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(Load and Resistance Factor Method)

Abraham J. Rokach

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THEORY AND PROBLEMS

OF

STRUCTURAL STEEL DESIGN

(Load and Resistance Factor Method)

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ABRAHAM J. ROKACH, MSCE

Associate Director of Education
American Institute of Steel Construction, Inc.

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ABRAHAM J. ROKACH is Associate Director of Education of the American Institute of Steel Construction, Inc. Previously, he had been a practicing structural engineer for twenty years. He holds a B.E. degree from the City University of New York and an M.S. from the Massachusetts Institute of Technology. He has lectured at the University of Illinois and elsewhere and is the author of *Guide to LRFD* and the *Reliability of Expert Systems for Computer-Aided Structural Design*. He is a member of the American Society of Civil Engineers, the American Society for Engineering Education, and the National Institute of Building Sciences.

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Preface

In 1986 a new method of structural steel design was introduced in the United States with the publication of the *Load and Resistance Factor Design Specification for Structural Steel Buildings.* Load and resistance factor design, or LRFD, has joined the old allowable stress design (ASD) method as a recognized means for the design of structural steel frameworks for buildings.

Although ASD has enjoyed a long history of successful usage and is familiar to engineers and architects, the author and most experts prefer LRFD because it is a truer representation of the actual behavior of structural steel and unlike ASD, it can provide equivalent margins of safety for all structures under all loading conditions (as explained in Chap. 1). For these reasons it is anticipated that LRFD will replace ASD as the standard method of structural steel design.

This work is the first Schaum's Outline on the subject of structural steel design. After a long and rewarding use of other titles in the Schaum's Series (first as an undergraduate and graduate engineering student, then through 20 years of professional practice, and as a university professor), the author is pleased to have been given the opportunity to write this book. Because of the newness of LRFD and the scarcity of instructional materials, this book was written for as wide an audience as possible, including students enrolled in undergraduate and graduate engineering and architectural curricula, and practicing engineers, architects, and structural steel detailers. The author believes that everyone in need of instruction and/or experience in LRFD can benefit from the Schaum's approach of learning by problem-solving. The only prerequisite for an understanding of this text is the same as for an undergraduate course in structural steel design: a basic knowledge of engineering mechanics.

The author wishes to thank Mr. John F. Carleo, Publisher; Mr. John A. Aliano, Executive Editor; Ms. Margaret A. Tobin, Editing Supervisor, of the Schaum Division at McGraw-Hill, and their staff for their valuable contributions to this work. Special thanks go to the author's wife, Pninah, for her patience and assistance with typing the manuscript. Too numerous to mention, but significant in developing his knowledge and enjoyment of the subject matter, are his mentors and professional and academic colleagues, especially the people at AISC.

ABRAHAM J. ROKACH

CONTENTS

Introduction

This book covers structural steel design for buildings using the *load and resistance factor design* (LRFD) method. The following authorities on the LRFD method are cited frequently in the text, usually in abbreviated form.

AISC: American Institute of Steel Construction, Inc., Chicago, Illinois.

AISC LRFD Specification: *Load and Resistance Factor Design Specification for Structural Steel Buildings,* published by AISC.

AISC LRFD Manual: *Load and Resistance Factor Design Manual of Steel Construction,* also published by AISC.

Equations in this text are numbered as follows. Equations taken from the AISC LRFD Specification are accompanied by their AISC numbers in parentheses, thus ( ); other equations are numbered in brackets, thus [ ].

Chapter 1

Structural Steel

NOTATION

E = modulus of elasticity of steel = 29,000 kips per square inch (ksi)

F_u = tensile strength, ksi

F_y = yield stress, yield point, or yield strength, ksi

DEFINITIONS

Structural steel, as defined by AISC (in the LRFD Specification and elsewhere), refers to the steel elements of a structural frame supporting the design loads. It includes steel beams, columns, beam-columns, hangers, and connections.

Beam—A structural member whose primary function is to carry loads transverse to its longitudinal axis. Beams are usually horizontal and support the floors in buildings. (See Fig. 1-1.)

Column—A structural member whose primary function is to carry loads in compression along its longitudinal axis. In building frames, the columns are generally the vertical members which support the beams. (See Fig. 1-1.)

Beam-column—A structural member whose function is to carry loads both transverse and parallel to its longitudinal axis. A building column subjected to horizontal forces (such as wind) is actually a beam-column.

