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Structural Engineering Education in the Twentyfirst Century

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The unceasing quest of the society to enhance the quality and standards of living invariably culminates at the plans for the development of infrastructure. The prosperity of any country can be judged by its structures, be it buildings, bridges or towers. A vibrant economy and poor infrastructure rarely co-exist. A nation invests in the infrastructure not only for day-to-day needs but also for commerce, trade, defence, recreation and future development. Structural engineering is in the forefront of development wherever civilisation flourished. The challenges of structural engineers have increased enormously through centuries particularly in the current century with the dreams of multi-kilometre high towers and long bridges besides of establishing colonies on far off planets. Some of the aspects of structural engineering, its education and future trends are discussed in this brief article.

Keywords: computer applications, development, education, infrastructure, structural engineering

1. Introduction

The developments in infrastructure parallel the fiscal growth of a country, and reflect the standards of living as well as the vision and courage of engineers. Recent strides in globalisation and liberalisation led to extensive development of infrastructure all over the world. In general, infrastructure includes a wide range of systems such as roads, buildings, bridges, flyovers, communications, transportation, airports, harbours, storage, water supply, services and industry.

Any developmental activity involves structural engineering; housing, transportation, water resources, disposing of waste materials, recreation and commemorating an event invariably begin with planning and construction of a wide variety of structures. Even disaster mitigation and management involve structures to sustain and control nature's fury manifest as earthquakes, floods and tornadoes.

It can be said that engineers in general, and structural engineers in particular, not only sustain but also improve the quality of life continuously. There is barely any material, natural or industrial byproduct, which structural engineers cannot use to transform the society and protect environment from degradation.

The development of a nation depends essentially on structural engineers; growing more food, generating more power, keeping the nation on the move, commuting, shelter, flood control, environmental protection, and every other conceivable and inconceivable project to improve the quality of life. Structural engineers plan, design, construct, operate, maintain and rebuild infrastructure and environmental systems that are critical to the survival of human race and vital ecological systems (Grigg et al, 2001).

Structural engineering encompasses a wide range of disciplines ___ an aspect not always appreciated; besides the basic sciences (physics, chemistry and mathematics), it also includes material science, earth sciences, social sciences, commerce, forensic science, eco systems, languages, law, entrepreneurship, management, history, public relations and communications skills (Weichaert et al, 2001 and Yuzuriha, 1998). Since structural engineers deal with society and citizens directly more than any other stream of engineering, they interface with all sections of the society. Obviously the works of structural engineers are not only highly utilitarian but also are of high visibility, and stand out as land marks everywhere.

The challenges of structural engineers have increased enormously through centuries particularly in the current century with the dreams of multi-kilometre high towers and long bridges besides of establishing colonies on far off planets (Petroski, 1999). Structural forms, design process, and construction technology changed immensely over the centuries. Simple structural forms of Brooklyn and Stroemsund bridges pioneered the exciting forms of Alamillo and Akashi Kaikyo bridges (Rao, 2003); similarly, the Empire State Building inspired Burj Dubai and Petronas Towers. Manual methods of construction adopted in the ancient monuments such as Pantheon, Acropolis, and Pyramids, are replaced by highly mechanised systems in as much as the availability of high speed computing systems and versatile software have revolutionised structural forms and design processes. These developments have led to further challenges to structural engineers and university curriculum. It is essential that universities recognise these challenges and train young aspirants of the profession by modifying and extending the education programmes.

Some of the aspects of structural engineering, education, training and future trends are discussed in this brief article along with the revolutionary changes in the profession over the centuries with a few typical examples.

2. A BRIEF HISTORY

Civilization is replete with monuments built to challenge and inspire society to strive for new and better orders. Ancient Romans were possibly the best documented builders, who strove for utilitarian structures with pleasing features; some of these structures survive even today (Coliseum and Pantheon besides bridges and aqueducts). Marcus Vitruvius Polio's De Architectura is one of the rare documents that survived to tell us about Roman organisational structure (Hill, 1984). Vitruvius insisted that the three significant qualities of structures were *firmitas* (strength), *utilitas* (functionality) and *venustas* (aesthetics). The Roman system and concepts are not much different from what we have in vogue today.

