractor’s input and owner involvement during the design process. The contractor is often more informed of material availability and recyclability than the rest of the design team. The contractor can inform the design team of typical dimensions and size of materials that can affect design decisions. This may add an additional upfront cost, but over the duration of the project can provide a more streamlined process and end result, and therefore minimize cost.
Another factor that affects the construction process is the use of prefabricated elements, and the efficiency is even greater if a single unit type can be used repetitively in a project. Because prefabrication is typically done offsite in a shop under controlled conditions, it is easier to obtain more precise elements and a therefore a more efficient use of materials. Cost and material efficiencies are often found through mass production. Also, by producing the elements in a shop’s controlled atmosphere, material waste can be better and more easily controlled. Conditions can be established to control dust, noise and air pollution, and therefore minimize it on the construction site. These factors likely decrease the overall cost as well.

**Structural Systems**

The structural engineer has the opportunity to evaluate structural systems for their suitability for the present and future use of the building. The engineer also has the unique opportunity to communicate the benefits of performance-based engineering in the selection of a structural system and its impact to the life cycle cost analysis of sustainable design investment.

**ADAPTABILITY FOR FUTURE USE**

It is not uncommon for existing buildings to be partly or completely demolished before the lifetime of the building is near its end. This is mainly the solution owners seek when their individual buildings no longer serve as desirable space for occupancy, whether the owner desires flexibility in the tenant space, or the surrounding neighborhood redevelops to cater to a different set of customers altogether. In order to make the most of energy, labor, and materials used during new construction, it is beneficial to consider possible changes in use or occupancy that may occur over the lifetime of the building. Future possibilities for use should be discussed, established and accounted for in the initial layout and design process.

To allow for changes in use, consideration of floor vibrations can be made to ensure serviceability for a wider variety of future uses. The design load for floor systems can be increased from the minimum code level, not only to damp out vibrations, but also to support potential increases in load. For partial overhauls of gravity or seismic systems, a higher floor-to-floor height can allow for either deeper beams or a more open tenant space.

The structural system layout can be designed to accommodate unknown future tenant improvements that will almost certainly occur during the life of a building. Large open spans in an initial structural layout allow for more architectural options within that layout. The potential elimination of a column requires a redundant system, and if designing in steel, beams could be switched out for stronger ones if the connections are bolted.

**PERFORMANCE-BASED ENGINEERING**

The investment of design effort and thoughtfulness in the implementation of sustainable systems of a building deserves a corresponding amount of thoughtful design effort and owner investment in the structural system of the building. If the conscientious intent of sustainable design includes conserving operating costs and resources in the building and maintaining and prolonging the useful life of the building, then the design approach should extend beyond the building shell to the building contents as well. The building and its contents together comprise the sustainable design system. The consequences of the structural performance on the building contents and systems should be considered because the building performance can protect and prolong the benefits of the sustainable systems and of the other investments that the owner has committed to.

The selection of a structural system for a building has direct consequences when that system is tested during an earthquake. The performance of the structural system is manifest in the level of damage after the earthquake. There are two primary causes of damage: floor accelerations and interstory drift. High floor accelerations can cause damage to ceilings and lights, building equipment, elevators, and building contents. High interstory drift can cause damage to the structural frame, piping and ductwork and electrical systems, façade and window systems, and partitions. With the constant cyclic development of our engineering knowledge that incorporates observed damage from earthquakes and the implementation into practice, there is typically a predictable damage scenario that can be portrayed if the structural system, building type, contents, and cladding system are known. The intent of the code is to provide “life-safety”, and does not
preclude damage. The damage has a cost associated with it. If the damage is to be repaired, the repair effort uses resources in the form of labor, raw materials, and business resources that are suspended or redirected. If the damage is extensive enough that repair is not pursued, then resources are used to dismantle the building, and the building components are hauled away to landfill.