Hanger—A structural member carrying loads in tension along its longitudinal axis.

Connection—The material used to join two or more structural members. Examples of connections are beam-to-beam and beam-to-column.

MECHANICAL PROPERTIES

The major advantage of steel is its high strength relative to the strengths of the other common structural materials: wood, masonry, and concrete. Unlike masonry and concrete, which are weak in tension, steel is strong in both tension and compression. Because of its high strength, structural steel is widely used in construction. The tallest and longest-span structures are predominantly steel.

Typical stress-strain curves for structural steel are shown in Fig. 1-2. They are based on the application of tensile forces to a test specimen. The ordinates (i.e., vertical axes) indicate *stress,* which is defined as load divided by cross-sectional area. Units for stress are kips (or kilopounds; i.e., 1000 lb) per square inch, commonly noted as ksi. The abscissas (i.e., horizontal axes) indicate *strain,* which is a measure of elongation under tension and is defined as the increase in length divided by the original length. Units for strain are inches per inch; strain is dimensionless.

The stress-strain curve in Fig. 1-2(a) is that of A36 steel, the most commonly used structural steel. Note the linear relationship between stress and strain in the "elastic range," that is, until the yield point is reached. The most important design properties of A36 steel [see Fig. 1-2(a)] are

F_y, the *yield point,* the stress at which the proportionality between stress and strain ceases. A36 steel has both an upper and a lower yield point. For design purposes, the yield point of A36 steel is taken as $F_y = 36$ ksi, the minimum lower yield point.

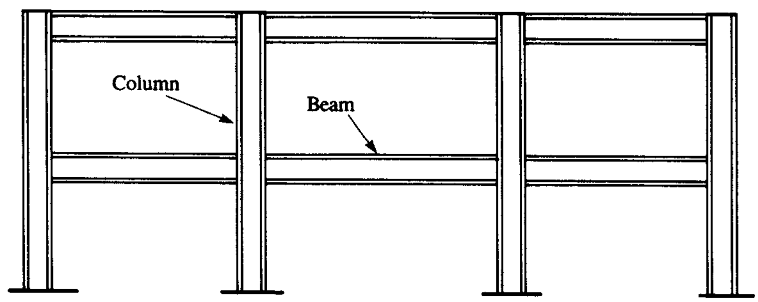


Fig. 1-1 Structural steel frame

F_u, the *tensile strength*, the maximum stress that the material is capable of sustaining. For A36 steel, $F_u = 58$ to 80 ksi.

E, the *modulus of elasticity*, which is the (constant) ratio of stress to strain in the elastic range. For A36 steel, $E = 29{,}000$ ksi.

The stress-strain curve in Fig. 1-2(b) is characteristic of several of the higher-strength steels. All structural steels have the same modulus of elasticity ($E = 29{,}000$ ksi). Unlike A36 steel, however, the higher-strength steels do not have a definite yield point. For these steels, F_y is the *yield strength* as determined by either of the two methods shown in Fig. 1-2(b): the 0.2 percent offset value or the 0.5 percent strain value.

In the AISC Specifications and Manuals, F_y is called the *yield stress* and, depending on the grade of steel, can be either the yield point or the yield strength, as defined above.

