DESIGN OF STEEL STRUCTURES

Including Applications in Aluminum

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McGRAW-HILL BOOK COMPANY, INC.
New York Toronto London
1957

PREFACE

The authors have attempted to present the subject matter of structural design in a way that will promote understanding of its basic philosophy. The book is intended for the usual courses in civil engineering and deals with the design of structural members and their connections, with applications to steel bridges and building frames. In addition, some attention is given to aluminum because of its increasing importance as a structural metal.

Each topic is introduced with a discussion of the relevant theory and, wherever it is feasible, with references to experimental evidence. The relation of theory and tests to standard design specifications is emphasized. Illustrative examples and problems for the student follow this introduction. Every effort is made to relate both examples and problems to practical situations. Although this approach has resulted in occasional review of topics in elementary strength of materials, the authors believe that their treatment is novel enough to justify the repetition.

There are new and original treatments of the subjects of bending about both principal axes, of lateral-buckling characteristics of beams subjected to such bending, and of several other topics that are noted in the text. There are adequate references to the literature to help the student who wants to pursue further some topic of interest, and to help particularly the practicing engineer. Finally, a chapter on the application of theories of ultimate strength—plastic design, as it has come to be called in this country—gives the student an introduction to this development and an opportunity to appraise the elastic theory as a basis for design.

Although the comprehensive nature of the treatment in this book should make for efficient use of time in the classroom, there is more material than can be covered in the time usually allotted to undergraduate study in structural engineering. The authors hesitate to single out topics for omission; they believe that this should be left to the interest and discretion of the individual instructor. This may result in occasional references to articles that have been passed by, but no great harm should come of that. It is worth noting that parts or all of Chap. 12 may be taken up during (or following) study of Chap. 5.

A feature of the book that should appeal to both the student and the practicing engineer is the presentation and discussion of the design calculations for several structures that have actually been built. Specifically, the examples mentioned have to do with a plate-girder bridge for the Pennsylvania Railroad, the truss spans and approach spans of a highway bridge in Maryland, and the wind bracing for the Lever House in New York City. The authors are grateful to the Pennsylvania Railroad Company, J. E. Greiner Company, Consulting Engineers, and Weiskopf and Pickworth, Consulting Engineers, for their courtesy and help in furnishing design calculations, design drawings, and photographs of these structures.

In addition, the industrial building that is discussed in Chap. 9 is patterned after an ore-storage building at the Mobile Works of the Aluminum Company of America, and the authors acknowledge the assistance of the company's Construction Engineering Division in furnishing design drawings and photographs of this structure. T. F. Higgins, director of engineering and research, and Edward R. Estes, Jr., research engineer, both of the American Institute of Steel Construction, have been of considerable help. Thanks also are due many other firms and individuals who have supplied photographs, information, and suggestions. The list is too long to enumerate, and the authors hope that those who have given them help will accept this anonymous recognition.

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NOTATIONS

Abbreviations

ft-c	foot-candle
klf	kips per lineal foot
kli	kips per lineal inch
ksi	kips per square inch
mph	miles per hour
pcf	pounds per cubic foot
plf	pounds per lineal foot
psf	pounds per square foot
psi	pounds per square inch

Symbols

A	area
A_f	area of flange plate; area of plate-girder flange
A_w	area of plate-girder web
b	width of plate or beam flange; spacing of stringers
C	shape coefficient for torsion
c	distance from neutral axis to extreme fiber
D	diameter of rivet
D, DL	dead load
d	depth of number; spacing of stiffeners; diameter of pin or rocker
E	modulus of elasticity in tension and compression
E_t	tangent modulus of elasticity
e	eccentricity
f	shape factor
G	modulus of elasticity in shear
g	gage; gravitational acceleration
h	unsupported height of plate-girder web; diameter of rivet hole
h_g	distance between centers of gravity of plate-girder flanges
I	moment of inertia; impact
I_c	moment of inertia of compression flange of beam
I_p	polar moment of inertia
I_s	moment of inertia of web stiffener
I_t	moment of inertia of tension flange of beam
I_{xy}	product of inertia
J	shape coefficient for torsion; polar moment of inertia
K	column effective-length coefficient
L, l	length of beam, plate, weld, or other element
L, LL	live load
M	bending moment
M_{cr}	critical bending moment
M_p	plastic moment of resistance