There is a negative financial impact with damage. If there is damage to the building and its contents, then the owner can lose initial advantages of any sustainable design decisions if there is significant value of earthquake damage. Other losses are in the downtime of the business, as well as in the efforts afterwards to recoup damage, such as creating duplicate functions to cover the losses until the damaged portion is repaired. The recovery efforts have physical and time components: repair and recovery of the physical plant as well as recovery of the interruption of business.

In order to avoid these negative cost and time scenarios, structural systems can be selected using a performance based design method, as informed by interaction with site characteristics. Typical structural systems such as braced frames and shear walls result in stiff structures with low drift and high accelerations. Other systems such as moment frames result in more flexible structures with high drifts and low accelerations. Energy dissipating systems such as isolation systems can reduce accelerations, and viscous dampers with moment frames can reduce drifts.

In the evaluation of different systems, the interaction of the site, building shell, and building contents should be considered. Life cycle cost implications should also be evaluated. The initial cost of implementing a structural system should be considered with respect to the value of the sustainable design components, the savings in operating costs, damage prevention, and the prolonged life of the building. Typically, the initial costs of a total new building consist of a structural system in the cost range of 10% - 20%, with the remaining 90% to 80% consisting of architectural, mechanical, electrical, and plumbing systems. Any slight premium in the small percentage of structural costs of the initial structure can be offset by the amplified benefits in the protection of the non-structural components.

Performance considerations of a structural system can have different criteria, depending on the function and objectives set out for the building. Good performance can be one where damage to the building shell and contents is minimized if the intent of the design is to have the building as intact and functioning soon after a seismic event. For another type of building and set of objectives, a measure of acceptable performance may be more extensive damage, but the damage is controlled. Evaluating and choosing a structural system for either scenario involves the same process of evaluating and balancing considerations in a probabilistic risk and cost analysis that includes performance metrics (accelerations, drift, damage), performance for different seismic levels, initial first cost, cost of repair or re-engagement of the building system.

Synergies

Synergy refers to the acting together of building parts or systems to the benefit of the building as a whole. The concepts of heat radiation and absorption using thermal mass, light and controls, photo-voltaics (PVs), and green roofs are presented, along with the structural engineer’s participation in the synergistic design process.

NIGHT TIME HEAT PURGE

Structure can work in synergy with a building’s cooling system by providing thermal mass for night heat purge, also referred to as nighttime cooling. In locations such as the west coast and desert regions of the United States, where the climate has daytime to nighttime (diurnal) temperature change of about 30 degrees F, mechanical engineers can design cooling systems that take advantage of radiating cool from the structure.

The temperature people sense in a building comes from the temperature of the surrounding air and the heat or cool temperature radiating from surrounding walls, floors, and ceilings. Traditional mechanical cooling systems provide cool (conditioned) air blown down from air supply diffusers in the ceiling, with 100% of the cooling provided by air handling units that consume energy to cool and drive air into the mechanical duct work. Night time heat purging, on the other hand, utilizes the mass of the structure to absorb heat generated by the building occupants and/or by sunlight entering the building during the day that is then exhausted at night,
resulting in cool walls, floors, and ceilings that radiate cool to the building occupants during the day.

The concept behind nighttime heat purge is straightforward. Introducing cool night air into a building can cool the interior of a building. Walls, floors, and/or ceilings that are exposed to the introduced air will be cooled by cool air passing over their surfaces, and if they are constructed of concrete, CMU, stone, or other materials with high volumetric heat capacity or “thermal mass”, they will radiate cool during the day while absorbing heat. At the end of the day, when the occupants have left the building, the cycle begins again. The coolness that the exposed structural elements radiate will reduce or eliminate the need to introduce conditioned air into the building, with a corresponding reduction in energy needed to produce the cooled air.

Lag effect: Thermal mass stores up heat and releases it later

When incorporating nighttime heat purge in the design of a cooling system, the mechanical engineer will minimize sources of solar heat gain. The architect will need to carefully insulate the building and seek to minimize direct sunlight entering the building. Natural day lighting of a building is an integral part of sustainable design, so rather than eliminate or restrict window size and placement, the architect will include sunshades above windows, allowing diffuse light to enter while blocking direct sunlight from entering the building. With the external source of heat gain minimized, the cooling system will utilize the mass of exposed walls, ceilings, and floors, to “exchange” cool for heat generated by the building’s occupants and activities.