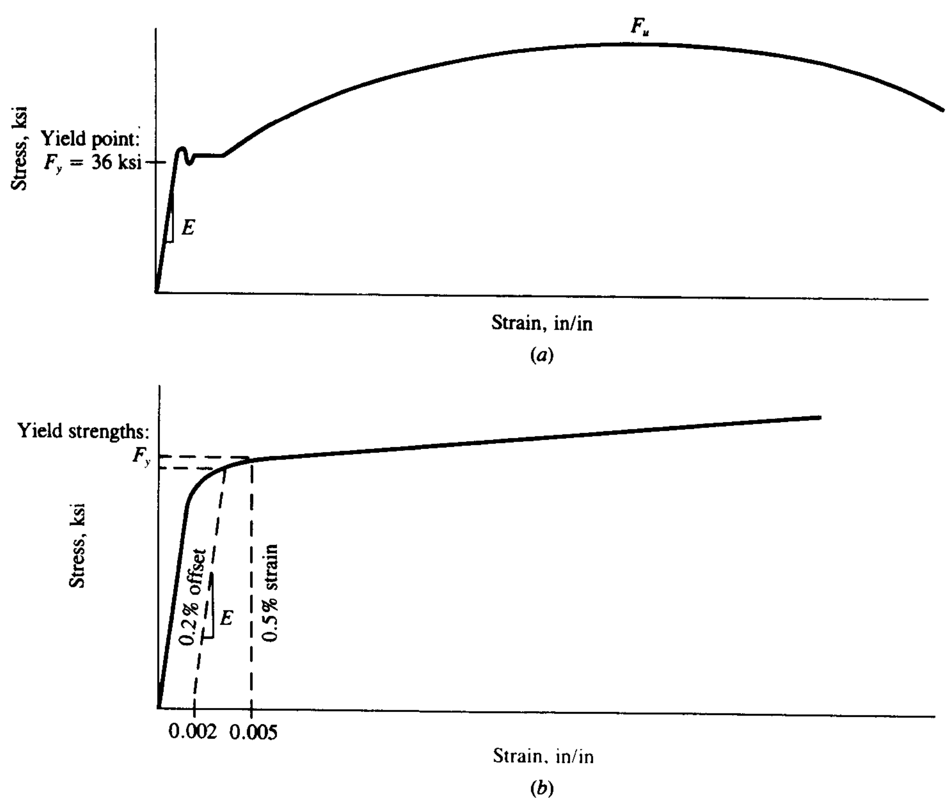


Fig. 1-2 Stress-strain curves for structural steels: (a) A36 steel; (b) High-strength steel

AVAILABILITY

Fourteen types of structural steel have been approved by the AISC LRFD Specification for use in buildings. In the LRFD Specification, Sec. A3.1, they are listed by their ASTM (American Society for Testing and Materials) specification numbers. The yield stress of these steels ranges from 36 ksi for the common A36 steel to 100 ksi for A514 steel. As can be seen from Table 1-1 (adapted from Part 1 of the AISC LRFD Manual), the yield stress of a given grade of steel is not a constant. It varies with plate thickness; very thick structural shapes and plates have reduced yield stresses.

A36 steel is by far the most commonly used type of structural steel for two reasons:

1. In many applications, the loads and stresses are moderate. Little, if any, saving would result from the use of higher-strength steels.
2. Even where stress considerations would favor the use of lighter (possibly more economical) high-strength members, other criteria may govern. Heavier members may be required to provide increased *stiffness* to prevent overall or local instability or excessive deflection. Because stiffness is a function of the geometric properties of the member and is not affected by strength, no advantage would be gained from using high-strength steel in such cases.

Table 1-1 Availability of Structural Steel

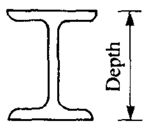
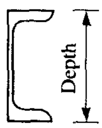
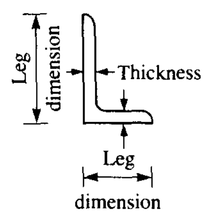
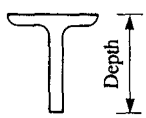
Steel Type	ASTM Designation	F_y, ksi	Plate Thickness, in
Carbon	A36	36	≤8
		32	>8
	A529	42	≤$\frac{1}{2}$
High-strength low-alloy	A441	50	≤$1\frac{1}{2}$
		46	$\frac{3}{4}$–$1\frac{1}{2}$
		42	$1\frac{1}{2}$–4
		40	4–8
	A572—Grade 65	65	≤$1\frac{1}{4}$
	—Grade 60	60	≤$1\frac{1}{4}$
	—Grade 50	50	≤4
	—Grade 42	42	≤6
Corrosion-resistant high-strength low-alloy	A242	50	≤$\frac{3}{4}$
		46	$\frac{3}{4}$–$1\frac{1}{2}$
		42	$1\frac{1}{2}$–4
	A588	50	≤4
		46	4–5
		42	5–8
Quenched and tempered alloy	A514	100	≤$2\frac{1}{2}$
		90	$2\frac{1}{2}$–6

STRUCTURAL SHAPES

A structural member can be a *rolled shape* or can be *built up* from two or more rolled shapes or plates, connected by welds or bolts. The more economical rolled shapes are utilized whenever possible. However, special conditions (such as the need for heavier members or particular cross-sectional geometries) may dictate the use of built-up members.

