CHAPTER 1

INTRODUCTION

1.1 FROM THE METAL COLUMN TO THE STRUCTURAL SYSTEM

This guide contains a summary of modern knowledge on the behavior of metal columns, a knowledge that over time has been expanded and generalized to include any member, component, or structural system with significant portions in compression. Advances in the application of the metal structural column have involved the interrelated development of theory, materials, testing machines, test instruments, design procedures, and design standardization. The history of column theory goes back to the work of the Swiss mathematician Leonard Euler, who in 1744 published his famous column formula (Euler, 1744). The theoretical developments since then represent some of the finest achievements in the discipline of applied mechanics. Bruce G. Johnston, editor of the first three editions of this guide, has given a clear review of this history in the paper “Column Buckling Theory: Historic Highlights” (Johnston, 1983).

Since 1944, when the Column Research Council (CRC) was founded, much of the theoretical and practical work related to metal column design was performed under the auspices of the Council. In 1976 the name of the Council was changed to Structural Stability Research Council (SSRC) to reflect the broadened scope of the research. The history of the CRC-SSRC—its accomplishments and the personalities involved—has been recounted by Bruce G. Johnston (1981) from the firsthand point of view of an active and creative initial and continuous participant.

Ever since its inception the Council has played a leading role in developing rational design criteria based on research not only for metal columns but also for all types of structures and structural elements in which stability can impact behavior. This accumulated knowledge has been disseminated by the SSRC in many forms, but the chief vehicles for presenting the sum of it have been the five previous editions of this guide (1960, 93 pages; 1966, 217 pages; 1975, 616 pages; 1988, 786 pages; 1998, 911 pages). The present sixth edition aims to continue this tradition.

1.2 SCOPE AND SUMMARY OF THE GUIDE

The continued importance and vitality of the research on stability problems is due to technical and economic developments that demand the use of ever-stronger and ever-lighter structures in an increasingly wider range of applications. Such an expansion of use is made possible by developments in (1) manufacturing, such as metallurgy, cold forming, extruding, and welding; (2) theory and understanding of behavior under load; (3) fabrication technology, such as the automated assembly of structural members; (4) computer-aided design; (5) economic competition from nonmetallic materials; and (6) construction efficiency. These developments continually not only change the way in which traditional structures are designed and built, but they also make possible the economical use of material in other areas of application, such as offshore structures, transportation vehicles, and structures for outer space. In all these applications the demands of higher strength and lighter weight inexorably lead to structures in which a consideration of stability must play a crucial role in design. Increased strength and increased slenderness invariably lead to problems with instability.

The third edition of this guide (published in 1975) was a substantial expansion over the second edition (published in 1966), introducing a number of new chapters that reflected the expanded scope of the council. The fourth edition (published in 1988) added three new chapters, two on the fundamental topics of stability theory and finite element analysis of stability problems and one on box girders which dealt with the special stability problems of these structures having very slender plate elements. The fifth edition (published in 1998) included not only several new chapters but also a significant amount of reorganization to make room for these chapters. New topics included the stability of horizontally curved beams, stability of angle members, bracing, and stability under seismic loading.

Although no new chapters have been added in this sixth edition, many of the chapters have been significantly revised to reflect recent developments in various areas of stability research and recently adopted design criteria. Such areas not only include fundamental structural components such as columns, beams, and beam-columns, but also box girders, curved girders, bracing, composite systems, thin walled metal construction, frame stability, arches, stability under seismic loading, and stability analysis by finite element analysis. A few of the chapters, which deal with topics that did not receive a great amount of research interest from the task groups of the SSRC, were left relatively unchanged except for some updating of the literature and introducing one or two new topics. The previously appearing chapter entitled “Selected Topics in Dynamic Stability” was deemed to be somewhat extraneous to present SSRC concerns and in an effort to provide space for additional material has been removed from this edition.