The efficacy of this method of cooling requires that the structural thermal mass elements must be directly exposed to the building occupants so that the structure can absorb heat gained during the day, and radiate (or release) heat during the night. Ceilings, floors, and walls that are covered with finishes will not be as effective in cooling a building.

Concrete buildings naturally lend themselves to nighttime heat purge because of their high thermal mass and because their fire resistance permits the structure to be exposed. Generally speaking, exposing the concrete ceiling soffit and using appropriate carpeting over a concrete floor will provide sufficient thermal mass for heat exchange. Concrete walls can provide additional thermal mass. Concrete fill on steel deck used in steel buildings can provide thermal mass, but if the underside of the deck is fireproofed, its ability to transfer heat will be greatly reduced, thus reducing the effectiveness of night time heat purge to cool a building. Structural CMU walls, if exposed, can provide sufficient thermal mass for some buildings. The architect will usually require units with architectural finishes, and will require precise lay up and high quality workmanship. The structural engineer will need to coordinate with the architect to include these requirements in the CMU specification section when the engineer provides this section.

Specifications should be tailored to address exposed structure; this was previously presented in the concrete material discussion.

When laying out the structural system, the structural engineer should consider accommodating the movement of air through the building. Outside air is introduced into the building, often through operable windows or vents located along the entirety of the building’s perimeter. One strategy to move cool night air through a building is to locate fan units located on the roof that then pull the air through the rooms and into a plenum located above a corridor ceiling, where upon the air will travel to a shaft and then up and out of the building. As noted previously, not all of a ceiling need be exposed. Concrete shear walls will need to be located, or will require penetrations, to accommodate the air movement. Drop panels in ceiling plenums can interfere with the free airflow; stud rails can be used to provide slab punching shear capacity in place of drop panels. Likewise, beams perpendicular to the direction of desired airflow cause an encumbrance that can be resolved by upturning the beams and installing a raised floor. Raised floors, also known as access floors, have the added benefit of providing a location for mechanical, electrical, and plumbing ducts, conduits, and pipes.
STACK EFFECT

The stack effect is created by a vertical passageway for the hot air to naturally rise and pull cooler air from outside into the openings provided near the bottom of floors. This passage can be in the form of a tower along the exterior of the building that is heated by direct sun exposure, or by an atrium in the middle of the floor plan, through several stories, that is topped with a vented skylight. Note how this strategy lends itself synergistically with natural daylighting.

Anglia: Night Cooling and Stack Effect

If the air outside is not cool enough for occupant comfort, under-floor cooling in the form of forced air (air-conditioning) or radiant cooling (chilled water pipes) can supplement the system. Providing for the stack effect means that the structural engineer needs to be aware of the pathway needed, and not obstruct it with structural walls or other large elements. The engineer also should be aware of the materials used around the pathway and how they may help or hinder efficiency of the stack effect. For example, a material that heats up quickly when exposed to sunlight can be used along exterior towers to draw hot air towards it.

SUNSHADES AND LIGHT SHELVES

As noted above, naturally lighting a building is an integral part of sustainable design. Because sunlight will heat the interior of the building, sunshades may be placed above windows on the south and west facing walls, blocking mid-day and afternoon sun, while allowing light to enter the building. Sunshades are usually placed even with the tops of windows and project out horizontally outward from the face of the building. As sunshades are often quite light, upward wind pressures are typically the controlling design load. Where architecturally acceptable, rods or cables located above and below the sunshades and angled back to the building provide a good means of support. Attention to connection detailing is frequently required when using rods and cables as the connections are frequently visually exposed.

The architect often prefers a clean look that does not permit using rods and cables. In this case, sunshades are cantilevered out from the face of the building. Torsionally stiff square or rectangular HSS sections that span between columns or other supports can be integrated into curtain wall systems to support cantilevering sunshades.