Even the ancient builders dreamt of obstruction free spaces with primitive technology of yonder years. Various structural forms such as arches, domes and shells besides the ubiquitous post and lintel systems reflect the genius of structural engineers (Reiss, 2004).

No nation can overlook the contribution of structural engineers to the development of society and its prestige. Whenever a nation decides to showcase its accomplishments, it is always in the form of a new structure __ a bridge stretching a few more metres longer or a building rising a little higher than its predecessor. The ancient pyramids rising 140 m over plain sands gave way to the rising skyscrapers of the nineteenth century. The alluring arch spans of ancient bridges inspired the present day structures planned to stretch from continent to continent over vast seas.

The magnificent structural features of Alamillo Bridge (Spain, 1993), Akashi Kaikyo Bridge (Japan, 1998) and the Millennium Bridges (UK, 2000) would not have been achievable without structural engineers pushing the frontiers of materials and technology a little farther (Rao, 2003).

The fascinating and spectacular structures of yesteryears as well as those designed and built in the last few decades are pointers that many more fantastic structures may be in the offing (Ali, 1996). These structures were always preceded by the developments in materials and construction techniques, and reflect the vision and courage of the builders in adopting unconventional methods. Consequently, several structures are planned all over the world for the range of parameters not considered viable a few years ago.

The highrise buildings (skyscrapers) grew in size over the years in the previous century with Petronas Towers (Kuala Lumpur, Malaysia) reaching a height of 452.0 m (Petroski, 1999). Several structures are of comparable height in China, Taiwan, Japan and Hong Kong besides America. Plans are afoot already for an 840.0 m high millennium tower in Japan, and yet another to reach a kilometre height (Bennet, 2003). Even the Burj Dubai reaching a height of 600 m, and the ambitious 2 400 m high Dubai City Tower may soon be dwarfed.

Bridge spans and forms are even more fascinating; the one kilometre main span barrier of bridge structures was exceeded for the first time in 1931 by the George Washington Bridge over River Hudson, New York, USA (168.0 + 1066.7 + 168.0 m) to be quickly overtaken by the Golden Gate Bridge in 1937 with a main span of 1281.0 m

(San Francisco, USA), and extended to 1298.45 m by the Verrazano Narrows Bridge in 1964 (Reier, 1977 and Wittfoht, 1972).

The spans grew to incredible two kilometres well within a century of breaking the one kilometre barrier. The longest span of nearly two kilometres in the world is presently that of Akashi Kaikyo Bridge, Japan, 1996 (960.0 + 1 991.0 + 960.0 m), and will possibly extend to a few kilometres soon with further development of high quality materials (strength and ductility) and construction technology (Rao, 2003).

Hydraulic structures, that not only control floods but harness the flow to irrigate lands and generate power, are all the creations of structural engineers. The thirst of the society and the needs of industry for more and more water can only be satiated by magnificent structures like the Three Gorges Dam (China).

All these developments are possible because of the significant progress in material science and construction technology. Ultra high performance concrete (UHPC) with not only ultra high strength but also high workability, compaction, and durability was developed over the previous couple of decades, and found extensive applications in highrise buildings and bridges. Concretes of high pumpability, and self-compacting and self-curing properties have enhanced the possible spans of bridges, and have led to their adoption in highrise structures. The compressive strength of concrete in bridges increased to 350 MPa generally from a paltry 20 MPa strength that was possible a few decades back, but strengths of the order of 810 MPa were obtained using reactive powder technology (Rao, 2003).

Fibre reinforced plastics with their high strength to weight ratio are considered as the materials of future structures. Several bridges are built already using composite plastics. Nano carbon tubes are likely to stretch the bridge spans to a few kilometers from the longest present day span of nearly two kilometers.

The creations of structural engineers never deface nature or create wastage; no other industry can think of utilising waste products from another industry. Structural engineers enhance the quality of not only society but also of environment and eco-systems by utilising industrial wastes such as flyash.

