STRUCTURAL, GEOTECHNICAL AND EARTHQUAKE ENGINEERING

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Keywords: structural analysis; structural design; earthquake engineering; geotechnical engineering; seismic protection; structural engineering

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Summary

An overview of essential topics in structural and geotechnical engineering with particular focus on those related to earthquake engineering is presented. One of the objectives of this introductory chapter is to eventually provide readers with insights into seismic analysis and design. Beginning with a brief history of structural engineering, topics in structural analysis and design are reviewed. This is followed by a brief overview of geotechnical engineering with emphasis on foundation design and modeling for geotechnical applications. The final section focuses on earthquake engineering covering both structures and foundations and highlighting both traditional seismic design and innovative seismic protection.

1. Introduction

The subject areas that encompass structural, geotechnical and earthquake engineering can all be regarded as topics within the broad field of civil engineering. While structural engineering focuses on the design of the visible part of a finished structure, geotechnical engineering is concerned with the design of the structural foundation below the soil surface. Together, structural and geotechnical engineers must ensure the safety of the soil-foundation-structure system during a strong earthquake. While there continues to be observed damage and failure following a major earthquake, ongoing research and innovation are contributing to increased safety of structures under extreme loads.

2. Structural Engineering

Structural engineers are responsible for ensuring the integrity and structural safety of buildings by designing the primary structural framework of all structures to withstand stresses and deformations resulting from all expected sources of loading. This requires an in-depth knowledge of the mechanics of building materials as well as linear and nonlinear structural analysis under both static and dynamic loads.

2.1. Brief Historical Perspective of Structural Analysis and Engineering

The earliest feats of structural engineering date back to the construction of the pyramids in Egypt. It is acknowledged that the first structural engineer known today by name is possibly Imhotep, the Egyptian official to whom the building of a stepped pyramid of the Pharaoh Djoser is attributed. Structural engineering prior to the industrial revolution can best be described as an immature field that relied mostly on trial-and-error and experiences of the past. It was not until the advent of scientific revolutions of the 17th and 18th century that the mechanics of materials and structures were adequately understood to enable the design of robust and efficient structures.

Many great minds have contributed to our understanding of structural mechanics and engineering:

- Notes by Leonardo da Vinci include concepts in strength of materials and detailed illustrations of structures (including a bridge spanning over 200 m) and machines.
- Galileo's *Dialogue*, published in 1638, provided insights into strength of materials, beam theory and structural dynamics.

The other principal contributions came from:

- Robert Hooke (relationship between force and elastic deformation),
- Isaac Newton (laws of inertia, force and reaction),
- Daniel Bernoulli (principle of virtual work, beam theory),
- Leonhard Euler (theory of buckling, beam theory),
- Claude-Louis Navier (theory of elasticity),
- Carlo Alberto Castigliano (theorem of least work),
- Otto Mohr (statically indeterminate structures, graphical method for analyzing stresses),
- Timoshenko (beam theory),
- Hardy Cross (moment distribution method for continuous beams), and
- Ray Clough (matrix structural analysis and formalization of the finite element method).

Looking back to the evolution of structural forms at the element level, the beam is perhaps the oldest and dates back to prehistoric times. Beams carry load by bending action which causes axial tension and compression in the longitudinal fibers of the beam. However, it is not suited for long spans which therefore led to the development of arches and trusses. The simplest way to transmit a vertical load to the supports is using a cable which carries only tensile forces. Modern examples of cable-based structural forms are suspension and cable-stayed bridges. An inverted cable that is rigid (as opposed to cables that are flexible) represents an arch and carries load primarily through compression. If the arch cannot be constructed as an exact inversion of the cable shape (also called funicular) under the expected loads, some bending forces will also be introduced in the arch. The final form of a skeletal structure is the truss which is an assemblage of members that resist axial forces only if the connections are truly pinned (i.e. permit rotation without restraint).