Anglia: Daylighting, Sunshades and Lightshelves

Light shelves are located on the interior side of windows, and serve to introduce natural light deeper into the interior of the building. Light shelves reflect light upward and inward against the ceiling where it is then reflected downward and inward into the room. In this case, the horizontal elements, both external sunshade and internal light shelf, need to be located below the top of the window, so that sunlight may penetrate into the interior.

Like sunshades, light shelves are lightweight, so that strategies for supporting light shelves are similar to those used for sunshades, where the self weight is combined with seismic inertial forces as the governing load case. Often the magnitude of vertical force is small enough that the light shelf support can be incorporated into the window system. In this case, the structural engineer’s role is usually limited to writing performance specifications that provide design loads that the design-build window supplier must use when designing the window system to support the light shelves. The structural engineer then typically reviews the submitted design and accompanying structural calculations.
Horizontal elements are best for blocking sunlight on the south side of the building. On east and west exposures, vertical fins are more efficient. This is because of the movement of the sun across the building through the day. For vertical elements, the structural engineer needs to examine wind load normal to its face, much like designing for parapets. Note, for a site in the southern hemisphere, the building will experience most of its solar gain on its north side, instead of its south side. In general, an understanding of the sun’s path across the site is key to efficient sunshade design.

SOLAR ARRAYS / PHOTOVOLTAIC (PV)

There are several different types of solar arrays. One type is an array of solar panels, where individual panels are mounted on armatures that are anchored on roofs, walls, or the ground. Solar arrays can also be composed of solar panels integrated into roofing systems. Another type of array consists of a solar film that is applied to skylights, while another consists of shingles, similar to composition shingles, which are used as roofing.

Solar panels are lightweight, on the order of 5 psf. Wind outward or uplift pressure is usually the governing load case. Resistance to uplift can be provided by connecting armatures to the structure, though doing so often entails frequent penetrations and increases the risk of leaks. Alternatively, when mounted on roofs, armatures can be designed to engage ballast so that the weight of the system exceeds the wind uplift pressures. This strategy can be used at buildings with roofs that are strong enough to support ballast that can weigh 20 psf to 25 psf.

Solar arrays are often added to existing buildings. When added to the roof of an existing light wood framed structure, solar arrays may add sufficient mass that the existing seismic force resisting system requires checking. This is because large areas of roof are often covered with arrays composed of panels and armatures, with a combined weight of approximately 8 psf. This represents a substantial increase in weight when such lightweight roofs often weigh less than 20 psf.

Orientation and placement of the PV face perpendicular to the direction of the sun is critical for maximum efficiency. Thus, understanding the angle of the sun at a specific site—through the year and through the day—is very important. Additionally, PV cells require direct sunlight; hence any shadows on the PV face will impede its effectiveness significantly.

Positioning the solar arrays at an angle introduces another synergy. To better utilize the space created under the tilt, the design team can slope the roof and provide a row of openings at the top of the highest wall.
Along with openings—most likely operable windows—along the bottom of the short wall, this creates a pathway for hot air to rise, providing for natural ventilation diagonally across the section of the space. This is a general example of implementing the stack effect.

Audobon Center Los Angeles (EHDD, Wade Webb): Flat panel solar arrays

RADIANT HEATING

Regarding under-floor temperature control systems, radiant heating is often a more efficient way to heat a space than forced air through the ceiling. Since occupants are nearer the floor than the ceiling, and since heat rises, a radiant heating system will not need to heat all the air between the occupants and the ceiling, to achieve the desired comfort level. Because fluids have a higher heat capacity than air, delivering the heat through pipes takes up much less volume and requires less pump energy as well.

California Academy of Sciences (Arup): Radiant Heat Tubing Installation

For larger scale commercial construction, under-floor coils can be installed in the topping slab of both cast-in-place concrete floors, and concrete-filled metal decking. For example, for a 5/8” diameter coil, this may add approximately 2” of concrete, of which at least 1” is above the pipes, plus a layer of welded-wire fabric above the pipes to prevent cracking. Alternatively, coils or pipes can be embedded in the structural slab. To insure the structural integrity of the floor, an additional amount of concrete depth should be added equal to the diameter of the coils, similar to the way in which conduits are treated. In all cases, there is risk in damaging the coils if future slab penetrations are required, as it is not easy to locate the coils. Furthermore, the coils are typically difficult to repair.