Available rolled shapes are catalogued in Part 1 of the AISC Manual. Those most commonly used in building construction include wide flange (or W), angle (or L), channel (or C), and tee (or WT). They are shown in Table 1-2 with examples of their nomenclature. Examples of common built-up shapes are given in Fig. 1-3.

Table 1-2 Rolled Structural Steel Shapes and Their Designations

Type of Shape	Cross Section	Example of Designation	Explanation of Designation
W (wide flange)		W14×90*	Nominal depth, 14 in; weight, 90 lb/ft
C (channel)		C12×30	Depth, 12 in; weight, 30 lb/ft
L (angle)		L4×3×$\frac{1}{4}$	Long leg, 4 in; short leg, 3 in; thickness, $\frac{1}{4}$ in
WT (structural tee cut from W shape)		WT7×45*	Nominal depth, 7 in, weight, 45 lb/ft

* Cutting a W14×90 in half longitudinally results in two WT7×45.

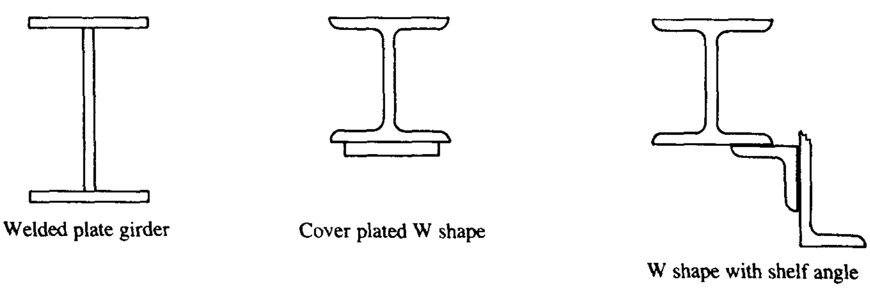


Fig. 1-3 Common built-up structural shapes

DESIGN METHODS

Two methods for selecting structural steel members are recognized in current engineering practice in the United States. The *allowable stress design* (ASD) method has been codified by AISC, from 1923 to the present, in nine successive editions of their *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings* (also known as the *AISC Specification*). This document has been incorporated by reference in virtually every building code in the United States. Containing the AISC Specification as well as numerous design aids for the ASD method has been the AISC *Manual of Steel Construction* (also known as the *AISC Manual*). The new *load and resistance factor design* (LRFD) method was introduced officially by AISC in 1986 with their publication of the *Load and Resistance Factor Design Specification for Structural Steel Buildings* (also known as the *AISC LRFD Specification*) and the *Load and Resistance Factor Design Manual of Steel Construction* (also known as the *AISC LRFD Manual*). The LRFD Manual contains the LRFD Specification and many tables and charts to assist users of the LRFD method.

This book, devoted exclusively to the LRFD method of structural steel design, is based on the AISC LRFD Specification. At the date of publication of this text, almost all U.S. jurisdictions have approved the use of the AISC LRFD Specification. It is anticipated that LRFD will soon be universally accepted in this country and will eventually become the standard method of structural steel design.

ASD VERSUS LRFD

(This section, which compares the two methods of structural steel design, is not essential for an understanding of the LRFD method or the remainder of this book. Hence, it may be skipped by students and others. It should, however, be of interest to those readers who have used ASD or are otherwise familiar with it.)

The ASD method is characterized by the use of one judgmental factor of safety. A limiting stress (usually F_y) is divided by a factor of safety (FS, determined by the authors of the Specification) to arrive at an allowable stress

$$\text{Allowable stress} = \frac{F_y}{\text{FS}}$$

Actual stresses in a steel member are calculated by dividing forces or moments by the appropriate section property (e.g., area or section modulus). The actual stresses are then compared with the allowable stresses to ascertain that

$$\text{Actual stress} \leq \text{allowable stress}$$

No distinction is made among the various kinds of loads. Because of the greater variability and uncertainty of the live load and other loads in comparison with the dead load, a uniform reliability for all structures is not possible.

The LRFD method is explained in detail in Chap. 2 and the succeeding chapters. Briefly, LRFD uses a different factor for each type of load and another factor for the strength or resistance. Each factor is the result of a statistical study of the variability of the subject quantity. Because the different factors reflect the degrees of uncertainty in the various loads and the resistance, a uniform reliability is possible.