1.3 MECHANICAL PROPERTIES OF STRUCTURAL METALS

Knowledge of the material stress–strain relationship during the elastic and initial inelastic ranges of behavior is an essential requisite to compression member analysis. In the elastic range there are accepted average values of the modulus of elasticity, and test values vary within reasonably small limits. Specified values of the yield point or yield strength[1] (depending on whether the initiation of yielding is a sudden or gradual process) are provided by the various specifications of the American Society for Testing and Materials (ASTM) and by product information from manufacturers.

The initial portions of the typical stress–strain curves for structural metals in tension or compression are shown in Fig. 1.1. The strengths of beams and columns are determined largely by stress–strain characteristics in the range shown. It should be noted that plotting complete curves to the same scale as Fig. 1.1 would take up a horizontal space between 20 and 30 times that available on the page, which is an indication of the inherent ductility of the metals shown.

The structurally significant aspects of a stress–strain curve for carbon or high-strength low-alloy structural steels can be characterized by the following five properties (see Fig. 1.1):

E = modulus of elasticity (slope of stress–strain curve in the elastic range)

σ_{uy} = upper yield point (maximum stress prior to yield stress level)

σ_y = yield-stress level (stress at a constant strain rate in the flat portion of the stress–strain curve after initial yield)

ϵ_{st} = strain at initial strain hardening

$E_{st} = (d\sigma/d\epsilon)_{\epsilon=\epsilon_{st}}$ (initial strain-hardening modulus)

These properties are generally sufficient for calculation of the inelastic strength and plastic deformation of structural steel members.

Structurally significant properties of the aluminum alloys, quenched and tempered steels, cold-worked steels, and stainless steels include the modulus of elasticity E; the yield strength σ_y, preferably determined by the offset method (ASTM Designation A370); and the tangent modulus $E_t = d\sigma/d\epsilon$, which varies with stress for strains greater than the elastic limit. For all steels and aluminum alloys the maximum tensile (ultimate) strength, based on original area, is also a part of the mill test report, although of no direct relevance to compression member behavior.

[1]In this guide the term *yield stress* generally is used to denote either the yield point or yield strength, whichever is applicable.

