J.C. SMITH

STRUCTURAL STEEL DESIGN:

LRFD FUNDAMENTALS

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PREFACE

This book was written to serve as the undergraduate level textbook for the first structural steel design course in Civil Engineering when the AISC Load and Resistance Factor Design(LRFD) Specifications are used. Some of the material in Chapters 1 and 6 may be more appropriate for the second structural steel design course. Also, this book is intended to serve as a brief introduction to the LRFD Approach for structural design practitioners.

When the LRFD Manual became available, I began to use it in two graduate level courses. One course deals only with plastic analysis and design of continuous beams and plane frames. The other course deals with buckling of frames, second order effects, elastic analysis, and computer aided design of multistory buildings. After these two favorable experiences with the LRFD Manual, I decided to begin using the LRFD approach in the first undergraduate steel design course. Since reliable sources revealed that the first LRFD textbook probably would not be available until about the fall semester of 1989, I began to write a camera ready textbook which would contain only the material I planned to teach in the first undergraduate steel design course. I had always begun with tension members in the ASD approach for the first undergraduate steel design course, but I had not dealt with the LRFD approach for tension members in the two graduate level courses. Consequently, the first chapter I wrote was on the behavior and design of tension members by the LRFD approach. There is not time enough in the first undergraduate course to discuss all types of connections, so I decided not to include a chapter on connections. However, the behavior and design of tension members is dependent on the type of member end connections. Therefore, I chose to include a very brief introduction to fillet welded and bearing-type bolted connections for tension members at appropriate locations in Chapter 3. Thus, I treated member end connections for tension members as an integral part of the behavior and design process of tension members whereas in most texts connections are discussed in a separate chapter.

Although the LRFD Specifications permit either an elastic factored load analysis or plastic analysis, my decision to use only the elastic factored load analysis was almost automatic. We have a second structural design course at the undergraduate level in which the students are required to design a six story office building as an unbraced frame using steel members and to design the same building using reinforced concrete members. I have written a computer program to perform a second order plastic analysis of a plane frame and use it in the graduate level courses. However, the ACI Code permits only an elastic factored load analysis. I did not want to require my students to learn how to use two different computer analysis packages, so I decided to use only the elastic factored load analysis approach in the second undergraduate structural design course. When I made this decision, I also decided to include some textual material which would give structural design practitioners and the students in our second undergraduate steel design course a brief but realistic introduction to analysis and design of unbraced frames in the LRFD approach. Consequently, I included the last two sections of Chapter 6 and Appendix A.

I do not use the textual material associated with Appendix A in the first undergraduate course. Also, I do not use any of the text example problems in my classroom presentations. Instead, I make up simpler and completely different examples for my classroom presentations. This provides the students with at least two examples which they can study for a thorough understanding of what is being numerically illustrated.

Appendix B was included to serve as review material since the students need a thorough understanding of principal axes for column action and for beam action.

Until the students become familiar with the organization of the LRFD Manual and Specifications, they do not know precisely where to look for the needed information. Therefore, throughout this text I chose to give the applicable page numbers in the LRFD Manual in addition to the applicable LRFD Specification numbers. The applicable page numbers in the LRFD Manual were given to aid the students in quickly finding the needed information.

ACKNOWLEDGEMENTS

I hereby acknowledge that Harper & Row, Publishers, Inc. granted me permission to use the following indicated portions of my textbook entitled *Structural Analysis* [1] copyright 1988:

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Also, I appreciate the list of detected errors and detailed comments on chapter 3 given to me by my teaching assistant, Mr. E. T. McMurray, during the first semester this text was being used in an undergraduate steel design class.

When I encountered something that could not be done as described in the Macintosh II user's manual and in the software manuals, I went to see my Mac II guru, John F. Ely, who is also my colleague. He had always been there before me and correctly told me how to do what I was wanting to do. He saved me from numerous hours of frustration and I thank him profusely.