3. STRUCTURAL ENGINEERING CURRICULUM

Structural engineering education involves the training to meet the greatest challenges of the society comprising not only the basic needs but also the ever growing quest for better quality of life. The curriculum should include not only conventional analysis and design, but prepare the candidates to use effectively information technology as well. Study of new construction materials, management and finances impart the skills needed to plan and execute the large projects that will be taken up in near future. New structural forms that stretch the column free covered spaces (airports, sports stadia and auditoria) should be taught to nurture creative talents of the young professionals, and enable them to evolve new forms not thought of so far.

The curriculum should commence with the study of the basic principles of analysis and design, encompass the materials of construction, and lead to the concepts of large structures seen around every day (tall buildings, long span bridges, rail tracks and roads connecting the nations, communications towers and water supply systems). The course plans should deal with practical aspects as much as with the theoretical formulations with emphasis on the development of mental faculties and computer skills. Only structural engineering teaches young professionals to dream, visualise, conceptualise and realise the projects to the benefit of society. The immediate goals and long term planning should make the course challenging, inspiring and rewarding.

The debris generated by inevitable structural damage in disasters such as earthquakes, floods requires transportation, recycling, and disposal. Structural engineers should learn the techniques of debris and waste management to reduce the environmental impact, and enhance quality of life.

The course should include new areas of development to prepare the young aspirants to meet future challenges. Besides extensive use of computers, software and information technology, the course should include basic engineering skills and communication skills as well. Quality control, assessment of structural condition, instrumentation and electronics, material science, and management (personnel, finance, and project) besides critical thinking and ethics are some of the areas that have to be incorporated in the curriculum.

Further, in view of the growing litigation in construction industry, it is essential that engineers are familiar with law as well (Grigg et al, 2001). Besides litigation, contractual disputes and arbitration are likely to test the mettle of structural engineers in future. Consequently, future engineers should be familiar with legal disputes and redressal techniques.

3.1 Analysis, design and construction

Earlier designers had the choice of construction site for their structures, which was an advantage. As the cities expand, and population increases, the location of structures is unlikely to be governed by design or construction considerations. Future engineers have to learn to deal with any construction site that may be far from ideal. Engineers should be trained to utilise the available sites rather than insist on ideal construction sites when the world population is likely to rise to 10 billion by the middle of the century.

They should also be able to visualise the problems associated with the given site conditions, and find suitable solutions. The design process comprises primarily the creation and analysis of alternative proposals, and developing the most feasible structural system for the given set of constraints. The geometric and material possibilities that could be explored were severely limited by the analytical tools earlier. Many of the interesting structural forms could never even be given serious consideration due to the limitations of design processes and construction techniques.

The pioneering cable stayed bridge, Stroemsund Bridge was built with only four cables in each pylon because of the computational limitations in the 1950s, while the complex profiles of Alamillo Bridge and the bridge over River Elbe in Aussig (Czechoslovakia, 1998) do not deter designers any more. Similarly, the approximate method of analysis adopted for the Empire State Building in the late nineteenth century are replaced by sophisticated analysis and design procedures adopted for Guggenheim Museum, Bilbao (Spain) for its intricate structural shells.

The scientific and technological advances of the industrial revolution radically transformed construction. New materials and systems helped builders and planners transcend the hitherto critical constraints on building size and complexity, leading to the development of skyscrapers, long span structures and large obstruction free spaces (Rao, 2004).

Structural engineers have to be familiar with the current developments and technology, and utilise them effectively.

3.2 Computer Applications

The availability of high speed computer systems with versatile software have revolutionised analysis and design procedures, and led to innovative concepts that were not possible earlier. Computer Aided Design (CAD) systems allow the creation of very complex three-dimensional geometric models with ease, and exploration of various models before developing final system. In addition, the sophisticated computer systems and simulation software render the approximations redundant; structural systems with near exact boundary conditions and environmental effects can be analysed with considerable reliability.

