# STRUCTURAL STEEL ANALYSIS AND DESIGN: FUNDAMENTALS

**Eric M. Lui**
*Department of Civil & Environmental Engineering, Syracuse University, Syracuse, NY 13244-1240 USA*

**Keywords:** Structural steel, analysis and design, design philosophy, design formats, load and resistance factor design, required strength, design strength, factored load, tension members, compression members, flexural members, beam-columns, frames, effective length, notional load.

## Contents





## Summary

The design of structural steel members subjected to tension, compression, flexure, shear and combined axial force and bending moments is discussed. Emphasis is placed on the use of the American Institute of Steel Construction (AISC) Load and Resistance Factor Design (LRFD) approach. Examples are given to elucidate the procedures used in the design of trusses, beams and frames.

## 1. Introduction

Steel is a good construction material because it is strong (i.e., it has high yield strength $F_y$ and high tensile strength $F_u$), ductile (i.e., it can undergo large strain before fracture) and it possesses high toughness (i.e., it can absorb a large amount of energy). It is also an isotropic material (i.e., the material properties are the same in all directions) and the material properties are the same in both tension and compression. Because of this, steel can be used in a variety of applications. Commonly used steel shapes include wide flange (W), channel (C), angle (L), tee (WT), and hollow structural sections (HSS), with wide flange sections being used the most often.

The main components of steel are iron, carbon (0.15-1.7% by weight), and manganese (0.5-1.7% by weight). Other components include silicon, aluminum (deoxidizers that help form a more fine-grained crystalline structure for steel); copper, chromium, nickel (to enhance corrosion resistance); columbium, molybdenum (to enhance strength); and vanadium (to enhance fracture toughness). The types of steel that are most commonly used in construction are:

*Carbon Steels* (e.g., ASTM A36) - These steels contain carbon (maximum content=1.7%), manganese (maximum content=1.65%), and silicon and copper (<0.6%). Depending on the amount of carbon content, they can further be classified as:

- *Low carbon steel* – carbon content <0.15%
- *Mild carbon steel* – carbon content in the range 0.15 to 0.29%
- *Medium carbon steel* – carbon content in the range 0.30 to 0.59%
- *High carbon steel* – carbon content in the range 0.60 to 1.70%

*High-strength Low Alloy Steels* (e.g., ASTM A572, A618, A913, A992) - These steels process enhanced strength as a result of the presence of one or more alloying elements such as chromium, copper, nickel, silicon, vanadium, and others in addition to the basic elements of iron, carbon, and manganese. Normally, the total quantity of all the alloying elements is below 5% by weight of the total composition. Some corrosion-resistant high-strength low alloy steels such as A242, A588, A847 have higher corrosion-resistant capability than carbon steels. For instance, ASTM A588 steel has an enhanced corrosion-resistant capacity because of the addition of copper as an alloying element. Corrosion in this type of steel is severely retarded when a layer of reddish-brown patina (an oxidized metallic film) is formed on the steel surface.

*Quenched and Tempered Alloy Steels* (ASTM A514, A852) - The quantities of alloying elements used in these steels are in excess of those used in carbon and low alloy steels. In addition, they are heat treated by quenching and tempering to enhance their strengths. These steels do not exhibit well-defined yield points. These steels, despite their enhanced strength, have reduced ductility.

*High-Performance Steel* - High-performance steel (HPS) is a name given to a group of high-strength low-alloy steels that exhibit high strength, higher yield to tensile strength ratio, enhanced toughness, and improved weldability. One type of HPS that is currently in use for bridge construction is HPS70W. HPS70W is a derivative of ASTM A709 Grade 70W steel. Compared to ASTM A709 Grade 70W, HPS70W has improved mechanical properties and is more resistant to post-weld cracking even without preheating before welding.

The stress-strain curves for several types of steel are shown in Figure 1. Note that:

- They all exhibit linear behavior at the onset of loading.

- Even though $F_y$ and $F_u$ are different for different steel grades, the elastic modulus $E$ remain unchanged.
- They all possess relatively high ductility although the amount of ductility tends to decrease with increasing steel strength.