Also, I must thank Cliff Robichaud, engineering editor of John Wiley & Sons, for being confident that I would prepare an acceptable camera ready textbook.

J. C. Smith

October 1988

A Note on the Production of this Text

An Apple Macintosh II personal computer having only 1MB memory and a 40MB hard disk was used in the preparation of this text. The author printed the text on an Apple LaserWriter and Wiley photographed the LaserWriter copy to obtain the camera ready pages. The software applications used were Microsoft Word for word processing, MacDraw I for the graphics, and MathWriter for the more complex equations. The Times 12 point font was chosen for the text, and either 9 or 10 point fonts were chosen for the subscripts and superscripts.

About the Author

J. C. Smith was born in 1933 near Hudson, North Carolina and lived there until he began his studies in the Civil Engineering Department at North Carolina State University where he received his B.C.E. degree in 1955 and entered graduate school. His master's degree studies were interrupted by a two year tour of duty in the U. S. Army where he served as a Civil Engineering Assistant doing planning studies on the blast and fallout effects of nuclear weapons. He received his M.S. degree from North Carolina State University in 1960, became an Instructor for one year, and began his doctoral studies. He received a faculty Ford Foundation Grant for two years to pursue his doctoral studies in Civil Engineering at Purdue University where he received his Ph.D. degree in January 1966. In 1965 he accepted a faculty position at North Carolina State University where he is now an Associate Professor of Civil Engineering. He is the author or coauthor of 20 technical papers and the author of 3 other texts. His areas of expertise are in the analysis and design of steel and reinforced concrete structures with special emphasis on computer applications. He is a registered professional engineer in the state of North Carolina. On numerous occasions he has been asked to serve as a consultant to structural engineering firms and to privately owned companies engaged in construction and in engineering. He is a Fellow of the American Society of Civil Engineers. He has been Secretary-Treasurer of the North Carolina Section of ASCE, Vice-President of the North Carolina Section of ASCE, and the Faculty Advisor of the Student Chapter of ASCE at North Carolina State University.

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Chapter 1

INTRODUCTION

1.1 STRUCTURAL BEHAVIOR, ANALYSIS, AND DESIGN

A *structure* is an assembly of members interconnected by joints. A *member* spans between two joints. The points at which two or more members of a structure are connected are called *joints*. Each support for the structure is a boundary joint which is prevented from moving in certain directions as defined by the structural designer.

Structural behavior is the response of a structure to applied loads and environmental effects (wind, earthquakes, temperature changes, snow, ice, rain, etc.).

Structural analysis is the determination of the reactions, member forces, and deformations of the structure due to applied loads and environmental effects.

Structural design involves:

1. arranging the general layout of the structure to satisfy the owner's requirements (for non-industrial type buildings, an architect usually does this part)
2. preliminary cost studies of alternative structural framing schemes or/and materials of construction
3. preliminary analyses and designs for one or more of the possible alternatives studied in item 2
4. choosing the alternative to be used in the final design
5. performing the final design which involves:
   a) choosing the analytical model to use in the analyses
   b) determination of the loads
   c) performing the analyses using assumed member sizes which were obtained in the preliminary design phase
   d) using the analysis results to determine if the trial member sizes satisfy the design code requirements
   e) resizing the members, if necessary, and repeating items b) thru e) of step 5, if necessary
6. checking the steel fabricator's shop drawings to ensure that the fabricated pieces will fit together properly and behave properly after they are assembled

7. inspecting the structure as construction progresses to ensure that the erected structure conforms to the structural design drawings and specifications

Structural analysis is performed for structural design purposes. In the design process, members must be chosen such that design specifications for deflection, shear, bending moment and axial force are not violated. Design specifications are written in such a manner that separate analyses are needed for *dead loads* (permanent loads), *live loads* (position and/or magnitude vary with time), *snow loads*, and effects due to *wind* and *earthquakes*. Influence lines may be needed for positioning live loads to cause their maximum effect. In addition, the structural designer may need to consider the effects due to fabrication and construction tolerances being exceeded; temperature changes; and differential settlement of supports. Numerical values of E and I must be known to perform continuous beam analyses due to differential settlement of supports, but only relative values of EI are needed to perform analyses due to loads.

