Design of Steel Structural Systems

Structural designer’s work

The aim of the structural designer is to produce the design and drawings for a safe and economical structure that fulfils its intended purpose. The steps in the design process are as follows:

1. Conceptual design and planning. This involves selecting the most economical structural form and materials to be used. Preliminary designs are often necessary to enable comparisons to be made

2. Detailed design for a given type and arrangement of structure, which includes:
   - idealization of the structure for analysis and design;
   - estimation of loading;
   - analysis for the various load cases and combinations of loads and identification of the most severe design actions;
   - design of the foundations, structural frames, elements and connections;
   - preparation of the final arrangement and detail drawings.

The materials list, bill of quantities and specification covering welding, fabrication, erection, corrosion protection and fire protection may then be prepared. Finally the estimates and tender documents can be finalized for submission to contractors.

The structural designer uses his/her knowledge of structural mechanics and design, materials, geotechnical and codes of practice and combines this with his/her practical experience to produce a satisfactory design. He/she takes advice from specialists, makes use of codes, design aids, handbooks and computer software to help him/her in making decisions and to carry out complex analysis and design calculations.

COMPARATIVE DESIGN AND OPTIMIZATION

Preliminary designs to enable comparisons and appraisals to be made will often be necessary during the planning stage in order to establish which of the possible
structural solutions is the most economical. Information from the site survey is essential because foundation design will affect the type of superstructure selected as well as the overall cost.

Arrangement drawings showing the overall structural system are made for the various proposals. Then preliminary analyses and designs are carried out to establish foundation sizes, member sizes and weights so that costs of materials, fabrication, construction and finishes can be estimated. Fire and corrosion protection and maintenance costs must also be considered. However, it is often difficult to get true comparative costs and contractors are reluctant to give costs at the planning stage.

By optimization is meant the use of mathematical techniques to obtain the most economical design for a given structure. The aim is usually to determine the topology of the structure, arrangement of floors, spacing of columns or frames or member sizes to give the minimum weight of steel or minimum cost. Though much research has been carried out and sophisticated software written for specific cases, the technique is not of general practical use at present. Many important factors cannot be satisfactorily taken into account.

The design of individual elements may be optimized, e.g. plate girders or trusses. Again, in optimizing member costs it is essential to rationalize sizes, even if this may lead to some oversized items. Floor layouts and column spacing should be regular and as a consequence, fabrication and erection will be simplified and cost reduced.

**Aims and factors considered in design comparison**

The aim of the design comparison is to enable the designer to ascertain the most economical solution that meets the requirements for the given structure. All factors must be taken into consideration. A misleading result can arise if the comparison is made on a restricted basis.

Factors to be taken into account include:

- materials to be used;
- arrangement and structural system and flooring system to be adopted;
- fabrication and type of jointing;
- method of erection of the framework to be used;
- type of construction for floor, walls, cladding and finishes;
installation of ventilating/heating plant, lifts, water supply, power etc.;
Corrosion protection required;
Fire protection required;
Operating and maintenance costs.

Aesthetic considerations are important in many cases and the choice of design may not always be based on cost alone. Most structures can be designed in a variety of ways.

**Specific basis of comparisons for common structures**

In the following sections a classification is given on which design comparisons for some general purpose structures may be made.

**(a) Single-storey, single-bay buildings**

For a given plan size the designer can make the following choices.

**Type of building and design method**

![Diagram of Structures](image)

The design may be fully welded or with rigid joints mode using high-strength bolts.

**Design variables**

The basic variable is column spacing which governs the size of purlins, sheeting rails, main frame members and foundations. Designs may be made with various column spacings to determine which gives the most economical results. Various roof shapes are possible such as flat, ridge, sawtooth, monitor or mansard (Figure (a)). The roof slope is a further variable; the
present practice is to use flatter slopes. In the longitudinal direction these buildings are in braced simple design. The gable ends are normally simple design.

**(b) Single-storey, multi-bay buildings**

Three common types of single-storey, multi-bay buildings are the lattice girder roof, multi-bay portal and cable suspended roof (Figure (b)). The comments from (a) above apply.

**(c) Multi-storey buildings**

Many different systems are used and many parameters can be varied in design. Some important aspects of the problem are as follows.

(i) **Overall framing**

The column spacing can be varied in both directions. The locations of the liftshaft/staircase can be varied. Not all columns may be continuous throughout the building height. Plate girders can be used to carry upper columns over clear areas. Economy can be achieved if the bottom storey columns are set in, allowing girders to cantilever out.