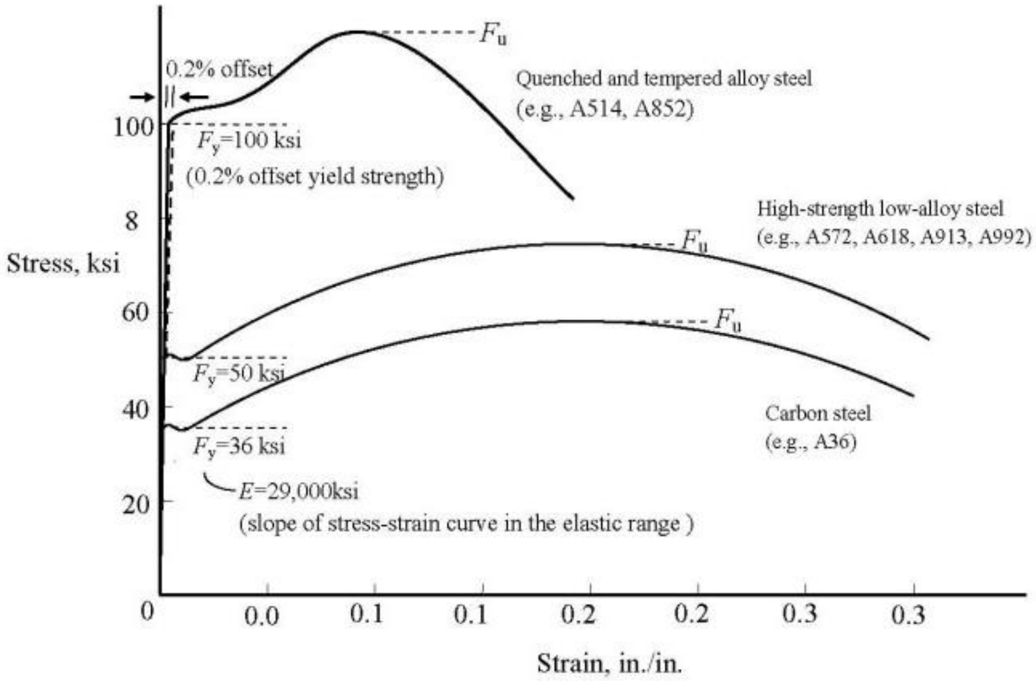


Figure 1. Stress-strain curves for selected steels (1 ksi = 6.895 MPa)

Some properties of steel that are useful for design are given below.

- Yield strength: $F_y$ varies from 36 to 100 ksi (250 to 690 MPa), depending on the type of steel
- Tensile strength: $F_u$ varies from 58 to 130 ksi (400 to 900 MPa), depending on the type of steel
- Modulus of elasticity: $E$ =29,000 ksi (200 GPa)
- Shear modulus: $G$ =11,200 ksi (77 GPa)
- Poisson's ratio: $\nu$ =0.29
- Specific weight: $\gamma$ =490 lb/ft$^3$ (77 kN/m$^3$)
- Coefficient of thermal expansion: $\alpha$ =6.5×10$^{-6}$/°F (11.7×10$^{-6}$/°C).

[For calculations at temperatures above 150°F (65°C), $\alpha$ =7.8×10$^{-6}$/°F (14×10$^{-6}$/°C).]

Although steel is an incombustible material, its strength ($F_y, F_u$) and stiffness ($E$) reduce quite noticeably at temperatures normally reached in fires when other materials in a building burn. Figure 2 shows the degradation of $F_y, F_u$ and $E$ with temperature. In the figure, $F_{ym}, F_{um}$ and $E_m$ represent the modified values of $F_y, F_u$ and $E$, respectively. It can be seen that these values reduce quite drastically in the 400°C to

800°C range and become zero when the temperature reaches 1200°C. Note that the melting point of structural steel is usually in the range 1400°C to 1540°C depending on the carbon content and the concentration of other alloying elements.