Structural engineers deal with the analysis and design of buildings, bridges, conveyor support structures, cranes, dams, offshore oil platforms, pipelines, stadiums, transmission towers, storage tanks, tunnels, pavement slabs for airports and highways, and structural components of airplanes, spacecraft, automobiles, buses, and ships. The same basic principles of analysis are applicable to each of these structures.

The engineer in charge of the structural design must: 1) decide how it is desired for the structure to behave when the structure is subjected to applied loads and environmental effects; and, 2) ensure that the structure is designed to behave that way. Otherwise a designed structure must be studied to determine how it responds to applied loads and environmental effects. These studies may involve making and testing a small scale model of the actual structure to determine the structural behavior (this approach is warranted for a uniquely designed structure -- no one has ever designed one like it before). Full scale tests to collapse are not economically feasible for one of a kind structures. For mass produced structures such as airplanes, automobiles, and multiple unit (repetitive) construction, the optimum design is needed and full scale tests are routinely made to gather valuable data which are used in defining the analytical model employed in computerized solutions.

Analytical models (some analysts prefer to call them mathematical models) are studied to determine which analytical model best predicts the desired behavior of the structure due to applied loads and environmental effects. Determination of the applied loads and the effects due to the environment is a function of the structural behavior, any available experimental data, and the designer's judgment based on experience.

A properly designed structure must have adequate *strength*, *stiffness*, *stability*, and *durability*. The applicable structural design code is used to determine if a structural component has adequate *strength* to resist the forces required of it based on the results obtained from structural analyses. Adequate *stiffness* is required, for example, to prevent excessive deflections and undesirable structural vibrations. There are two types of possible *instability* : 1) a structure may not be adequately configured either externally or internally to resist a completely general set of applied loads; and, 2) a structure may buckle due to excessive compressive axial forces in one or more members. A skateboard, for example, is externally unstable in its length direction. If a very small force is applied to a skateboard in its length direction, the skateboard begins to roll in that direction. Overall internal structural *stability* of determinate frames may be achieved by designing either truss-type bracing schemes or shear walls to resist the applied lateral loads. In the truss-type bracing schemes, members which are required to resist axial compression forces must be adequately designed to prevent buckling, otherwise the integrity of the bracing scheme is destroyed. Indeterminate structural frames do not need shearwalls or truss-type bracing schemes to provide the lateral stability resistance required to resist the applied lateral loads. However, indeterminate frames can become unstable due to sidesway buckling of the structure.

In the coursework that an aspiring structural engineer must master, the traditional approach has been to teach at least one course in structural analysis and to require that course as a prerequisite for the first course in structural member behavior and design. This traditional approach of separately teaching analysis and design is the proper one in the author's opinion, but in this approach the student is not exposed to the true role of a structural engineer unless the student takes a structural design course which deals with the design of an entire structure. In the design of an entire structure, it becomes obvious that structural behavior, analysis, and design are inter-related. The most bothersome thing to the student in the first design of an entire structure using plane frame analyses is the determination of the loads and how they are transferred from floor slab to beams, from beams to girders, from girders to columns, and from columns to supports. Transferral of the loads is dependent on the analytical models which are deemed to best represent the behavior of the structure. Consequently, in the first structural design courses the analytical model and the applied loads are given information, and the focus is on structural behavior and learning how to obtain member sizes that satisfy the design specifications.