M_y	moment of resistance at first yielding
n	factor of safety; number of rivets at uniform pitch
P	axial load; load
P_E	Euler load
P_T	twist-buckling load
P_y	axial yield load
p	pressure; pitch
Q	moment of area about neutral axis
q	shear per lineal inch
R	reaction; force on rivet
r	radius; radius of gyration
S	section modulus
S_p	plastic section modulus
s	axial stress; rivet spacing
s_{cr}	critical stress
s_g	bending stress at center of gravity
s_{pl}	proportional-limit stress
s_{yp}	yield-point stress
T	twisting moment; tension in rivet or bolt
t	thickness of plate, flange, web, weld, etc.
V	shearing force; velocity
v	shearing stress; velocity
v_{cr}	critical shearing stress
W	total load on beam
WL	wind load
w	intensity of distributed load; width of plate
δ, Δ	deflection
ϵ	unit elongation
μ	Poisson's ratio

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Library of Congress Catalog Card Number 57-6391

THE MAPLE PRESS COMPANY, YORK, PA.

CONTENTS

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INTRODUCTION

1-1. Engineering structures. Engineering structures that require formal application of the science of mechanics to their design are of such variety as to defy any attempt to enumerate them except in a general way. In the design of bridges and buildings the civil engineer draws upon the same fundamental principles of statics, dynamics, and strength of materials as does the aeronautical engineer in his design of aircraft, the mechanical engineer in his design of machines, and the naval architect in his design of ships. The countless problems which arise in the design of these diverse structures have prompted engineers to specialize in the design of particular structures or groups of related structures, and it is profitable to study design somewhat according to customary areas of specialization. Although the complete design of many structures is the result of the coordinated efforts of several branches of engineering, we refer sometimes to the design of a structure having in mind only that part of the design which comes within the province of one of the branches.

The principal structures that are designed by civil engineers are bridges, buildings, transmission towers, storage vessels, dams, retaining walls, docks, wharves, highway pavements, and aircraft landing strips. Even this group of structures is too large for convenient study as a unit. In this book we shall limit ourselves to a study of structural members in metal and the methods by which they are usually connected, together with applications to the design of bridges and buildings.

1-2. The design procedure. The first and often the most difficult problem in design is the development of a plan that will enable the structure to fulfill effectively the purpose for which it is to be built. If the structure is a building, for example, the designer must create a plan that is adapted to the site; that provides a suitable arrangement of rooms, corridors, stairways, elevators, etc.; that will be aesthetically acceptable; and that can be built at a price the client is prepared to pay. This phase of design is sometimes called functional planning. It calls for a designer with a high order of skill and imagination.

Although the structural scheme is never independent of the functional plan, it is convenient for the purposes of our discussion to think of its development as a second major step in the design procedure. The extent to which the scheme must be developed during the functional-planning stage depends upon the structure. For example, the location of the columns in a building usually must be worked out with the functional plan, and sufficient space must be anticipated between finished ceiling and finished floor of adjacent stories to accommodate the floor construction. The functional plan and structural scheme of a highway bridge usually are not so interdependent. The roadway grade and alignment of a highway bridge are influenced principally by clearance requirements with respect to whatever is to be bridged and the necessity of providing adequate approaches to collect and disperse traffic, while the width depends upon the number of lanes required to accommodate the expected traffic. Many different types of bridge structure can be adapted to a given functional plan.

It is often necessary to make tentative cost estimates for several preliminary structural layouts. Sometimes this may have to be done while the functional plan is being developed; sometimes it can be done later. Selection of structural materials must be based upon consideration of availability of specific materials and the corresponding skilled labor, relative costs and wage scales, and the suitability of the materials for the structure. Successful development of an efficient structural scheme hinges on the engineer's familiarity with the many types of supporting structure which have been developed in the past. On the other hand, however, the designer who leans too heavily on tradition may fail to see the possibilities in new and better solutions.

The third stage of the design is a structural analysis. Although design specifications and building codes usually prescribe the nature and magnitude of the forces to which it is assumed the structure may be subjected, at times the engineer must make the decision. Once the external forces are defined, a structural analysis must be made to determine the internal forces which will be produced in the various members of the framework. Although this is a fairly routine procedure, since it is based on the laws of statics, the designer always finds it necessary to exercise initiative and judgment, since simplifying assumptions must invariably be made before the principles of mechanics can be applied.

