Sustainable Engineering: The Future of Structural Design

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Abstract

Structural engineers face significant challenges in the 21st century and among them, global environmental challenges must be a priority for our profession. On a planet with finite natural resources and an ever-growing built environment, engineers of the future must consider the environmental, economic, and social sustainability of structural design. To achieve a more sustainable built environment, engineers must be involved at every stage of the process.

To address the broad issue of sustainability for structural engineers, this paper is divided into three sections:

1) Global environmental impact: The trends in steel and concrete consumption worldwide illustrate the growing environmental impact of structural design. In particular, the emissions of greenhouse gases due to structural materials are a primary global concern that all structural engineers should consider.

2) Solutions for today: There are many steps that each structural engineer can take to mitigate the environmental impact of structural design. Furthermore, there is growing demand for engineers who are knowledgeable of environmental issues in construction. This section presents several options that are available today for engineers interested in reducing environmental impacts. Case studies will illustrate examples of more sustainable structural design.

3) Challenges for the future: Although short-term solutions exist to reduce the environmental impact of construction, there are significant long-term challenges that we must address as a profession. By facing these challenges, we can take a leadership role in matters of vital global importance.

In summary, the paper identifies the global sustainability challenges facing our profession and suggests possible solutions. The conclusion is that structural engineering has an enormous global environmental impact and our profession should work harder to offer solutions to society. Working for a more sustainable built environment is in the best interest of our profession as well as the interest of future generations.

Global Environmental Impact

On a planet with finite natural resources, the human population is growing and the rate of resource consumption per person is growing. This cannot continue indefinitely. In 1974, a landmark study by an interdisciplinary research group at MIT illustrated the various global scenarios that may occur depending on a range of possible technological, economic, and social assumptions (Meadows et al. 1974). Almost all of the possible scenarios predicted a collapse of natural resources followed by a collapse of human populations and decreased quality of life. Recently, a 30-year update reconfirmed the key conclusions of this study and illustrated the grave challenges facing global society in the future (Meadows et al. 2004). Increasing greenhouse gas levels, rising global temperatures, rising sea levels, and dramatic resource depletion have all occurred at increasing rates in the last 30 years.

The growing need to address these challenges has become more accepted in the last decade and civil engineers have begun to play an important role. Since the 1987 Brundtland report defined sustainable development as meeting "the needs of the present without compromising the ability of future generations to meet their own needs," the concept of sustainability has become an ethical standard and a goal for both government and industry (Brundtland 1987). Though civil engineers have not provided global leadership on this issue in recent decades, it is clear that the profession of civil engineering will play an integral role in achieving more sustainable development in the future (ASCE 2001). Over the last 200 hundred years, the definition of civil engineering has evolved from "directing the great sources of power in Nature for the use and convenience of Man" (Chrimes 1991) to a more recent definition that "Civil engineers are the custodians of the built and natural environment" (Agenda 2003). This shift illustrates the fundamental change in the relationship between engineers and the natural world. Man and nature are not separate entities. Engineers today must design for a planet with limited natural resources, complex problems with no clear answers, and increasing environmental concerns.

As a testament to the growing awareness of sustainability for structural engineers, the International Association of Bridge and Structural Engineers (IABSE) dedicated a recent issue of *Structural Engineering International* to sustainable engineering design. In particular, the emissions of greenhouse gases due to structural materials are a primary global concern that all structural engineers should consider. The trends in steel and concrete consumption worldwide demonstrate the growing environmental impact of structural design, as illustrated in Figure 1. The production of Portland cement has doubled in less than 30 years, and this exponential growth is expected to continue well into the next century (Chaturvedi and Ochsendorf 2004). Furthermore, each ton of cement is responsible for approximately one ton of CO_2 emissions and the cement industry alone contributes about 7% of global CO_2 emissions.[2]

[2] There is some debate about the contribution of cement production, with estimates ranging from 5% to 10% of total global CO_2 emissions.