Mechanical Detail (Arup): Floor with Radiant Heat Coils

This system is most commonly used for residential units, since they tend to be heating critical, compared to buildings with a large internal heat load, such as offices and theaters, which are cooling-critical. There are several installation options for wood-constructed systems. The key is the thermally insulating layer that must be placed below the coils. This is usually a few inches of foam between floor joists, which adds very little to the weight of the floor.
Structural Engineering Strategies Towards Sustainable Design
SEAONC Sustainable Design Committee

The structural engineer may be asked to embed the radiant heat pipes in a suspended structural slab. In this situation the engineer will prefer to center the coil in the slab; this often places it too far from the concrete surface to efficiently heat (or cool) the building. Coils located near columns will reduce punching shear capacity, and a prudent engineer may well restrict coil placement near openings or other areas of geometric irregularity. Coils embedded in concrete fill on steel deck that frequently cross steel beams may reduce composite action, particularly in areas of high bending demand. And coils placed in concrete slabs or fill may affect the assembly fire rating. These issues can all be avoided by placing coils in topping slabs. In this situation the added weight of the topping slab becomes the principal structural concern.

GREEN ROOFS

Green, or “living” roofs are becoming more popular as a sustainable design strategy. These are roofs almost completely covered with a layer of soil and planted with natural grasses and wildflowers as found in the surrounding area. These roofs serve three primary purposes. First, they channel and filter storm water runoff, decreasing the amount of total run-off and pollutants that enter our storm drains. Second, they provide a habitat for some of the birds, insects, and other ecology displaced by the building. And third, they create additional thermal insulation, reducing the energy required to control the temperature of the inside space.

The added weight of the soil and planting depends on the green roof system. While the first projects designed in the US with green roofs used an additional 100 psf for varietal grasses and 6” of soil, recent advances in lighter weight material has decreased the load to about 40 pcf of soil. The structural engineer should design for a saturated condition, where the weight of water is 62.4 pcf.

California Academy of Sciences: Layers in Green Roof (Renzo Piano Workshop)

The most important elements in an adequate design of a green roof are waterproofing and drainage systems. If water gets backed up on the roof without this consideration in the design, failure of roof beams under the additional load can be catastrophic. Compounding this is the popularity for green roofs to mimic the shape of grassy hills, in which drainage will naturally run towards the valleys, but if the drainage system does not work properly, the valleys can act as bowls for the water to collect in. The structural engineer should closely review roof drainage patterns and account for potential water accumulation in the roof’s structural design. An additional consideration is the anchorage of soil on sloping roofs. Soil anchorage is not in the structural engineer’s purview, but the engineer should understand how soil remains anchored in a seismic event and/or consider the consequences should it move.

The Future

Structural engineering is an integral part of sustainable design on a number of fronts: judicious and selective use of materials, resourceful use and application of structural systems, and provisions for future adaptability of the buildings that are designed today. Material selection can be optimized, and recycled and reclaimed or salvaged materials can be used. The performance, reliability, and reparable of structural elements in the seismic force resisting system contribute to sustainable design. The viability of the structural system and building shell to
accommodate future renovation becomes important. Structural design that considers the eventual deconstruction of a building increases the likelihood that the building components can be reused in another form. Collaboration with other design professionals is critical to the structural engineer’s successful role on a project - understanding lighting, stacking, thermal mass, cooling and heat gain strategies enables the structural engineer to anticipate and respond to these issues in the building structure.

As structural engineers, we have the opportunity to become an instrument of change in the industry. By encouraging the responsible use of our natural resources, and considering total building performance over its life cycle, we can proactively collaborate and participate in the “best practices” of structural engineering and sustainable design.

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