In the fourth phase of the design the engineer proportions the members of the structural system. They must be chosen so that they will be able to resist, with an appropriate factor of safety, the forces which the structural analysis has disclosed. The designer must approach this stage of his work with a sound knowledge of strength of materials. Proficiency in the branch of mechanics called *elastic stability* is becoming increasingly important. Familiarity with the methods and processes of fabrication, and their limitations, and with the techniques of construction, and their limitations, is indispensable.

The preceding description of the planning of a structure from its inception to the completed plans as a step-by-step procedure is an attempt to help the student understand the relationship of his course work in mechanics, strength of materials, and structural analysis to the total problem of design. It should be understood that the four steps are seldom, if ever, distinct, and in many cases they must be carried along more or less simultaneously. Furthermore, the four steps assume varying degrees of importance relative to one another. For example, in the design of a house the architect will rarely, if ever, need a structural analysis and design. On the other hand, both the analysis and the design are fully as important as the functional planning in the case of a suspension bridge.

1-3. Loads. The determination of the loads for which a given structure or class of structure should be proportioned is one of the most difficult problems in design. Several questions must be answered: What loads may the structure be called upon to support during its lifetime? In what combinations may these loads occur? To what extent should a possible but highly improbable load or combination of loads be allowed to dictate the design?

The weight of a structure is called *dead load.* It can be determined with a high degree of precision, although not until after the structure has been designed. For this reason it is necessary to estimate dead load before a structural analysis is made, in order that the part of the internal forces due to weight can be taken into account. Experienced designers can often guess the weight of a structure or its parts with good accuracy. Certain rules which are helpful in predicting dead load will be given at appropriate points in this book. The actual weight must always be determined and compared with the estimated weight and correction made if the difference is significant. The designers of the ill-fated first Quebec bridge across the St. Lawrence River neglected this point. After the collapse of the bridge during erection, with the resulting death of more than 100 workmen, investigation disclosed dead loads 20 to 30 per cent larger than those assumed for the design. Although this discrepancy was not the cause of the failure, it would seriously have handicapped the bridge had it been possible to complete it as originally designed.

All loads other than dead load are called live loads. Live loads may be steady or unsteady; they may be fixed, movable, or moving; they may be applied slowly or suddenly; and they may vary considerably in magnitude. The history of some live loads—notably the weights of the heaviest highway trucks—is one of more or less continual increase in magnitude. The live loads which usually must be considered are:

1. The weight of people, furniture, machinery, and goods in a building
2. The weight of traffic on a bridge
3. The weight of snow, if accumulations of snow are possible and probable
4. Dynamic forces resulting from moving loads
5. Forces resulting from the action of wind
6. The pressure of liquids in storage vessels
7. Forces resulting from temperature change, if expansion and contraction are impeded
8. The pressure of earth, as on retaining walls and column footings

Dynamic forces induced by earthquakes should be considered if the structure is to be located in a region where destructive shocks are likely to occur. The development of the atomic and the hydrogen bomb has focused attention on the problem of providing resistance to blast loading.

The primary effect of gravity loads on structures is calculated from their weight; i.e., they are considered to be static loads. However, live loads in motion may produce forces that are considerably greater than those resulting from the same loads at rest. These are the dynamic forces mentioned in (4) above. Because of slight irregularities in the track, unbalance of the wheels, and sway, a moving train may exert much larger forces than will a stationary one. On the other hand, the forces resulting from random movement of a crowd of persons are not significantly different from those produced by stationary crowds. Dynamic force caused by motion is called *impact* if the effect is equivalent to additional gravity load and *lateral* or *longitudinal force* (depending upon its direction relative to the path of the vehicle) when the result is equivalent to load in the horizontal plane. Lateral force may result from motion in a curved path (centrifugal force) or from the swaying motion of a train on a straight track. Longitudinal forces are caused by acceleration and deceleration of moving vehicles.

1-4. Live loads on building floors. Buildings serve such diverse purposes and present such random arrangements of physical equipment and persons as to make it extremely difficult to estimate suitable design loads. Although a number of systematic surveys have been made, there is still a lack of adequate data. Many municipalities assume responsibility for the public safety by controlling the design of buildings through building codes which specify live-load requirements as well as other factors pertaining to design, and several organizations have issued codes for national or regional use. Among the latter are the American Standard Building Code (ASBC) Requirements A58.1—1945 of the

U.S. Chamber of Commerce (sponsored by the National Bureau of Standards) and the National Building Code recommended by the National Board of Fire Underwriters.

