Failure Modes in Steel Members

An Online Continuing Education Course for Engineers

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Failure Modes in Steel Members

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1. Introduction:

Understanding the potential failure modes in steel structures is crucial for any structural engineer. While many engineers perform code checks diligently, they often do so without visualizing the actual failure shapes for each check. This course bridges that gap by illustrating how each code check translates into real-world scenarios, helping you move beyond just equations to truly grasp the behavior of steel members under load.

A deep understanding of failure shapes, or failure modes, offers significant advantages. Primarily, it empowers you to achieve both safe and economical designs by enabling you to anticipate and prevent potential issues. Furthermore, this knowledge is invaluable for diagnosing failure modes in actual structural collapses, providing critical insights for forensic analysis and future design improvements. This course dives into each code check specified by AISC 360-22, focusing on the practical application rather than intricate equations. You'll gain a clear understanding of how yielding, buckling, and fracture failures manifest in real-life structures due to various straining actions like tension, compression, shear, and flexure. This will greatly assist you in preparing case studies and comprehensive structural safety reports.

Specifically, we'll cover a comprehensive range of failure modes, including but not limited to: tensile, compressive, flexural, and shear yielding; various local and global buckling phenomena such as flexural-buckling, torsional-buckling, and web buckling; and critical rupture failures like tensile rupture, shear rupture, block shear rupture, and even bolt and weld rupture. By the end of this course, you'll have a robust understanding of how these mechanisms dictate the ultimate strength and safety of steel structures.

2. Introduction:

Steel members, when subject to a load higher than their nominal strength, fail under certain and known modes of failure. Generally, these modes are as follows:

1. Yielding.
2. Buckling.
3. Rupture (fracture).

The above-listed modes have many forms and could result from different types of internal forces acting in the member, such as tension, compression, shear, and flexure.

a. Yielding:

The yielding mode is defined as a change in the length of the member or the element in a member due to tension, and maybe compression stress.

The element of a member may be a flange or web of a W-shape section, leg of an angle, side of an HSS section, etc.

As a general rule, to know if a code check is a check for yielding, the designer can see the specified minimum yield strength (F_y) in the equation of the check.

b. Buckling:

The buckling mode is defined as a deviation of the member or the element in a member from its longitudinal axis due to compression stress applied to an imperfect case of the member or the element.

As a general rule, to know if a code check is a check for buckling, the designer can see the buckling compressive strength (F_{cr}) in the equation of the check.

c. Rupture:

The rupture mode is a brittle failure resulting from the high concentrated stresses applied to the steel element at the holes of bolts or at the welded joints. This mode is undesirable because it does not give any alerts before the failure. This mode may be a result of tensile stress or shear stress.

As a general rule, to know if a code check is a check for yielding, the designer can see the rupture strength (F_u) in the equation of the check.

It shall be noted that the resistance factor of the rupture mode is lower than its counterpart of the yielding mode because it is a sudden failure.

Rupture failures are also occurring in bolts and welds.

Since each mode of failure may result from tension, compression, flexure, shear, or torsion stresses, there are a lot of interferences between those internal stresses and the corresponding modes of failure. To demonstrate the topic in an easy way, the following sections discuss the modes of failure relative to the cause of internal stress.

3. Yielding Modes:

As mentioned earlier, the yielding mode is a change in the length of the member or the element in a member. It may be caused by tension or compression stress.

In this section, all yielding modes resulting from different applied stresses are discussed.

a. Tensile yielding of a member:

This mode occurs in the whole member subject to tensile stresses, such as a tension member in a bracing system or a truss system.

When the member is subject to tensile stress, the whole member tends to elongate till it reaches the yield point. At this point, the applied stress exceeds the nominal tensile yielding strength of the member, the sectional cross area is decreased, and the member length is increased.

This mode is not a brittle one; therefore, the resistance factor (say for LRFD) is only 0.90.

Figure (01) shows the shape of the "member tensile yielding" mode.