Other basic structural forms include surface structures, such as plates and shells. Returning to the beam element, a collection of beams can form a frame (which comprises both horizontal and vertical beam elements) or a grid structures (if the beams are in the same plane). As a beam grid is refined (meaning the spacing between beams is reduced), it will evolve into a plate when the spacing of the beams in each direction reduces to zero. Plates carry load by so-called two-way action, i.e. bending about both axes. However, as the aspect ratio (length-to-width) increases, a plate responds similar to a beam by resisting loads through one-way action. Finally, shell structures resist loads through in-plane or membrane action. Shells provide one of the most attractive structural forms – as is evident from large span roofs of auditoriums, arenas, etc. Illustrations of these basic forms are shown in Fig. 1.

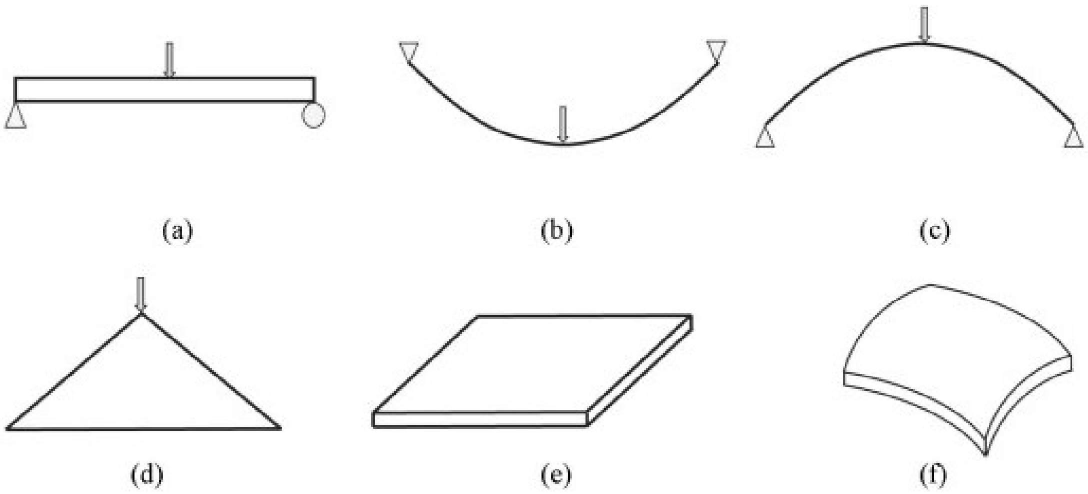

Figure 1. Component structural forms: (a) beam; (b) cable; (c) arch; (d) truss; (e) plate; (f) shell

Structural engineering comprises roughly five sequential though often inter-related activities as follows:

(1) Development of the structural form and dimensions based generally on the intended function of the structure (for major structures, this is performed by an architect with or without consultation with a structural engineer);
(2) Estimation of the type, magnitude and frequency of different loads that will be imposed on the structure during its lifetime;

(3) Development of a structural framework to resist imposed loads, establishing proper load paths from structural members to the foundation, followed by structural analysis of the framework to ensure adequacy of the design (this is usually an iterative process);
(4) Selection of structural materials for various parts of the structure (this activity may often occur during the development of the structural form but may be changed as the structural analysis reveals issues and concerns with the initial selection); and
(5) Construction of the final design.

2.2. Linear and Nonlinear Analysis of Structures

In general, structural analysis involves the estimation of response quantities such as deformations, stress resultants (shear, bending moment, etc.), support reactions, etc. under the action of specified dead and live loads including other effects such as temperature changes, etc. Additionally, it may be necessary to determine internal stresses in a connection or component through more detailed analysis using advanced tools such as finite element software (continuum finite element analysis is beyond the scope of this chapter).