Buildings may be classified according to occupancy as follows:

1. Residential (including hotels)
2. Institutional (hospitals, sanatoriums, jails)
3. Assembly (theaters, auditoriums, churches, schools)
4. Business (office-type buildings)
5. Mercantile (stores, shops, salesrooms)
6. Industrial (manufacturing, fabrication, assembly)
7. Storage (warehouses)

Except for studies of combustible contents made in connection with fire-resistance classifications, apparently there are no published reports of residential live loads which are the results of an actual weighing of contents. *Building Materials and Structures Report* 92, Fire-resistance Classifications of Building Constructions (U.S. Department of Commerce), reports average combustible contents of about 4 psf of floor area, with a maximum of 7.3 psf except in one portion which served as a library. These figures are probably good approximations of total contents excluding persons. A residential room containing 1 person to every 6 ft^2—surely adequate allowance for a crowd—would average, say, 25 psf. At the most, then, we might expect residential live loads to be 35 psf over relatively small areas, with an average of about 10 psf over an entire building. The 40-psf design requirement found in most building codes is ample.

Live loads for institutional occupancy may be expected to be about the same as those for residential occupancy. Several surveys of crowded hospital wards have been made, and even those wards which contained 1 bed for every 30 ft^2 supported average live loads of only 9 psf. Building codes are in substantial agreement on 40 psf as a minimum live load for institutional private rooms, but some codes specify as much as 80 psf for wards. The latter figure is unduly large.

There have been a number of investigations of live loads due to crowds of people. At the University of Iowa, students packed for the purpose of testing dynamic loads on balcony construction resulted in a load of 116 psf. Observations of normal loading conditions on the elevators at Grand Central Terminal in New York City showed live loads of about 100 psf. In a test by the Milwaukee Board of Education in 1920, a room normally intended for 48 pupils was crowded with 258 pupils, filling all seats double and all aisles and open space. The resulting live load, including furniture, was 41.7 psf. The range of minimum-live-load requirements for assembly occupancy, as specified by various building codes, is given in Table 1-1. The table is not intended to be complete, but rather to show representative loads. The student may refer to the American Institute of Steel Construction's (AISC) Steel Construction Manual for the recommendations of the U.S. Department of Commerce referred to previously.

TABLE 1-1. LIVE LOADS FOR TYPICAL ASSEMBLY OCCUPANCIES
Range in values required by building codes

Type of space	*Live load, psf*
School classrooms (fixed seats)	40–60
School classrooms (movable seats)	40–100
Assembly halls (fixed seats)	50–60
Assembly halls (movable seats)	100
Theaters (not necessarily balconies)	50–60
Dance halls	100–120

The U.S. Public Buildings Administration sponsored live-load studies of the Internal Revenue Building and the Veterans Administration Building in Washington.[1] In the former building, 20 psf or less of actual average live load was found on 70 per cent of its area, 40 psf or less on 88 per cent, and 60 psf or less on 96.5 per cent. The maximum average live load of 106 psf occupied 825 ft^2 (0.5 per cent of the total area). In the latter building, 95 per cent of the floor area supported an average load of 20 psf or less, 97.8 per cent supported 40 psf or less, and 99.5 per cent supported 60 psf or less. The maximum average live load of 90 psf was found on 1,176 ft^2 of the tenth floor (0.5 per cent of the total area). Somewhat similar prior studies of the Equitable Building in New York City disclosed average loads of 11.6 psf over three selected floors. The maximum load was 78.3 psf, the minimum 0.87. Building-code requirements for office-space buildings range from 50 to 80 psf. These provisions would seem to be ample and reasonable.

The Office of Technical Services of the U.S. Department of Commerce undertook recent detailed studies, similar to those mentioned above, of mercantile, industrial, and storage occupancies. The results are published in *Building Materials and Structures Report* 133, Live Loads on Building Floors. The studies include two department stores, two mattress factories, one men's clothing factory, one dress factory, two furniture factories, one newspaper plant, one printing plant, and two warehouses. As might be expected, wide variations in live load were found. For example, the maximum live load in one of the mattress factories was only 41 psf, on 0.3 per cent of the total floor area, while in the other it was 101 psf on 11.1 per cent of the area. The latter load is somewhat misleading, since it was found in a cotton warehouse. Maximums for

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[1] J. W. Dunham, Design Live Loads in Buildings, *Trans. ASCE*, vol. 112, p. 725, 1947.