Computers were adopted by structural engineers sooner than other professionals (Rao, 2004). The celebrated structures, Sydney Opera House of Jorn Utzon and Guggenheim Museum, Bilbao of Frank Gehry provide sharply contrasting examples of the influence of computers on structural design and construction. Both were regarded as breakthrough buildings of their time, both caught the public imagination, and both became instantly emblematic of the cities in which they were built. While the Sydney Opera House was hampered by the inability to transform the exact profiles envisaged by the architect into the structural system in the late 1950s, the developments in CAD / CAM by the 1990s facilitated the design and construction of Guggenheim Museum to a great degree. Gehry's initial sketches and models for a museum were even more audacious assemblage of free-form curved surfaces than Utzon's in the 1950s. But by the 1990s, accurate modelling for analysis and construction was no longer a problem. Gehry's office employed CATIA, (Computer Aided Three Dimensional Interactive Application) an advanced CAD system mostly used, until then, in aerospace and automobile design. CATIA provides a repertoire of spline surfaces, ruled surfaces, and other surface types that can be instantiated and assembled within a three-dimensional Cartesian coordinate system to model just about any form a designer might imagine. The CATIA digital model, rather than a conventional set of drawings, served as Gehry's definitive design representation.

Whereas Utzon in the 1950s had been forced to rely on laboriously handmade drawings and scale models in his explorations of visual and spatial effects, Gehry in the 1990s employed visualisation software to produce, almost instantaneously, whatever views were needed. He could also utilise rapid prototyping devices to generate physical models automatically. The digital model also provided input data needed for structural and other analyses. The complexity of these analyses no longer presented a difficulty either; the available algorithms had improved enormously in versatility and scientific accuracy since the 1950s of Utzon's days, and the computer power needed to execute them had become abundant and inexpensive.

Even at the construction stage, the digital model was used to control CAD / CAM fabrication processes. This greatly reduced the necessity for shape uniformity and component repetition. Gehry did not have to simplify the structural profiles, like Utzon's resort to spherical patches. The chasm between what could be dreamed of, and what could be produced has narrowed dramatically with the advent of software systems.

While the Sydney Opera House commenced with the international competition in 1957, and could be completed in 1973 with several disputes and controversies, Bilbao Museum with all the advantages of the CAD / CAM systems was opened in 1997 within five years of the conceptual designs.

Structural engineers of the future should be familiar with a wide range of software systems including CAD / CAM systems, GIS, drafting and data processing besides possessing extensive analytical and design skills.

3.3 Quality control and Non-Destructive Testing

It is essential to transform the designs into the envisaged structural forms, and ensure their long maintenance free service. Construction is never complete without quality control and quality assurance records. The most sophisticated designs are of little avail, if they cannot be translated into safe and economical structural systems. Structural engineers should also be familiar with quality control methods to ensure compliance with building standards.

Monitoring of structural response is an integral part of engineering design; the validity of mathematical model adopted in the analysis can be verified only by comparing it with the behaviour of the actual system. Earlier techniques, being mostly destructive, were confined to laboratory models or structural components. However, with the advent of sophisticated and reliable techniques, testing is extended from small scale elements to investigations on existing structures. The efforts to validate theoretical assumptions are extended to monitor the structural behaviour and health of the structures. Further, the destructive and semi-destructive methods have given way to Non-Destructive Testing (NDT) techniques.

Structural response encompasses a wide spectrum of parameters that control the behaviour of structures (Rao, 2007 a). Though a wide array of equipment are available for testing concrete structures, their application calls for considerable experience, judgment and comprehension of instrumentation as well as materials. The instrumentation depends upon several factors, such as the objectives of the test programme, its duration (short or long term), parameters to be monitored (strength, corrosion, quality, stress, deflections, vibrations, deficiencies and deterioration), time and finance available as well as the significance of the structure.

The techniques vary from simple sonic and ultrasonic pulse velocity (UPV) methods to those of infrared thermography (IRT) and ground penetrating radar (GPR) systems (Rao, 2007 b and c, 2008). These methods are widely adopted in engineering practice to estimate the quality and uniformity of the materials, to locate flaws (discontinuities and cracks), and to obtain sub-surface images. Dynamic response of structures provides an indication of structural performance and its variation with time.

Structural engineers are required to have an insight into the concepts, equipment, instrumentation, applications, and interpretation of data for monitoring and assessment of structural systems. The curriculum should provide training in the advanced techniques as well.