Linear structural analysis implies linear behavior – the material stress-strain response remains in the elastic regime and the deformations of the elements of the structure are small enough such that equilibrium equations can be formulated in the undeformed configuration. An obvious advantage with linear analysis is that calculated deformations and internal forces scale linearly with the applied loading. Moreover, the principle of superposition can be used to add the separate effects of multiple load cases. The linearity of response is typically enforced by the following assumptions: the displacements are infinitesimally small, the material is linearly elastic, and the boundary conditions remain unaltered during the application of the load. However, if any of these conditions is not true during any part of the analysis, the displacement response cannot be fully predicted using conventional linear procedures. In particular, the use of superposition principle is no longer valid. Most of the design of actual structures is based on linear analysis. Under normal service loads, the assumption of linearity is sufficient and adequate. Extreme loads (such as high winds and strong earthquakes) can deform a structural member beyond the elastic range and it becomes necessary to carry out a nonlinear analysis of the system to ensure reliability of the predicted behavior. Since a nonlinear analysis can be complex and time-consuming, approximate procedures exist to approximate nonlinear effects in a linear analysis. Likewise, dynamic effects are sometimes approximated by equivalent static procedures.

In the analysis of structures, two common factors causing nonlinearity are those due to variations in material property and changes in geometry. Material nonlinearity can be incorporated either by specifying the nonlinear constitutive relationship at the material level (as in continuum finite element analysis) or by specifying inelastic member behavior using resultant force-deformation models through rule-based hysteresis curves. Examples of specifying material nonlinear behavior is illustrated in Figure 2. Geometric nonlinearities arise when deformations become excessive and the original equations of equilibrium formulated in the undeformed configuration (first-order analysis) may no longer be valid in the deformed state of the system. While reinforced concrete structures can undergo significant inelastic deformations, a large-displacement formulation (using an updated or total Lagrangian formulation) is generally unnecessary. However, the additional moments and shear forces generated due to over-turning moments caused by excessive lateral displacements (particularly in the presence of large axial forces) must be incorporated. This is referred to as the P-delta effect which is a type of geometric nonlinearity (second-order effect) and involves the computation of a geometric stiffness matrix. Element forces are still computed assuming small displacements though material stress-strain behavior is nonlinear.

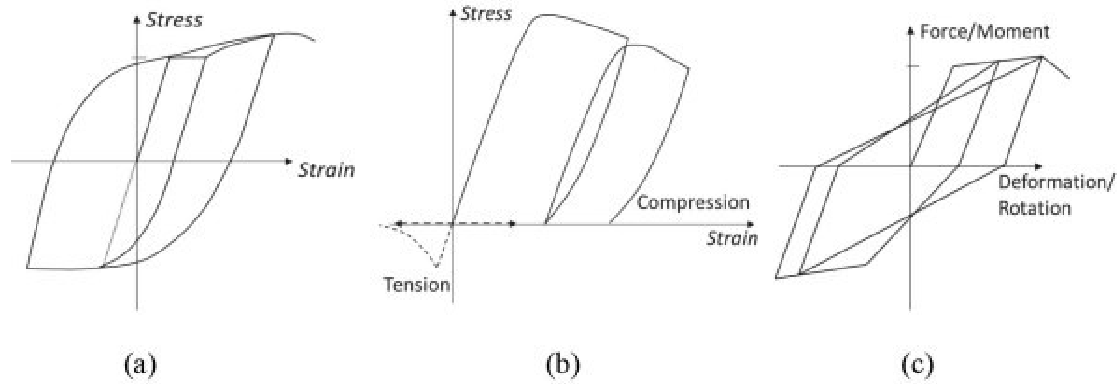

Figure 2. (a) Typical cyclic constitutive model for steel; (b) Typical cyclic constitutive model for concrete; (c) Typical cyclic model to represent overall member behavior

The process of carrying out a complete nonlinear analysis of a structural system can be divided into three phases:

(a) Modeling – which involves the creation of a mathematical model of the structure accounting for the requirements and limitations of the software being used in the analysis;
(b) Evaluation – which consists of the numerical analysis of the mathematical model created in the previous step under the specified loads; and
(c) Interpretation – which comprises the validation of the modeling and making sense of the results of a complex analysis of an idealized model.