Chapter 2

Introduction to LRFD

NOTATION

D = dead load
E = earthquake load
L = live load
L_r = roof live load
M = margin of safety
Q = load
R = rain load
R = resistance
R_n = nominal resistance
S = snow load
W = wind load
$\mathcal{B}$ = reliability index
γ = load factor
ϕ = resistance factor
σ = standard deviation

BASIC CONCEPTS

Load and resistance factor design (LRFD) is a method for designing structures so that no applicable limit state is exceeded when the strucure is subjected to all appropriate combinations of factored loads. *Limit state* is a condition in which a structure or a structural component becomes unfit. A structural member can have several limit states. *Strength* limit states concern safety and relate to maximum load-carrying capacity (e.g., plastic hinge and buckling). *Serviceability* limit states relate to performance under normal service conditions (e.g., excessive deformation and vibration).

The LRFD method, as applied to each limit state, may be summarized by the formula

$$\Sigma\gamma_i Q_i \leq \phi R_n \qquad [2.1]$$

In the terminology of the AISC LRFD Specification, the left side of the inequality is the *required strength* and the right side is the *design strength*. The left side represents the load combinations; that is, the summation (denoted by Σ) of the various loads (or load effects) Q_i, multiplied by their respective load factors γ_i. The left side is material-independent; the loads are taken from the governing building code and the LRFD load factors were derived from statistical building load studies. Loads and load combinations are covered later in this chapter. On the right side of the inequality, the design strength for the given limit state is the product of the nominal strength or resistance R_n and its resistance factor ϕ. Succeeding chapters of this text cover the limit states applicable to columns, beams, and other structural elements, together with the corresponding resistances and resistance factors.

Associated with each limit state are values for R_n and ϕ, where R_n (as calculated from the equations given in the subsequent chapters) defines the boundary of structural usefulness; ϕ (always less than or equal to one) depends on the variability of R_n. Test data were analyzed to determine the uncertainty in each resistance. The greater the scatter in the test data for a given resistance, the lower its ϕ factor.

PROBABILITY THEORY

The following is a brief, simplified explanation of the basis of LRFD in probability theory.

The load effect Q and the resistance R are assumed to be statistically independent random variables with probability distributions as shown in Fig. 2-1(a). Let the margin of safety

$$M = R - Q \qquad [2.2]$$

As long as M is positive (i.e., $R > Q$), a margin of safety exists. However, because Q and R are random variables, there will always be some probability of failure ($M < 0$). This unacceptable probability is shown shaded in Fig. 2-1(a) and (b). The latter figure is a probability distribution for M, which is also a random variable.