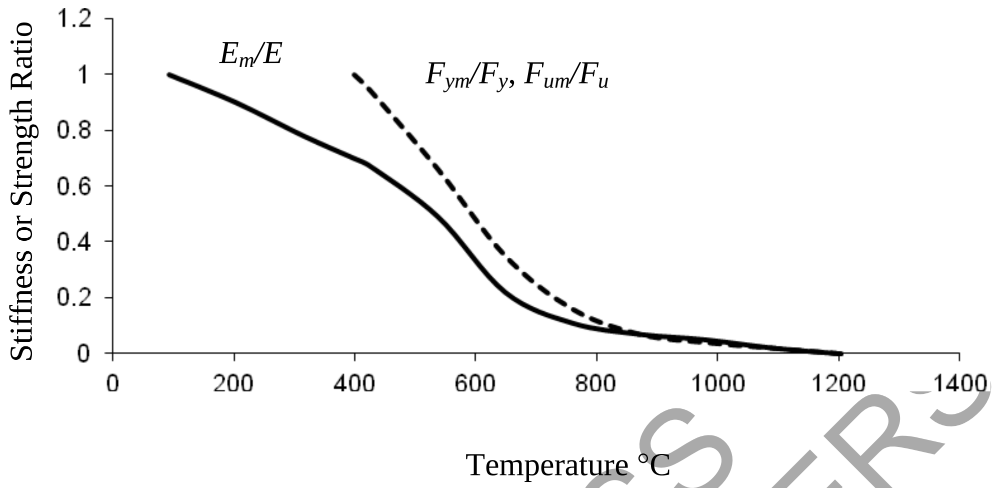


Figure 2: Effect of temperature on steel strength and stiffness

Exposed steel members that may be subjected to high temperature in a fire should be fireproofed to conform to the fire ratings set forth in city codes. Fire ratings are expressed in units of time (usually hours) beyond which the structural members under a standard ASTM Specification (E119) fire test will fail under a specific set of criteria. Steel members can be fireproofed by:

- the use of spray-on materials such as mineral fibers, perlite, vermiculite, gypsum, etc.
- the use of insulative paints. These special paints foam and expand when heated, thus forming a shield for the members.
- encasement in concrete, if a minimum cover of 2 inches (5.1mm) of concrete is provided.
- the use of a lath and plaster (gypsum) ceiling placed underneath the structural members supporting the floor deck of an upper story.
- placing steel members away from the source of heat.
- circulating liquid coolant inside box or tubular members.

Steel is susceptible to atmospheric corrosion. However, the rate of corrosion can be reduced if a barrier is used to keep water and oxygen from contact with the surface of bare steel. Some commonly used methods to protect steel from atmospheric corrosion include:

- Painting.
- The use of coating materials such as epoxies or other mineral and polymeric compounds.
- The use of corrosion resistance steels such as ASTM A242, A588, A847 steel. Corrosion resistant steels such as A588 retard corrosion by the formation of a layer of deep reddish-brown to black patina (an oxidized metallic film) on the steel surface after a few wetting-drying cycles, which usually take place within 1 to 3 years.

- The use of galvanized or stainless steel. Galvanized steel has a zinc coating. In addition to acting as a protective cover, zinc is anodic to steel. The steel, being cathodic, is therefore protected from corrosion. Stainless steel is more resistant to rusting and staining than ordinary steel primarily because of the presence of chromium as an alloying element.

Steel members are often connected together by bolts or welds. When welds are used, the weldability of steel becomes a design consideration. Generally speaking, weldability is considered very good for low-carbon steel (carbon level <0.15% by weight), good for mild steel (carbon levels 0.15-0.29%), fair for medium-carbon steel (carbon levels 0.30-0.59%), and questionable for high-carbon (carbon levels $\geq 0.60\%$ Because weldability normally decreases with increasing carbon content, special precautions such as preheating, controlling heat input and postweld heat treating, are normally required for steel with carbon content reaching 0.30%. In addition to carbon content, the presence of other alloying elements will have an effect on weldability. In lieu of more accurate data, the table below can be used as a guide to determine the weldability of steel.

| Element | Range for satisfactory weldability | Level requiring special care |
|---|---|---|
| Carbon | 0.06-0.25% | 0.35% |
| Manganese | 0.35-0.80% | 1.40% |
| Silicon | 0.10% max. | 0.30% |
| Sulfur | 0.035% max. | 0.050% |
| Phosphorus | 0.030% max. | 0.040% |

Table 1. Weldability of Steel

## 2. Design Philosophy and Design Formats

The primary objective of any structural design is to ensure that the structure is safe. Other objectives may include serviceability and economy. A good design is one in which the resulting structure is able to withstand the applied loads under extreme conditions, function properly under normal or service load conditions, and is cost effective to build and maintain.

At present, steel design in the U.S. can be performed in accordance with one of the following three formats:

*Allowable Stress Design (ASD)* or working stress design, requires that member stresses computed under service (or working) loads are lower than some predesignated values called allowable stresses. The allowable stresses are often expressed as a function of the yield stress ($F_y$) or tensile stress ($F_u$) of the material divided by a factor of safety. The factor of safety is introduced to account for the effects of overload, understrength and approximations used in structural analysis. The general format for an allowable stress design has the form

$$\frac{R_\text{n}}{F_\text{s}} \geq \sum_{i=1}^{m} Q_{\text{n}i} \qquad (1)$$

where $R_\text{n}$ is the nominal resistance of the structural component expressed in unit of stress (i.e., the allowable stress); $Q_{\text{n}i}$ is the service, or working stresses computed from the applied working load of type $i$; $F_\text{s}$ is the factor of safety; $i$ is the load type (dead, live, wind, etc.) and $m$ is the number of load types considered in the design.