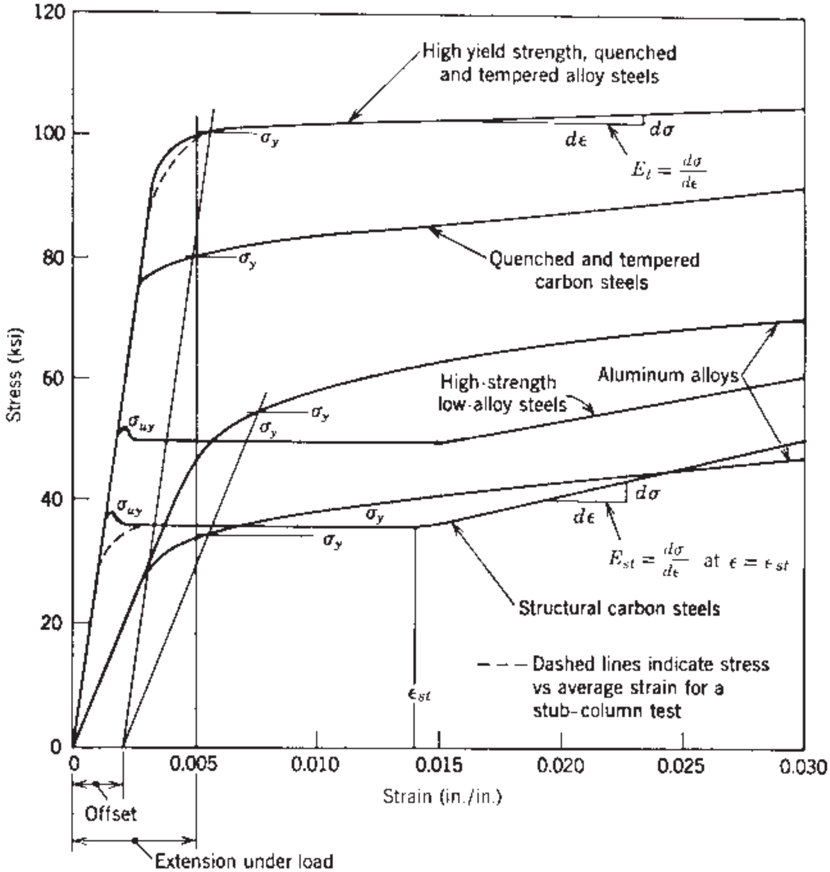

FIGURE 1.1 Initial stress–strain relationships for structural metals in tension or compression.

The yield stress of both steel and aluminum alloy varies with temperature, rate of strain, and the surface characteristics of the test specimen, as well as with the testing machine and test method. The yield stress is a function of the rate of strain, becoming lower as the testing speed is lowered. *Zero strain rate* defines a lower limit of the testing speed corresponding to the lowest yield-stress level for structural steels. ASTM specifications establish a maximum allowable strain rate. Tests made according to these specifications may be suitable for quality control but indicate yield-stress values as much as 15% greater than those from tests at low rates of strain. The influence of strain rate is less, percentagewise, for higher-strength steels.

For as-rolled structural steels, the yield-stress level in a tension or compression test can be regarded as the level of stress, after initial yield, that is sufficient at a given temperature and rate of strain to develop successively new planes of slip in the portions of the test specimen that remain in the elastic state. After initial yielding has proceeded discontinuously from point to point throughout the specimen, general strain hardening begins, and the stress rises with further increase in strain. The sharp yield point may disappear with cold work or heat treatment.

The yield-stress level is structurally more significant than the upper yield point, and its existence for relatively large average strains with no appreciable change in stress is taken advantage of in design methods based on inelastic analyses, which often make the assumption that the stress is constant and equal to the yield stress across yielded portions of the cross section.

The plot of average stress versus strain as determined by a stub-column test of an actual structural cross section is often somewhat different than that resulting from the test of a much smaller tension or compression specimen. Residual stresses that can result from the manufacturing process are one cause of these differences (indicated qualitatively as dashed lines in Fig. 1.1); other factors are the lack of uniformity of yield stress over the cross section and varying degrees of working during the rolling process. Similarly, strain hardening caused by the forming processes in cold-formed members may result in changes in yield stress which tend to shift the curve of average stress versus strain toward higher values of stress and more gradual yield development. Cold-forming effects are particularly pronounced for the stainless steels.

1.4 DEFINITIONS

The following list of terms defines their use in this guide. These terms are supplementary to the list of symbols provided in the notation and include primarily those for which variations in meaning are prevalent in the technical literature.

Beam: a straight or curved structural member, primarily supporting loads applied at right angles to the longitudinal axis. The internal stresses on a transverse cross section may be resolved into one or more of three resultant components: a transverse shear, a bending moment, and a torsional moment.

Beam-Column: a beam that also functions to transmit compressive axial force.

Bifurcation: a term relating to the load–deflection behavior of a perfectly straight and perfectly centered compression element at critical load. Bifurcation can occur in the inelastic range only if the pattern of postyield properties and/or residual stresses is symmetrically distributed so that no bending moment is developed at subcritical loads. At the critical load, a member can be in equilibrium in either a straight or a slightly deflected configuration, and bifurcation results at a branch point in the plot of axial load versus lateral deflection from which two alternative load–deflection plots are valid.

Braced Frame: a frame in which the resistance to both lateral load and frame instability is provided by the combined action of floor diaphragms and a structural core, shear walls, and/or a diagonal, K-brace, or other auxiliary system of bracing.

Buckle: to kink, wrinkle, bulge, or otherwise lose original shape as a result of elastic or inelastic strain.

Buckled: descriptive of the final shape after buckling.

Buckling Load: the load at which a compressed element, member, or frame collapses in service or buckles in an experimental loading test.