3.4 REHABILITATION, RETROFITTING AND RESTORATION

Rehabilitation and retrofitting of structures require considerable ingenuity and experience. The former implies the restoration of structures to its original state, while the latter involves strengthening the structure to sustain larger loads than those envisaged in the original design. Deterioration of structures due to poor construction practices or aggressive environment necessitates repairs and rehabilitation in order to restore them to the intended level of performance. Retrofitting may be a sequel to changes in structural usage or enhanced loading standards.

Restoration primarily refers to the maintenance and preservation of historical buildings, and structures of national importance. Structural engineers should be familiar with the techniques of rehabilitation and retrofitting, and update their knowledge continuously to learn the new developments, and adopt them. Several advanced repair materials and systems are developed in the past few decades, including fibre reinforced plastics.

4. FUTURE TRENDS

The growth in infrastructure, including housing, roads, recreation centres, commerce and trade zones besides airports and sea ports, all over the world render structural engineering as the destination career of the current century. Every country has to extend transportation facilities, housing, water resources, besides maintaining and rehabilitating the existing infrastructure. These require extensive human resources, trained in analysis, design, construction, testing, and maintenance besides the adoption of teaching technology (Wankat and Oreovicz, 1993, and Weichert et al, 2001).

Structural engineers of the current century should be capable of designing structures to resist abnormal loads imposed by explosions and severe fires caused by accident or terrorist acts, besides seismic and wind forces (ASCE, 1997 and Bangash and Bangash, 2006). Scarcity of building materials and environmental concerns require sustainable engineering practices and recycling of materials to reduce carbon foot print. Wide availability of smart materials and sensors are likely to facilitate continuous monitoring of structural performance of important bridges and buildings. Health monitoring of structures and infrastructure security are other areas of extensive development in near future. Micro-electromechanical systems (MEMS) and nano-electromechanical systems (NEMS) are likely to be deployed on a large scale to monitor continuously a wide range of parameters such as pressure, temperature, pH, strain, moisture levels and acceleration in structures (Saafi and Romine, 2005). The sensors are mixed with materials such as concrete, and are embedded in structures at the time of construction itself for continuous monitoring. Any changes in structural performance are sensed, and signals are generated. The signals from these devices, in combination with GPS and GIS, provide a powerful system to monitor the condition of structures, and trigger suitable corrective measures.

Seabed mining, cities under the seas, tunnels under ocean beds between continents, subterranean structures, colonies to be built on the moon and other planets involve primarily structural engineers. Familiarity with law will be essential in view of the growing litigation in the industry.

The available infrastructure is hardly adequate to meet the current needs; only intelligent planning and dedication of trained structural engineers will pitch fork the society into the realm of peace and prosperity.

5. CONCLUSIONS

The challenges and requirements of structural engineers in the current century are discussed briefly in this article. The prosperity and quality of life can be maintained only by continuous development of infrastructure to meet the needs of the society. Every aspect of life depends upon the infrastructure, and its development. It is essential that the university courses are reviewed and updated periodically in order to include current developments, and prepare the young aspirants to strive for the development of society.

The prosperity of any country can be judged by its structures, be it buildings, bridges or towers. A vibrant economy and poor infrastructure rarely co-exist. A nation invests in the infrastructure not only for day-to-day needs but also for commerce, trade, defence, recreation and future development.

Based on the discussions presented, it may be noted that the curriculum of structural engineering in the current century should be updated continuously to include advances in the additional subjects listed below.

- Computer Aided Analysis and Design (CAAD)
- Graphical systems
- Material science and technology
- Smart materials, sensors and control systems
- Repair, rehabilitation and restoration techniques
- Advanced Non-Destructive Testing (NDT), and quality control techniques
- GIS, and data base management
- Electronics, and instrumentation
- Waste and debris management, and recycling
- Management (personnel, finance, and project)
- Law, contract management, and arbitration
- Construction technology
- Entrepreneurship

It should not, however, be overlooked that structural engineers should have firm grounding on the basic principles of analysis and design, learn the algorithms, develop a keen sense of observation, and be involved with field work. Critical thinking, problem solving capabilities, social responsibility and ethical practices are an integral part of the profession, in any case.

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