*Plastic Design (PD)* makes use of the fact that steel sections have reserved strength beyond the first yield condition. When a section is under flexure, yielding of the cross-section occurs in a progressive manner, commencing with the fibers farthest away from the neutral axis and ending with the fibers nearest the neutral axis. This phenomenon of progressive yielding, referred to as plastification, means that the cross-section does not fail at first yield. The additional moment that a cross-section can carry in excess of the moment that corresponds to first yield varies depending on the shape of the cross-section. To quantify such reserved capacity, a quantity called shape factor, defined as the ratio of the plastic moment (moment that causes the entire cross-section to yield, resulting in the formation of a plastic hinge) to the yield moment (moment that causes yielding of the extreme fibers only) is used. Shape factors for hot-rolled I-shaped sections bent about the strong and weak axes have values of approximately 1.15 and 1.50, respectively.

For an indeterminate structure, failure of the structure will not occur after the formation of a single plastic hinge. After complete yielding of a cross-section, force (or, more precisely, moment) redistribution will occur in which the unyielded portion of the structure continues to carry any additional loads. Failure will occur only when enough cross-sections have yielded rendering the structure unstable, resulting in the formation of a plastic collapse mechanism.

In plastic design, the factor of safety is applied to the applied loads to obtain factored loads. A design is said to be satisfactory if the load effects (i.e., forces, shears and moments) computed using these factored loads do not exceed the nominal plastic strength of the structural component under consideration. Plastic design has the form

$$R_\text{n} \geq \gamma \sum_{i=1}^{m} Q_{\text{n}i} \qquad (2)$$

where $R_\text{n}$ is the nominal plastic strength of the member; $Q_{\text{n}i}$ is the nominal load effect from loads of type $i$; $\gamma$ is the load factor; $i$ is the load type and $\text{m}$ is the number of load types.

In steel building design in U.S., the load factor is given by the AISC Specification as 1.7 if $Q_\text{n}$ consists of dead and live gravity loads only, and as 1.3 if $Q_\text{n}$ consists of dead and live gravity loads acting in conjunction with wind or earthquake loads.

*Load and Resistance Factor Design (LRFD)* is a probability-based limit states design procedure. A limit state is defined as a condition in which a structure or structural component becomes unsafe (i.e., a violation of the strength limit state) or unsuitable for its intended function (i.e., a violation of the serviceability limit state). In a limit states design, the structure or structural component is designed in accordance to its limits of usefulness, which may be strength related or serviceability related. A design is considered satisfactory according to the strength criterion if the resistance exceeds the load effects by a comfortable margin. In actual design, a resistance factor $\phi$ is applied to the nominal resistance of the structural component to account for any uncertainties associated with the determination of its strength and a load factor $\gamma$ is applied to each load type to account for the uncertainties and difficulties associated with determining its actual load magnitude. Different load factors are used for different load types to reflect the varying degree of uncertainties associated with the determination of load magnitudes. In general, a lower load factor is used for a load that is more predictable and a higher load factor is used for a load that is less predictable. Mathematically, the LRFD format takes the form

$$\phi R_{\mathrm{n}} \geq \sum_{i=1}^{m} \gamma_i \, Q_{\mathrm{n}i} \tag{3}$$

where $\phi R_{\mathrm{n}}$ represents the design (or usable) strength, and $\sum \gamma_i Q_{\mathrm{n}i}$ represents the required strength (or factored load effect) for a given load combination. Table 2 shows examples of load combinations from an American Society of Civil Engineers (ASCE) publication – *Minimum Design Loads for Buildings and Other Structures* to be used on the right hand of (3). For a safe design, all load combinations should be investigated and the design is based on the worst case scenario.

$1.4(D+F)$

$1.2(D+F) + 1.6L + 0.5(L_{\mathrm{r}} \text{ or } S \text{ or } R)$

$1.2(D+F) + 1.6(L_{\mathrm{r}} \text{ or } S \text{ or } R) + (L \text{ or } 0.5W)$

$1.2(D+F) + 1.0W + L + 0.5(L_{\mathrm{r}} \text{ or } S \text{ or } R)$

$1.2(D+F) + 1.0E + L + 0.2S$

$0.9D + 1.0W$

$0.9(D+F) + 1.0E$

where
- $D$=dead load
- $E$=earthquake load
- $F$=load due to fluids with well-defined pressures and maximum heights
- $H$=load due to the weight and lateral pressure of soil and water in soil
- $L$=live load
- $L_{\mathrm{r}}$=roof live load
- $R$=rain load
- $S$=snow load
- $W$=wind load