1.2 IDEALIZED ANALYTICAL MODELS

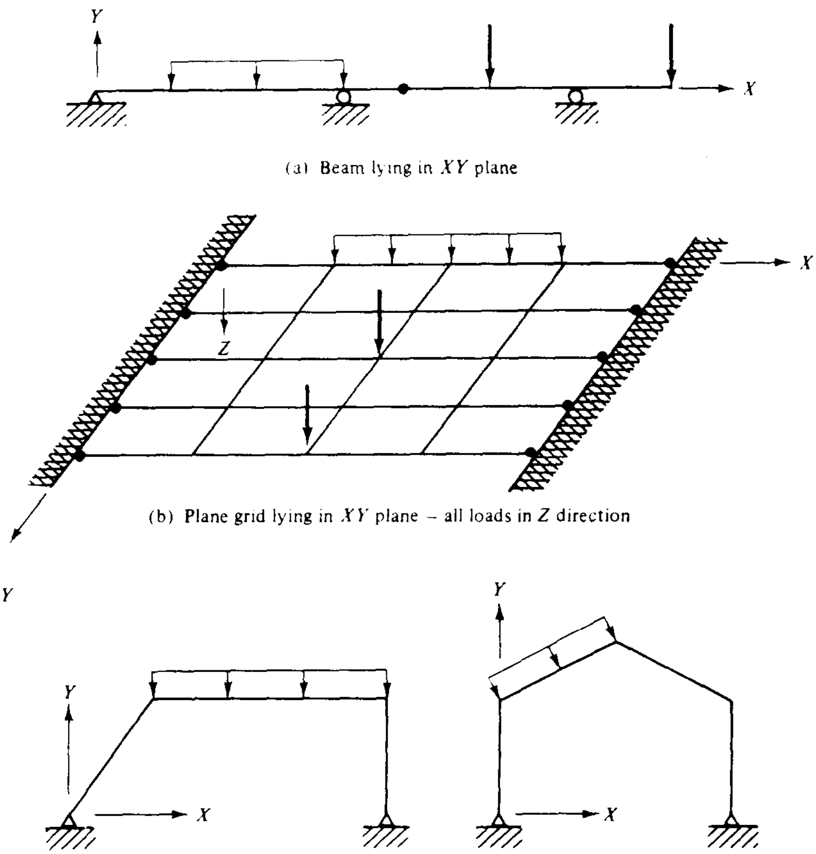
Structural analyses are conducted on an analytical model which is an idealization of the actual structure. Engineering judgment must be used in defining the idealized structure such that it represents the actual structural behavior as accurately as is practically possible. Certain assumptions have to be made for practical reasons: idealized material properties are used, estimations of the effects of boundary conditions must be considered, and complex structural details that have little effect on the overall structural behavior can be ignored (or studied later as a localized effect after the overall structural analysis is obtained).

All structures are three dimensional, but in many cases it is possible to analyze the structure as being two dimensional in two mutually perpendicular directions. This text deals only with either truss type or frame type structures. If a structure must be treated as being three dimensional, in this text it is classified as being either a space truss or a space frame.

A *truss* is a structural system of members that are assumed to be pin connected at their ends. Truss members are designed to resist only axial forces and truss joints are designed to simulate a no moment resistance capacity.

A *frame* is a structural system of members that are connected at their ends to joints that are capable of receiving member end moments and capable of transferring member end moments between two or more member ends at a common point.

If all of the members of a structure lie in the same plane, the structure is a two dimensional or planar structure. Examples of planar structures shown in Figure 1.1 are: beams, plane grids, plane frames, and plane trusses. Note that all members of a plane grid lie in the same plane, but all loads are applied perpendicular to that plane. For all of the other planar structures, all applied loads and all members of the structure lie in the same plane. In Figure 1.1 each member is represented by only one straight line between two joints. Each joint is assumed to be a point which has no size. Members have dimensions of depth and width, but a single line is chosen for graphical convenience to represent the member spanning between two joints. Thus, the idealized structure is a line diagram configuration. The length of each line defines the span length of a member and usually each line is the