(ii) **Flooring**

The type of flooring and arrangement of floor framing affect the overall design. The main types of flooring used are cast-*in situ* concrete in one- or two-way spanning slabs or precast one-way floor slabs. The cast-*in situ* slabs can be constructed to act compositively with the
steel floor beams. Flat slab construction has also been used with steel columns where a special steel shear head has been designed.

(iii) Stability
Various systems or framing arrangements can be used to stabilize multistorey buildings and resist horizontal loads. The building may be braced in both directions, rigid one way and braced the other or rigid in both directions. Alternatively, concrete shear walls or liftshafts can be used to provide stability. Tube construction is used for very tall buildings.

(iv) Design method
For a given framing system various design methods can be used. The methods given in LRFD AISC are simple, semi-rigid or rigid design. More accurate methods taking secondary effects into account are possible with elastic analysis. Analysis and design methods are discussed more fully in the next chapter.

(v) Fire protection
This is necessary for all steel-framed buildings, and solid casing of beams and columns may be taken into account in design. However, lightweight hollow or sprayed-on casing is generally used in modern practice. Methods have been developed for assessment of fire resistance for steel members.

(vi) Foundations
Types of foundations used for steel-framed buildings were set out above. The type selected for prevailing soil conditions can affect the choice of superstructure. One common case is to use pinned bases in poor soil conditions because fixity would be expensive to achieve. Again, where provision must be made for differential settlement, buildings of simple design perform better than those of rigid design. If a monolithic raft or basement foundation is provided, the superstructure can be designed independently of the foundation.
Trusses

• Fabricated from various steel sections available, jointed together by welding or by bolting usually via gusset plates.

• Plane trusses and space trusses.

• Bridge trusses and roof trusses.

• Members supporting heavy loads

• Members having longer span.

• Saving in weight.
Type of Trusses

Roof truss

Supporting truss

Bracing truss
Truss Analysis

• Pin-joint truss analysis
  ➢ method of joint, method of section, numerical simulation
  ➢ several analyses may be needed for different load combinations
• Analysis of load bearing members such as rafters
• Assessment of stresses due to eccentricity of the connections
• Assessment of the effects of joint rigidity and deflections
Roof Truss

- Roof rafters spanning more than 20 m can be designed
- Usual span-to-depth ratio of steep roof trusses is 7.5 to 12
- Panel width should be constant
- Even number of panels avoids cross-braces
- Diagonal web members should be in tension under worst-case loading
- Inclination angle of the diagonals should be between 35° and 50°
- If at all possible, the purlins and verticals should closely coincide
Roof Truss

Usual range of depths of roof trusses
# Approximate mass for roof trusses

<table>
<thead>
<tr>
<th>Diagram</th>
<th>Span, m</th>
<th>Mass, kg</th>
<th>kN</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td>5 – 7</td>
<td>160 – 210</td>
<td>1.6 – 2.1</td>
</tr>
<tr>
<td><img src="image2.png" alt="Diagram" /></td>
<td>8 – 11</td>
<td>210 – 270</td>
<td>2.1 – 2.7</td>
</tr>
<tr>
<td><img src="image3.png" alt="Diagram" /></td>
<td>12 – 14</td>
<td>270 – 400</td>
<td>2.7 – 4.0</td>
</tr>
<tr>
<td><img src="image4.png" alt="Diagram" /></td>
<td>15 – 16</td>
<td>400 – 620</td>
<td>4.0 – 6.2</td>
</tr>
<tr>
<td><img src="image5.png" alt="Diagram" /></td>
<td>17 – 20</td>
<td>620 – 950</td>
<td>6.2 – 9.5</td>
</tr>
<tr>
<td><img src="image6.png" alt="Diagram" /></td>
<td>22 – 30</td>
<td>950 – 1100</td>
<td>9.5 – 11.0</td>
</tr>
</tbody>
</table>
Approximate mass for roof trusses

<table>
<thead>
<tr>
<th>Span (m)</th>
<th>Self-weight (kN/m(^2)), over span × truss spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.11</td>
</tr>
<tr>
<td>20</td>
<td>0.12</td>
</tr>
<tr>
<td>30</td>
<td>0.16</td>
</tr>
<tr>
<td>40</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Out-of-Plane Load

- Wind loads acting on the upper half of the end walls
- Frictional drag effects on the roof, and
- Accumulated “lateral” bracing system restraint forces