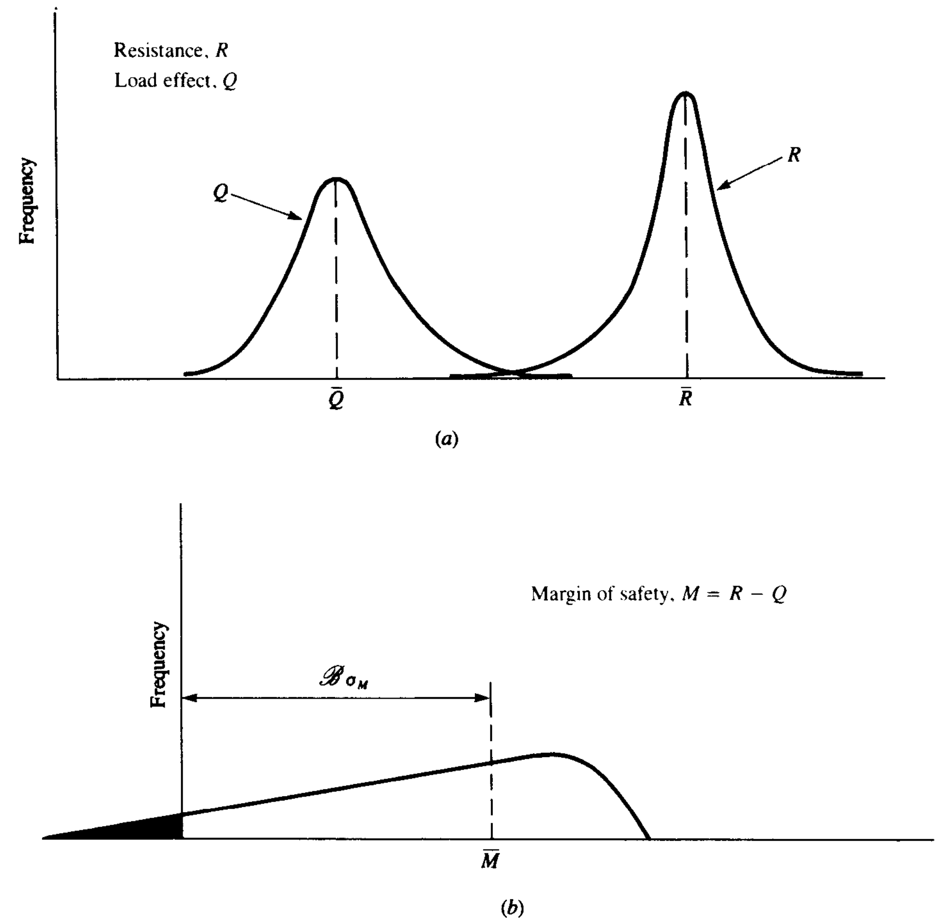


Fig. 2-1 Probability distributions: (a) load effect Q and resistance R; (b) margin of safety $M = R - Q$

Referring to Fig. 2-1(b), the probability of failure can be set to a predetermined small quantity (say, 1 in 100,000) by specifying that the mean value of M be $\mathcal{B}$ standard deviations above zero; i.e.

$$\bar{M} = \mathcal{B}\sigma_M \qquad [2.3]$$

where $\bar{M}$ = mean value of M

σ_M = standard deviation of M

$\mathscr{B}$ = reliability index

In Eq. [*2.1*], the one parameter left to the discretion of the authors of the LRFD Specification is ϕ; the load factors γ_i have been derived independently by others from load statistics. The resistance factor ϕ depends on $\mathscr{B}$ as well as on the uncertainty in the resistance R_n. The selection of a reliability index $\mathscr{B}$ determines the value of ϕ for each limit state. In general, to reduce the probability of failure, $\mathscr{B}$ would be increased, resulting in a lower value for ϕ.

LOADS

Structural loads are classified as follows.

Dead load (D)—The weight of the structure and all other permanently installed features in the building, including built-in partitions.

Live load (L)—The gravity load due to the intended usage and occupancy; includes the weight of people, furniture, and movable equipment and partitions. In LRFD, the notation L refers to floor live loads and L_r, to roof live loads.

Rain load (R)—Load due to the initial rainwater or ice, excluding the contribution of ponding.

Snow load (S).

Wind load (W).

Earthquake load (E).

In design, the dead load is calculated from the actual weights of the various structural and nonstructural elements. All the other design loads are specified by the governing building code. When beams support large floor areas or columns support several floors, building codes generally allow a live-load reduction. The reduced live load is used in LRFD.

LOAD COMBINATIONS

The *required strength* is defined in the AISC LRFD Specification as the maximum (absolute value) force obtained from the following load combinations.

$$1.4D \qquad (A4\text{-}1)$$

$$1.2D + 1.6L + 0.5\ (L_r \text{ or } S \text{ or } R) \qquad (A4\text{-}2)$$

$$1.2D + 1.6\ (L_r \text{ or } S \text{ or } R) + (0.5L \text{ or } 0.8W) \qquad (A4\text{-}3)$$

$$1.2D + 1.3W + 0.5L + 0.5\ (L_r \text{ or } S \text{ or } R) \qquad (A4\text{-}4)$$

$$1.2D + 1.5E + (0.5L \text{ or } 0.2S) \qquad (A4\text{-}5)$$

$$0.9D - (1.3W \text{ or } 1.5E) \qquad (A4\text{-}6)$$

[*Exception*: The load factor on L in combinations (*A4-3*), (*A4-4*), and (*A4-5*) shall equal 1.0 for garages, areas occupied as places of public assembly, and all areas where the live load is greater than 100 lb/ft^2.]

Loads D, L, L_r, S, R, W, and E represent either the loads themselves or the load effects (i.e., the forces or moments caused by the loads). In the preceding expressions, only one load assumes its maximum lifetime value at a time, while the others are at their "arbitrary point-in-time" values. Each combination models the design loading condition when a different load is at its maximum.