Critical Load: the load at which bifurcation (*see* Bifurcation) occurs as determined by a theoretical stability analysis.

Effective Length: the equivalent or effective length (KL) which, in the buckling formula for a pin-ended column, results in the same elastic critical load as for the framed member or other compression element under consideration at its theoretical critical load. Use of the effective-length concept in the inelastic range implies that the ratio between elastic and inelastic critical loads for an equivalent pin-ended column is the same as the ratio between elastic and inelastic critical loads in the beam, frame, plate, or other structural element for which buckling equivalence has been assumed.

Effective Width: a reduced width of plate, slab, or flat segment of a cross section which, assuming uniform stress distribution, leads to the same behavior of a structural member as the actual section of plate and the actual nonuniform stress distribution.

First Yield: a limiting stress level above which a permanent deformation results upon removal of a load.

Initial Imperfection: an unavoidable deviation from perfect geometry which is within the accepted practical tolerance of the particular applicable fabrication technology: for example, initial out-of-straightness (crookedness) of a member, initial out-of-plumb of a story, initial out-of-flatness of a plate, or initial denting or bulging of a shell.

Instability: a condition reached during buckling under increasing load in a compressive member, element, or frame at which the capacity for resistance to additional load is exhausted and continued deformation results in a decrease in load-resisting capacity.

Proportional Limit: the load or stress beyond which there is a significant amount of deviation from a prior linear load–deformation or stress–strain relationship. The term is usually used in connection with a tensile or compressive test, and the sensitivity of the strain or deformation measuring device is a determining factor in the evaluation.

Residual Stress: the stresses that exist in an unloaded member after it has been formed into a finished product. Such stresses can be caused by cold bending, finishing, straightening, flame cambering, oxygen cutting, welding, cooling after rolling, or quenching during heat treatment.

Restraint: deviation from the ideal articulated boundary condition or unbraced condition of an element, a member, or a structure.

Stability: the capacity of a compression member or element to remain in position and support load, even if perturbed slightly out of line or position by an added lateral force. In the elastic range, removal of the added lateral force would result in a return to the prior loaded position, unless the disturbance causes yielding to commence.

Strain-Hardening Modulus: for structural steels that have a flat (plastic) region in the stress–strain relationship, the strain-hardening modulus is the initial slope of the stress–strain curve just beyond the terminus of the flat region. It depends on prior strain and thermal history and exhibits a much greater range of variation than does the elastic modulus of the material.

Stub Column: a short compression test specimen utilizing the complete cross section, sufficiently long to provide a valid measure of the stress–strain relationship as averaged over the cross section, but short enough so that it will not experience flexural or torsional buckling in the elastic or plastic range.

Tangent Modulus: the slope of the stress–strain curve of material in the inelastic range, at any given stress level, as determined by the compression test of a small specimen under controlled conditions. The *effective tangent modulus* (as determined by a stub-column test) is modified by nonhomogeneity of material properties and by residual stresses.

Tangent-Modulus Load: the critical column load obtained by substituting E_t, the tangent modulus, for E in the Euler formula.

Tension-Field Action: a description of the postbuckling behavior of a plate girder panel under shear force, during which compressive stresses cause the web to form diagonal waves and tension stresses develop that are parallel to the wave troughs. These diagonal tensile stresses induce compressive stresses in the transverse (vertical) stiffeners.

Unbraced Frame: a frame in which the resistance to lateral load is provided primarily by the bending resistance of the frame members and their connections.

Yield Point: the maximum stress recorded in a tensile or compressive test of steel specimen prior to entering the plastic range.

Yield Strength: in a tension or compression test, the stress at which there is a specified amount of measured deviation from an extension of the initial linear stress–strain plot, commonly taken as the intersection of the stress–strain curve and a line parallel with the linear portion of the curve but offset by a strain of 0.002.

Yield Stress: a general term, denoting either yield strength, yield-stress level, or yield point, as defined herein.