The task of modeling a real structure is, undoubtedly, the most vital of the three, since the reliability of the resulting numerical evaluation is a direct function of the simplifications and/or approximations introduced in the modeling process. Real structures are essentially three-dimensional and composed of solids and surfaces that must be rendered into simple elements based on the limitations of the numerical tools being used in the analysis. The basic objective in modeling is to represent the structural configuration as accurately as possible so that a reliable evaluation of its response under the imposed loading is accomplished with optimal effort. This step assumes greater importance in the case of nonlinear or inelastic analyses because –

(a) The behavior of individual elements, and consequently the whole structure, is now governed by many more parameters and
(b) This requires a thorough knowledge of the mechanics of material behavior and associated numerical problems.

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Bibliography

Anderson, D. and Brzev, S. (2009). *Seismic Design Guide for Masonry Buildings.* Canadian Concrete Masonry Producers Association, Vancouver, BC, Canada. [This document is intended to assist practicing structural engineers in designing masonry buildings for seismic load effects according to the National Building Code of Canada]

ASCE (2013). *Seismic rehabilitation of existing buildings*. ASCE/SEI 41-13. American Society of Civil Engineers, Reston, VA. [This book is a performance-based guideline for seismic rehabilitation of existing buildings]

Bruneau, M., Uang, C-M and Sabelli, R. (2011). *Ductile Design of Steel Structures.* 2nd Edition, McGraw Hill. [This book provides comprehensive coverage of the background and design requirements for plastic and seismic design of steel structures]

Chopra, A. (2017). *Dynamics of Structures: Theory and Applications to Earthquake Engineering*. 5th Edition, Pearson/Prentice-Hall. [This book covers the fundamental theory of structural dynamics with a focus on applications in earthquake engineering]

Danatzko, J.M. and Sezen, H. (2011); Sustainable Structural Design Methodologies, *ASCE Practice Periodical on Structural Design and Construction*, 16 (4), pp. 186-190 [This paper investigates and discusses the following five sustainable structural design methodologies: minimizing material use, material production energy, embodied energy, life-cycle analysis/inventory/assessment, and maximizing structural system reuse].

Fajfar, P. and Krawinkler, H., editors (1997). *Seismic design methodologies for the next generation of codes*. Balkema Publishers, Rotterdam. [This paper reviews existing procedures and discusses future trends in performance-based seismic design]

Filiatrault, A. and Folz, B. (2002). Performance-Based Seismic Design of Wood Framed Buildings. *ASCE Journal of Structural Engineering,* 128 (1), 39-47. [This paper discusses the application of performance-based seismic design to wood framed buildings through a direct-displacement methodology

Krawinkler, H. and Miranda, E. (2004). Performance-based earthquake engineering. In *Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering*. (Bozorgnia and Bertero, editors), CRC Press.

Moehle, J. (2014). *Seismic Design of Reinforced Concrete Buildings*. McGraw Hill. [An excellent book on design of reinforced concrete structures subjected to seismic loads]

Paulay, T. and Priestley, M.J.N. (1992*). Seismic Design of Reinforced Concrete Buildings*. John Wiley & Sons. {this book provides an overview of seismic design principles with a focus on displacement-based design}

Vamvatsikos, D., and Cornell, C. A. (2002). Incremental dynamic analysis. *Earthquake Engineering & Structural Dynamics*, 31(3), 491-514. [This paper provides a detailed account of carrying out an incremental dynamic analysis of structures to assess their collapse stability under earthquake loads]

Biographical Sketch

Sashi Kunnath is Professor of Structural Engineering in the Department of Civil and Environmental Engineering at the University of California at Davis (UCD). He received his undergraduate degree from

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