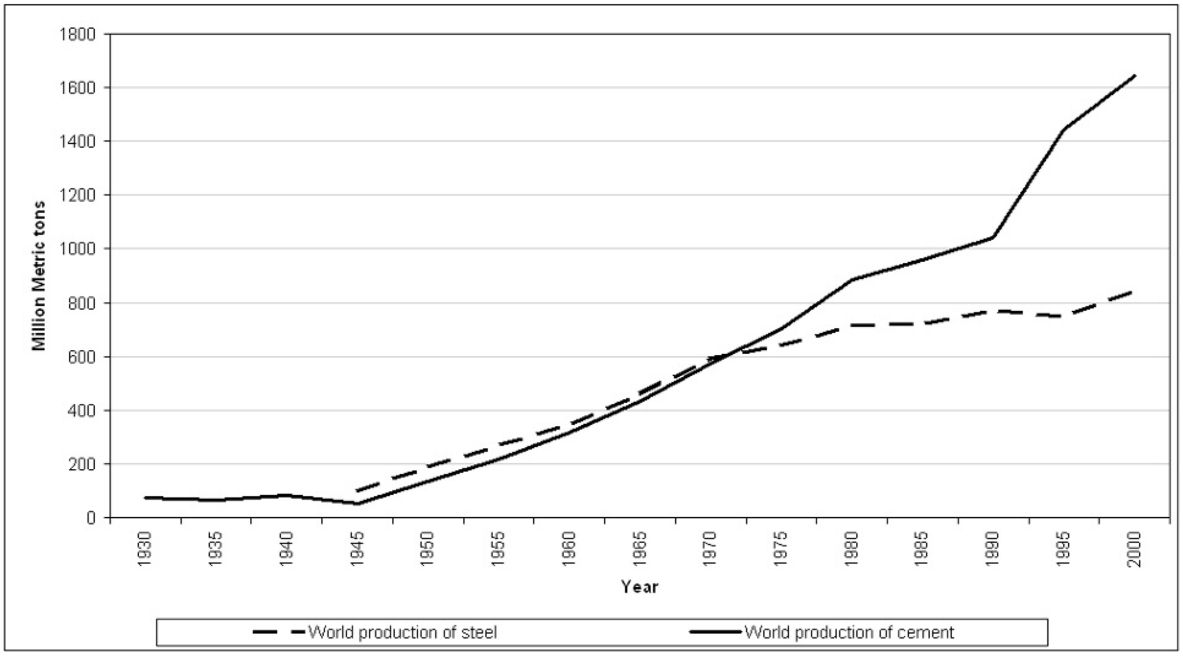

Figure 1: World production of cement and steel (Chaturvedi and Ochsendorf 2004)

Governments around the world are seeking to reduce CO_2 emissions in an effort to limit global warming. Many governments aim to go well beyond the goals of the Kyoto Protocol; for example, the United Kingdom has pledged to reduce CO_2 emissions by 60% by the year 2050. The construction industry and the built environment are responsible for a large percentage of total global CO_2 emissions, and therefore efforts to reduce global carbon emissions will require a strong emphasis on improving the sustainability of civil engineering.

Solutions for Today

There are many steps that each structural engineer can take to mitigate the environmental impact of structural design. Furthermore, there is a growing demand for engineers who are knowledgeable of environmental issues in construction. In the last ten years, the tremendous growth of the LEED rating system developed by the U.S. Green Building Council has illustrated the growing demand from clients and the general public (USGBC 2004). This section presents several options that are available today for engineers interested in reducing environmental impacts.

<u>Improve life cycle performance:</u> Currently most structures are designed to minimize the initial cost, rather than the whole life costs. For example, in the case of bridges, the maintenance and demolition costs often exceed the initial cost of construction, yet engineers rarely consider the whole life design costs. Small increases in initial costs could

dramatically reduce life cycle costs by decreasing maintenance and allowing for salvage or disposal at the end of life. By reducing life cycle costs, engineered structures can become much more sustainable than current practice. This is an obvious goal for engineering design, which can provide measurable improvements in the economic and environmental performance of construction. As an example of a more sustainable structure designed for improved life cycle performance, Joerg Conzett's Traversina Bridge in Switzerland was designed to be built using small sections of locally available timber (see Figure 2). A key design constraint was the need to replace any single piece of the structure without a need for auxiliary support. In this way, the structure could be maintained indefinitely using locally grown timber. This explicit design goal helped to achieve an elegant structure with low life cycle costs and improved environmental performance.