Notes:

In the third, fourth and fifth load combinations shown above the load factor for $L$ can be set to 0.5 for all occupancies (except for garages or areas occupied as places of public assembly) in which the design live load per square foot of area is less than or equal to 100

| |
|---|
| psf (4.79 kN/m$^2$).<br>If $H$ is present, its load factor is taken as 1.6 if it adds to the primary load effect, 0.9 if it resists the primary load effect, and 0 for all other conditions. |

Table 2. Load Factors and Load Combinations

Because load and resistance factor design represents the most up-to-date and rational way to proportion structures, discussion from here on will focus on this design approach. In particular, the American Institute of Steel Construction (AISC) LRFD approach will be followed.

In performing design using the LRFD approach, a preliminary analysis is first performed on the structure to obtain member forces and moments. These forces and moments (called load effects) in each individual member are to be multiplied by their corresponding load factors as shown on the right hand side of Eq. (3). The resulting quantities, called factored load effects or required strengths, are then compared to the corresponding design strengths computed using the code specified design equations (to be discussed in what follows) on the left hand side of Eq. (3). If Eq. (3) is satisfied for all members of the structure for different load effects and for all applicable load combinations, the design is considered satisfactory.

-

-

-



**Bibliography**

Aghavere, A. and Vigil, J. (2009). *Structural Steel Design, A Practice-Oriented Approach*, Pearson, Upper Saddle River, NJ. [This is a steel design book that gears toward the practicing engineers.]

Englekirk, R.E. (1994). *Steel Structure - Controlling Behavior Through Design*, Wiley, New York, NY. [This book gives an in-depth discussion of the relationship between the design and behavior of steel structures.]

Gaylord, H., Gaylord C.N., and Stallmeyer, J.E. (1992). *Steel Structures*, 3rd edition, McGraw-Hill, New York, NY. [This is a book that provides a general discussion of steel design.]

Geschwindner, L.F. (2012). *Unified Design of Steel Structures*, 2nd edition, Wiley, Hoboken, NJ. [This book presents a fresh look at steel design that is based on the concepts used by the Specification Committee to develop the unified ASD and LRFD provisions.]

Leet, K.M., Uang, C.-M., and Gilbert, A.M. (2011), *Fundamentals of Structural Analysis*, 4th edition, McGraw-Hill, New York, NY. [This book introduces basic techniques for analyzing various structural elements commonly used in construction.]

Kassimali, A. (2009). *Structural Analysis*, 4th edition, CL-Engineering. [This book discusses classical and computer methods of structural analysis.]

McCormac, J.C. and Csernak, S.F. (2012). *Structural Steel Design*, 5th edition, Pearson Prentice Hall, Upper Saddle River, NJ. [This book gives a good overview and introduction of steel design.]

*Minimum Design Loads for Buildings and Other Structures* (2010). ASCE Standard, ASCE/SEI 7-10, ASCE, Reston, VA. [This publication is used by professionals to develop load models for structural design.]

*Plastic Design in Steel – A Guide and Commentary* (ASCE Manual No. 41), American Society of Civil Engineers, New York, NY. [This publication provides guidelines for plastic design of steel structures.]

Salmon, C.G., Johnson, J.E. and Malhas, F.A. (2008). *Steel Structures - Design and Behavior*, 5th edition, Prentice-Hall, Upper Saddle River, NJ. [This book gives a rather comprehensive literature review and discussion of a variety of topics related to steel design.]

*Steel Construction Manual* (2010). 14th edition, American Institute of Steel Construction, Chicago, IL. [This is the steel design and construction manual used in the U.S.]

Vinnakota, S. (2006). *Steel Structures: Behavior and LRFD*, McGraw-Hill, New York, NY. [This book discusses steel design from the perspective of member and structural behavior.]

West, H.H. and Geschwindner, L.F. (2009). *Fundamentals of Structural Analysis*, 2nd edition, Wiley, Hoboken, NJ. [This book discusses [This book offers a comprehensive and well-integrated presentation of the foundational principles of structural analysis.]

## Biographical Sketch

**Dr. Eric M Lui** is Laura J. and L. Douglas Meredith Professor in the Department of Civil & Environmental Engineering at Syracuse University. He received his BSCE with high honors from the University of Wisconsin-Madison, and his MSCE and Ph.D. from Purdue University. Professor Lui's research and teaching interests are in the area of Structural Engineering with an emphasis on structural stability, structural dynamics, structural materials, numerical methods, computer-aided analysis and design, and earthquake engineering.