Notes:
(1) Unless special studies are made, lateral forces from rafters should be accumulated at the braced bay.
(2) $N'_c=$ compression force in top truss chord, which for illustrative purposes, is assumed to be the same for all roof trusses in the figure.
Design of Tension Members

Cl. 7.1, Design for axial tension

\[ N^* \leq \phi N_t \]

\( \phi = \) the capacity factor, see Table 3.4, \( \phi=0.9 \)

\( N_t = \) the nominal section capacity in tension

\[ N_t = A_g f_y \quad \text{and} \quad N_t = 0.85k_t A_n f_u \]

\( A_g = \) the gross area of the cross-section

\( f_y = \) the yield stress used in design

\( k_t = \) the correction factor for distribution of forces

\( A_n = \) the net area of the cross-section

\( f_u = \) the tensile strength used in design
Design of Compression Members

Cl. 6.1, Design for axial compression

\[ N^* \leq \phi N_s \quad \text{and} \quad N^* \leq \phi N_c \]

\( \phi \) = the capacity factor, =0.9

\( N_s \) = the nominal section capacity determined in accordance with Clause 6.2

\( N_c \) = the nominal member capacity determined in accordance with Clause 6.3.
Truss Node Connections

- **Direct connections**
  - Members are welded directly to one another, without the need for gussets or other elements (e.g. tubular joints).
  - When the chords are made from large angles or tee-sections, it is possible to connect angle web members directly to the chords.

- **Gusseted connections**
  - Predominant when rivets and bolts are used for connections.
  - Transfer of forces is indirect and not aesthetically pleasing.
  - Advantage: easier to make all members intersect at the theoretical node point— in contrast to direct connections, where some eccentricity is unavoidable.

- **Pin connections**
  - Generally used when aesthetics are important
Open Sections
Gusset-Free Connections

(a) centre of gravity lines intersect at the node;
(b) eccentric connection can be a practical way of detailing but additional bending stresses are induced
(a) Gussetless construction using Tee-chords; (b) gussets are required where diagonals carry large forces; (c) Tee-diagonals and chords, gussetless; (d) and (e) node detail for heavy trusswork, and (f) riveted/bolted nodes
Connections of Rolled-Steel Sections

(a) portal-type Pratt truss
(b) Fink truss with large eaves overhang
(c) alternative chord cross-sections
Closed Sections
Splices for Tubular Truss Members

(a) sandwich plate splice; (b) sandwich plate splice at chord reduction; (c) jacket splice; (d) welded butt splice; (e) welded butt splice with reducer, and; (f) flange splice.
Connections for Tubular Sections

(a) Direct contact overlap connection without eccentricity; (b) direct contact overlap connection with eccentricity; (c) direct contact gap connection with/without eccentricity (with chord face reinforcing plate shown—without reinforcing plate is very common); (d) T-joint with chord face reinforcing plate (for very heavy loads—otherwise no reinforcing plate is also popular); (e) connection detail at support (note vertical stub portion with flange splice for lifting onto support); (f) concentric reducer where chord section is stepped down (alternatively, if the overall section is not stepped down then the wall thickness is reduced—the latter applies for RHS/SHS); (g) slotted-gusset connections; (h) flattened end connections, and; (i) slit tube connections.
Example

Span of truss 16.0 m
Rise of truss 3.2 m
Roof slope 21.8°
Truss spacing 4.0 m
Rafter length 8.62 m
Gusset Plate

- Flat structural elements used to connect adjacent members meeting at truss panel joints and at diagonal brace connections.
- Help transmit loads from one member to another.
- Maybe welded or bolted to the members meeting at the joints.
- Minimum thickness used in design practice is usually 10 mm.
Gusset Plate at a Diagonal Brace

- Work point (WP)
- Unbraced length of gusset plate, $L_g \geq$ distance between adjacent bolt lines
- Double angles
- Gusset plate with thickness, $t$
- $2t$ (min.), $4t$ (max.)
Gusset Plate at a Truss Panel Point

- Slotted holes in HSS
- Gusset plate with thickness $t$
- Work point (WP)
- HSS web member
- $W$-shaped truss bottom chord
- Stiffeners (where required)
- Whitmore section effective width,
  \[ l_w = b + 2L_w \tan 30^\circ \]
Gusset Plate at a Truss Panel Point
Gusset Plate at a Truss Panel Point

- Whitmore section effective width, $l_w$
- W-shape truss top chord
- Gusset plate (near side and far side)
- W-shaped truss web members (typical)
Gusset Plate at a Truss Support
Design of Gusset Plate