Figure 2. Traversina Bridge, Switzerland, by Juerg Conzett (1996)

<u>Specify salvaged or recycled materials:</u> The traditional approach to construction is to mine natural resources and convert them into useful products. As natural resources are depleted, engineers must begin to look for alternative sources of materials. In particular, we should mine the existing built environment for materials. This is occurring out of necessity for some materials already. For example, it has been estimated that more copper exists currently in the built environment than in the natural environment. Clearly, future generations will salvage and recycle the materials that we are extracting from the earth at present. Growing landfill costs and waste disposal problems will provide new economic incentives for recycling and salvaging. Concrete in the future will be made largely from salvaged materials and waste products. Indeed, this is already occurring today, with recycled aggregates, fly ash, and other waste products replacing natural aggregates and

Portland cement. The resulting products can have better environmental performance as well as reduced costs and improved engineering performance (Meyer 2004). In addition, designers should seek to maximize the flexibility of any structural design, to allow for future changes in the use of the building. As an example of a building constructed with recycled materials and maximum flexibility, the Stansted Airport Terminal in England serves as a useful case study. The long spans provided by the steel modules allow for great interior flexibility and also allow the building to expand and contract as needed in the future. As building use changes over time, the ideal structure would allow the change to occur. Otherwise, an obsolete structure will be dismantled and greater material consumption will be required for additional new construction. Finally, in the event that the Stansted terminal is no longer required, the modules could be disassembled and reused on another building site. Salvaging existing steelwork is far preferable to recycling due to the high energy requirements for recycling steel. Structural engineers should seek opportunities to salvage and reuse existing structures wherever possible.

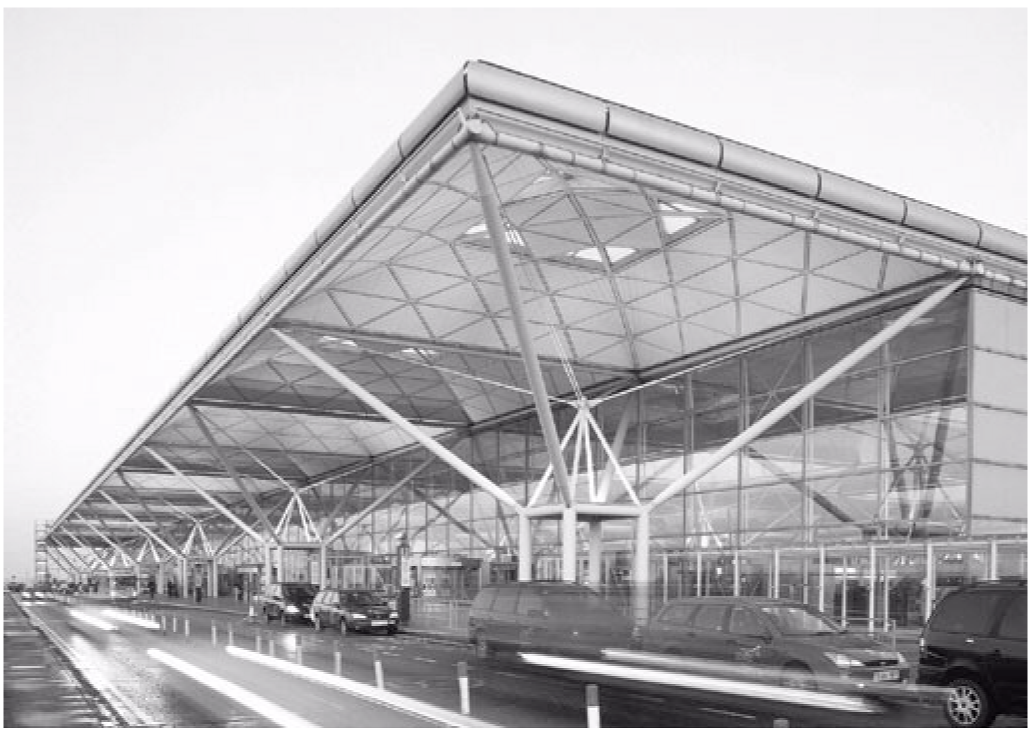

Figure 3. Stansted Airport, England, by Foster and Partners and Ove Arup (1991)

<u>Use alternative materials</u>: Structural engineering in the United States depends on two primary materials: steel and concrete. Unfortunately, both of these materials require tremendous amounts of energy to produce and are responsible for very high carbon emissions. These materials will continue to be dominant structural materials, for all of their inherent advantages. However, engineers can and should explore alternative materials. In particular, materials with lower environmental impact should be investigated. The Japanese Pavilion at the Hannover Exposition in 2000 illustrates the possibilities of alternative materials for structural systems (see Figure 4). The grid shell spanning up to 115 feet (35 meters) is produced primarily from paper tubes, which were

recycled at the end of the exposition. The architect Shigeru Ban worked closely with the engineering firm of Buro Happold to develop and implement the structural system composed of paper. In addition to the creative use of structural cardboard, the pavilion was supported by simple temporary foundations made of wood and sand, which could be easily removed at the end of the exhibition. Particularly for buildings with a short life span, engineers should explore alternative materials which achieve the engineering objectives of efficiency and economics, while reducing the environmental impact of construction.