Yield-Stress Level: for carbon- and low-alloy structural steels, the stress immediately beyond the elastic strain range, within which range the strain appears to increase without change in stress. It may be defined arbitrarily as the stress determined at a strain of 0.005.

1.5 POSTBUCKLING BEHAVIOR

Load-deflection relationships in the postbuckling range have an important bearing on the structural design significance of the critical load. For the idealized "perfect" compression element—one that is linearly elastic, devoid of imperfection, and within which the load-induced stress is perfectly uniform— there exists three different types of postbuckling behavior. As shown by the load–deflection curves in Fig. 1.2, these three cases may be demonstrated by the behavior of (1) a slender column, (2) a stiffened thin plate, and (3) a thin-walled cylinder. For each case, "perfect" elements will result in the behavior illustrated in Fig. 1.2 by solid lines, which for a given situation and corresponding buckling mode are unique and can be determined by a theoretical analysis. The dashed lines in Fig. 1.2 indicate the theoretical behavior for the same elements when a given degree of imperfection is assumed. The response of the imperfect elements (dashed lines) will approach that of the perfect elements (solid lines) as the degree of imperfection is assumed to diminish toward zero. The dashed lines are also indicative of what may be expected in a laboratory test or within an actual structure.

For the case of the elastic behavior of a slender column, the critical load for the perfect member and the maximum load carried by an imperfect one are in reasonable agreement; thus the critical load often provides a satisfactory basis for computing the design strength of the column. For the stiffened thin plate, an added postbuckling strength can be achieved with acceptably small lateral deflections, and the use of a greater strength in relation to the critical load may be justified

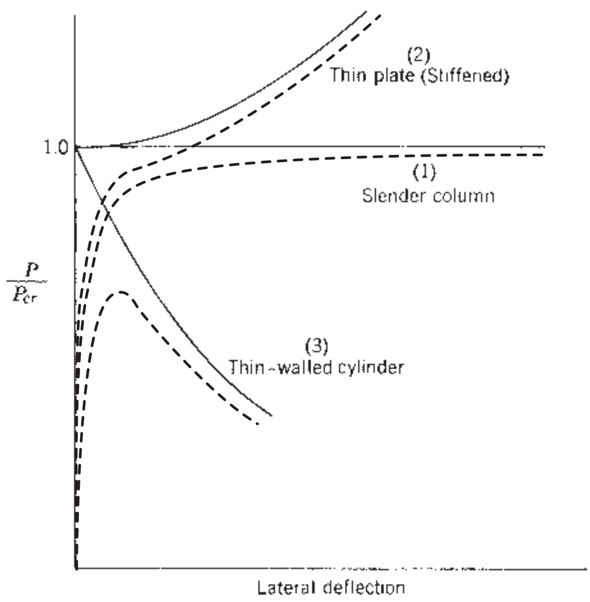

FIGURE 1.2 Elastic postbuckling curves for compressed elements.

in design. In contrast, the load-carrying capacity of a thin-walled cylinder is to an uncertain degree dependent on the amount of imperfection, and even with minimal imperfection can be drastically reduced with respect to the theoretical critical load. It is for this reason that the critical load would not be a suitable criterion on which to base the design strength of a thin-walled cylinder.

Inelastic material behavior may alter the elastic relationships depicted in Fig. 1.2. There are several conditions that may produce yielding. Although the critical load or buckling load may occur when the section is fully elastic (as indicated), subsequent postbuckling bending may produce additional stresses that when combined with the stress due to the axial load exceed the elastic stress range. On the other hand, both the critical and buckling loads may occur in the inelastic range as a result of the presence of residual stresses or the inherent nonlinearity of the material's stress–strain relationship.