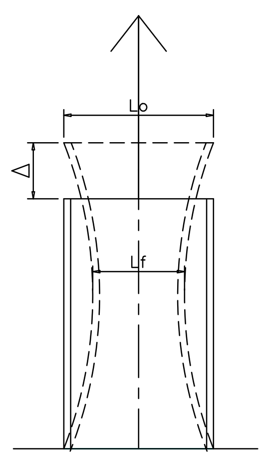


Figure (01).Tensile Yielding of Member

The tensile yielding strength of a member is determined by:

$P_n = F_y A_g$ (AISC360-D2-1)

$\phi_t = 0.90(\text{LRFD}) \qquad \Omega_t = 1.67(\text{ASD})$

b. *Compression yielding of a member:*

This mode occurs in the whole member when it is subjected to compressive stresses, such as compression members in a bracing system or in a truss system.

It rarely occurs in real-life applications because the member shall be very stocky, which is not a common practice in the design of compression members.

For a member subject to compressive yielding, the member reaches the yielding point, at which the applied compressive stress exceeds the nominal yielding strength of the member, but contrary to the tension members, the cross-sectional area of the member is increased and the member length is decreased, as shown in figure (02).

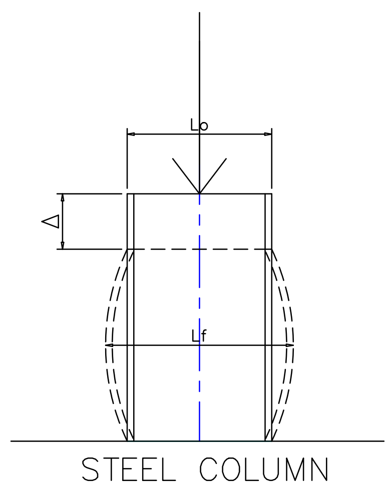


Figure (02). Compression Yielding of a Member

The determination of compression yielding strength of a member is not stated explicitly in AISC360. However, the equation of tensile yielding could be used for the compression yielding.

c. *Compression yielding of an element due to global compression (Local Yielding):*

For a compression member, when the overall slenderness ratio of the member is moderate, and the width-to-thickness ratio is low (non-slender element), the member compression yielding or member compression buckling will not govern the design, as well as the buckling of local elements. In this case, the governing failure mode is the inelastic buckling-local yielding of the element (web or flange).

Figure (03) shows the local yielding of a compression flange in a column.

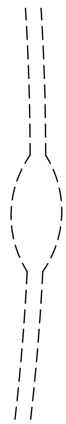


Figure (03). Local Yielding of Column Compression Flange

This mode occurs when one of the following conditions is met:

- $\frac{L_c}{r} \leq 4.71\sqrt{\frac{E}{F_y}}$.
- $\frac{F_y}{F_e} \leq 2.25$.

The inelastic compressive yielding (local yielding of the element in a member) is determined by:

$$P_n = F_{cr} A_g \qquad \text{(AISC360-E3-1)}$$

$$F_{cr} = \left(0.658^{\frac{F_y}{F_e}}\right) F_y \qquad \text{(AISC360-E3-2)}$$

$$\phi_c = 0.90(\text{LRFD}) \qquad \Omega_c = 1.67(\text{ASD})$$

d. Local Buckling of an element due to local compression:

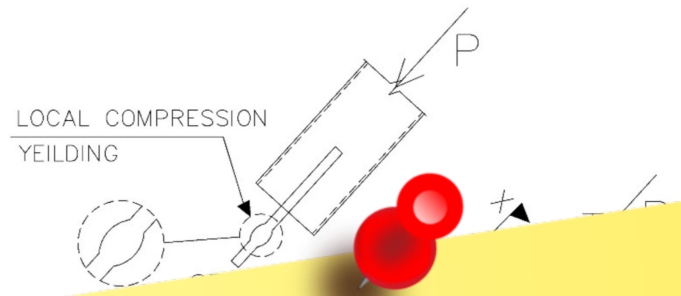
For a connection element subject to compression with $L_c/r \leq 25$, the element is yielding under this local compression.

The compressive yielding strength of the element is:

$P_n = F_y A_g$ (AISC360-J4-6)

$\phi = 0.90(\text{LRFD}) \qquad \Omega = 1.67(\text{ASD})$

Figure (04) shows the local yielding of a gusset plate in a bracing connection.



e. Flexural Yield

This mode occ

- Compac ... all beam elements, includin ... and forming a plastic hinge at the most stressed ... beam, such as the midspan of the simple beam, subject to a uniform distributed load.
- The beam must be laterally braced to prevent any lateral torsional buckling and flexural buckling.

This mode occurs when the required moment exceeds the plastic moment capacity of the beam.