Figure 4: Japanese pavilion at the Hannover Expo by Shigero Ban and Buro Happold

Challenges for the Future

Although many solutions exist today to reduce the environmental impact of construction, there are significant long-term challenges that we must address as a profession. By facing these challenges, we can take a leadership role in matters of vital global importance. In order to do so, the profession of structural engineering must consider the challenges in three key areas: practice, research and education.

Practice: The practice of structural engineering faces significant challenges in the effort to improve the sustainability of construction. The primary challenges are economic, and new policies will be required to help promote the economic incentives for sustainability. Firstly, the construction industry currently rewards engineers on the basis of initial cost, rather than life cycle costs. This leads to buildings and bridges with higher life cycle costs and higher environmental impact. For example, government spending on bridges as well as private sector spending on buildings could be drastically reduced through consideration of life cycle costs in construction. To allow for efficient whole life design in structural engineering, there is a need for policies which encourage accounting for the maintenance and disposal costs, as well as the initial costs, in structural design. Furthermore, there is a need to develop incentives to reduce material consumption in construction. In many sectors of the construction industry, payment is often proportional to the amount of material used, which encourages greater material consumption. Above all, the economics of construction should reflect the true costs, including the environmental impact of non-renewable resource depletion and the contribution of the construction industry to global environmental concerns. Though significant challenges exist in the sector of sustainable design, practitioners who can innovate in sustainable design will be poised to lead in the next century.

<u>Research:</u> Structural engineering is a mature field in comparison to nanotechnology and other emerging areas of research. As a result, research in structural engineering is increasingly focused on the assessment and maintenance of existing structures, as evidenced by the rise of non-destructive testing (NDT) methods and other new research areas in recent decades. A large portion of structural engineering work in the United States is focused on existing structures, rather than new construction, as owners try to keep up with maintenance requirements. The structural engineering community is already improving the sustainability of the built environment by increasing the life of existing structures rather than constructing new structures. However, in order to drastically improve the sustainability of the built environment, research in structural engineering must produce new options for practice. Above all, there is a need for new materials which can utilize waste products to build new structures with lower environmental and economic costs. Ideally, the built environment would help to absorb CO_2 and would utilize waste products from other sectors of society. In addition, the goal of a more sustainable built environment will require new cooperation between government, practice, and universities, as well as a broader outlook. Structural engineering research must engage with policy, design, economics, and social impacts, in addition to conventional research in mechanics and engineering science.

<u>Education:</u> To produce the future leaders of structural engineering, educators must be visionary. As with other academic fields, engineering education should promote critical thinking, where assumptions are questioned and students must solve open-ended problems with many possible solutions. We must go well beyond conventional structural analysis and we must teach design, as well as the broader thinking required to address the challenges of sustainable design, including the social and environmental impacts of structural design. Professional engineering associations are now requiring sustainable development principles in education. In the United Kingdom, the Royal Academy of Engineering has appointed visiting professors of sustainable development at 21 engineering departments in the last decade. The Royal Academy of Engineering "believes that the needs of sustainable development should become embedded in the thought

processes and methodologies of all practicing engineers and engineering designers."[3] This will help to alter the perception of engineers as narrow problem solvers standing in opposition to environmental protection (Ochsendorf 2003). Yet, engineering is a creative and vibrant profession with the ability to have a major impact on global environmental issues. Currently in the United States, less than 6 percent of college-bound high school graduates indicate that they will study engineering in college, down from 9 percent in 1992 (NY Times 2003). Engineering education can improve the perception of engineering while creating leaders in the realization of a more sustainable built environment in the next century.

Conclusions

As engineers, we have a responsibility to society to offer the best possible solutions. It is becoming increasingly apparent that existing engineering design does not minimize life cycle costs in terms of economics and environmental impact. To improve this situation, future engineers must develop a more holistic view of engineering design, which is commonly referred to as *sustainable design*. Achieving more sustainable design will require a concerted effort from practitioners, researchers, and educators.

What is sustainable engineering design? It is good design. It reduces material consumption, it improves the quality of life for people, it provides better economic performance, and it preserves natural resources for future generations. Engineering design in the 20th century has neglected the life cycle costs of infrastructure, and has not addressed the global environmental impact of the construction industry. We should strive to do better in the 21st century.

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[3] See http://www.raeng.org.uk/education/vps/sustdev.htm for this quote and other details of the scheme to incorporate sustainable development principles in engineering education in the UK.

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