When the yielding occurs after the elastic critical or buckling loads are reached, the curves shown in Fig. 1.2 will simply branch into new paths below those shown. For the cases of critical and buckling loads occurring in the inelastic range, the solid lines emanating from the critical-load bifurcation point will each take on a different initial increment of slope. In the case of the slender column, the horizontal solid line indicative of Euler buckling will be replaced by a curved line, initially sloping upward and reaching a maximum (instability) at a point somewhat greater than the critical load. A slender column with very small imperfections tends to approach this behavior as the imperfections lessen in size, with the result that with small imperfections a column under test may reach or slightly exceed the critical (tangent-modulus) load. Most important, the relevance of the critical load, or lack of relevance, is not altered from that pertinent to the completely elastic behavior, as discussed previously. Large initial imperfections, however, may cause the maximum buckling strength to be significantly lower than the critical load. In general, this behavior occurs for all types of structural systems and members and is covered in debt throughout this guide.

1.6 CREDITS FOR THE CHAPTERS IN THE SIXTH EDITION OF THE SSRC GUIDE

This book is the product of the many people who have given generously of their time and talent. This effort is gratefully acknowledged. Following is a recognition of those individuals and groups who have made major contributions arranged by chapters:

Chapter 1, "Introduction," was revised by the editor of this edition of the guide.

Chapter 2, "Stability Theory," was originally written by Alex Chajes for the fourth edition and only slightly modified by the editor of this edition.

Chapter 3, "Centrally Loaded Columns," was revised extensively by the members of SSRC Task Group 1 under the leadership of Robert Driver, with major contributions provided by Reidar Bjorhovde, Murty Madugula, Kim Rasmussen, Lip Teh, Yoon Duk Kim, and Donald White.

Chapter 4, “Plates,” was originally written by Shien T. Wang and completely reorganized and updated for this edition by Benjamin Schafer of SSRC Task Group 13.

Chapter 5, “Beams,” was fully revised by Donald White, with assistance from Bo Dowswell, Robert Driver, Yuhsi Fukumoto, Yoon Duk Kim, Dagowin la Poutré, and Jennifer Righman as well as advice from members of SSRC Task Group 15. The original text was written by the Theodore Galambos, with assistance from Sriramulu Vinnakota, Nicholas Trahair, Yuhsi Fukumoto, Joachim Lindner, David Nethercot, and Kit Kitipornchai.

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Chapter 11, “Stability of Angle Members,” was updated for this edition by Iraj Mamaghani of SSRC Task Group 26 with assistance from Theodore Galambos and David Dinehart.

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Chapter 14, “Circular Tubes and Shells,” was originally written for the fourth edition by former SSRC Task Group 18 Unstiffened Tubular Members and Task Group 22 Stiffened Cylindrical Member. It was updated for the fifth edition by former Task Group 18 Tubular Members and by Donald Sherman, who also updated the chapter for this edition with the assistance of the editor for this edition.

Chapter 15, "Members with Elastic Lateral Restraints," was originally written by Mo Elgaaly and Bruce Johnston and was revised minimally by the editor.

Chapter 16, "Frame Stability," was originally written for the fifth edition by Gregory Deierlein and Donald White. The chapter was updated for this edition by Andrea Surovek, Christopher Foley, the editor, and Ian MacPhedran of SSRC Task Group 4. A new section on structural integrity and disproportionate collapse resistance was prepared by Christopher Foley.

Chapter 17, "Arches," was significantly revised by Dagowin la Poutré.

Chapter 18, "Doubly Curved Shells and Shell-Like Structures," was written by Nicholas Morris and received some revision by the editor.

Chapter 19, "Stability under Seismic Loading," was written originally for the fifth edition by Subhash Goel with input from members of SSRC Task Group 24. The chapter was significantly revised and updated for this edition by Robert Tremblay of SSRC Task Group 24, with the assistance of Chia-Ming Uang for the section on steel moment-resisting frames.

Chapter 20, "Stability Analysis by Finite Element Methods," was completely rewritten by Christopher Earls.

Many of the above chapters include sections on aluminum design, all of which were reviewed and revised by J. Randolph Kissell. The appendixes were updated and slightly expanded by the editor with the assistance of Perry Green and SSRC Task Group 6.

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