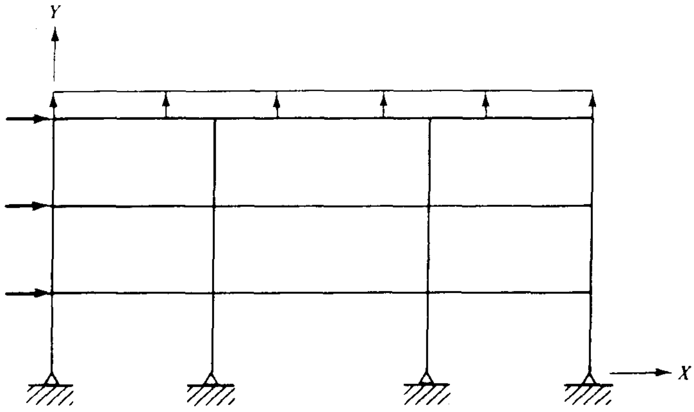


(a) Beam lying in XY plane

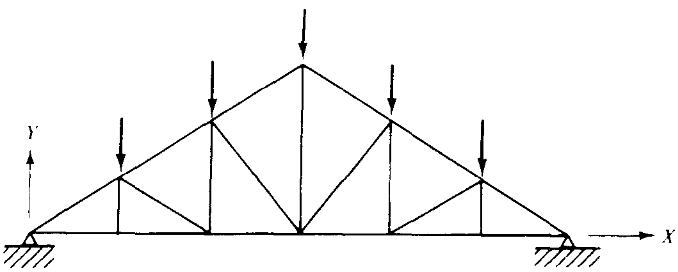
(b) Plane grid lying in XY plane – all loads in Z direction

(c) One-story plane frames lying in XY plane

Figure 1.1 Examples of planar structures



(d) Multistory, multibay, plane frame lying in XY plane



(e) Plane truss lying in XY plane

Figure 1.1 (continued)

trace along the member's length of the intersecting point of the centroidal axes of the member's cross section.

1.3 BOUNDARY CONDITIONS

For simplicity purposes in the following discussion, the structure is assumed to be a plane frame. At one or more points on the structure, the structure must be connected either to a foundation or to another structure. These points are called support joints (or boundary joints, or exterior joints). The manner in which the structure is connected to the foundation and the design of the foundation influence the number and type of restraints provided by the support joints. Since the support joints are on the boundary of a structure and since special conditions can exist at the support joint locations, the term boundary conditions is used for brevity purposes to embody the special conditions that exist at the support joints. The various idealized boundary condition symbols for the line diagram structure are shown in Figure 1.2 and discussed in the following paragraphs.

A *hinge*, Figure 1.2(a), represents that a structural part is pin connected to a foundation which does not allow translational movements in two mutually perpendicular directions. The pin connection is assumed to be frictionless. Therefore, the attached structural part is completely free to rotate with respect to the foundation. Since many of the applied loads on the structure are caused by and act in the direction of gravity, one of the two mutually perpendicular support directions is chosen to be parallel to the gravity direction. In conducting a structural analysis, the analyst guesses that the correct direction of this support force component is either opposite to the direction of the forces caused by gravity or in the same direction as the forces caused by gravity. In Figure 1.2, the reaction components are shown as vectors with a slash on them and the arrows indicate the author's choice for the guessed directions of each vector. It must be noted that the author could have guessed the opposite direction for each vector.

A *roller*, Figure 1.2(b), represents a foundation that permits the attached structural part to rotate freely with respect to the foundation and to translate freely in the direction parallel to the foundation surface, but does not permit any translational movement in any other direction. To avoid any ambiguity for a roller on an inclined surface, Figure 1.2(c), the author prefers to use a different roller symbol than he uses on a horizontal surface. A *link* is defined as being a fictitious, weightless, non-deformable, pinned-ended member that never has any loads applied to it except at the ends of the member. Some analysts prefer to use a link, Figure 1.2(d), instead of a roller to represent the boundary condition described at the beginning of this paragraph.

A *fixed support* , Figure 1.2(e), represents a bed rock type of foundation that does not deform in any manner whatsoever and the structural part is attached to the foundation in such a manner that no relative movements can occur between the foundation and the attached structural part.