• For diagonal bracing connection, several connection interfaces must be designed:
  ➢ diagonal brace-to-gusset connection
  ➢ gusset-to-column connection
  ➢ beam-to-column connection

• At truss joints, the gusset plates connect the web members to the chord members

• The centroidal axes of the members meeting at the joint coincide at one point, called the work point (WP)
Buckling of the Free or Unsupported Edge

Use the largest free unbraced length, 

\[ L_{fg} = \text{larger of } L_{fg1} \text{ or } L_{fg2}. \]
Yielding of Gusset Plate

- Design tension or compression yield strength

\[ \phi N_s = \phi f_y l_w t \]

Tension yielding is the most desirable form of failure because of the ductility associated with this failure mode
Tension Failure

Tension failure of the gusset plate due to fracture at a bolt line within the Whitmore effective area

\[ \phi N_s = \phi f_u (l_w - nd_{hole})t \]

\( f_u \): Tensile strength of the gusset plate
\( \phi \): 0.75
\( n \): Number of bolt holes perpendicular to the applied axial force for each line
\( d_{hole} \): Diameter of bolt hole

Least desirable form of failure because of the sudden and brittle nature of this failure mode
Combined Actions

\[
\frac{M^*}{\phi M_s} + \left( \frac{N^*}{\phi N_s} \right)^2 + \left( \frac{V^*}{\phi V_s} \right)^2 \leq 1.0
\]
Example

For the truss joint shown below, the gusset plate is made of Grade 400 steel with a yield stress $f_y = 400$ MPa, and tensile strength $f_u = 520$ MPa assuming a M20 bolts of Property Class 4.6, determine

i) Whitmore effective width for the gusset plate on diagonal web members A and B

ii) Compression buckling capacity of the gusset plate on diagonal member A

iii) Tension capacity of the gusset plate on diagonal member B
16 mm thick Gusset plate

align plate with slope of brace

A

B

C

271 kN

376 kN
\[ l_{wA} = 40 + b_A + (L_{wA} \tan 30^\circ) \]

Edge of gusset plate

\[ l_{wB} = b_B + (2L_{wB} \tan 30^\circ) \]
Solution

1) \[ l_{wA} = 40 + b_A + L_{wA} \tan \theta \]
   \[ = 40 + 80 + 150 \tan 30^\circ \]
   \[ = 206.6 \text{ mm} \]

\[ l_{wB} = b_B + 2L_{wB} \tan \theta \]
\[ = 80 + 2 \times 150 \tan 30^\circ \]
\[ = 253.2 \text{ mm} \]
2) \( L_g = 75 \text{ mm} \)

\[
I_A = \frac{1}{12} l_{wa} t^3 = \frac{1}{12} (206.6)(16)^3 = 70519.5 \text{ mm}^4
\]

\[
r_A = \sqrt{\frac{I_A}{A}} = \sqrt{\frac{70519.5}{(206.6)(16)}} = 4.62 \text{ mm}
\]

\[
\frac{L_g}{r_A} = \frac{75}{4.62} = 16.2
\]

\[
N_{cr} = \frac{\pi^2 EI}{l_e^2} = \frac{3.14^2 (200 \times 10^9)(70519.5 \times 10^{-12})}{(75 \times 10^{-3})^2}
\]

\[
= 2.4721 \times 10^7 \text{ N}
\]

\[
= 24721 \text{ kN}
\]

\[
\phi N_c = \phi N_{cr} = 0.9 \times 24721 = 22249 \text{ kN}
\]
3) Tension yielding capacity of the gusset plate on the diagonal element B

\[
\phi N_t = \phi f_y A_g = (0.9)(400 \times 10^6) \times (16 \times 10^{-3})(253.2 \times 10^3) \\
= 1458.4 \text{ kN}
\]

Tension capacity of the gusset plate due fracture

\[
\phi N_t = \phi 0.85 f_u A_u \\
= (0.9)(0.85)(520 \times 10^6) \times (16 \times 10^{-3})(253.2 - 2 \times 22) \times 10^{-3} \\
= 1331.5 \text{ kN}
\]
GENERAL LAYOUT
TRUSSES OVER STEEL COLUMNS
Roof Purlins

Main Truss

Longitudinal Bracing (SEC 2-2)

Main System (SEC 3-3)

Vertical Bracing (SEC 1-1)

End Gable (SEC 4-4)

Sheets
\[ H = \frac{B}{12 - 16} \]

\[ h \geq 1.0m \]
Verticals

h

H

a=1.5 → 2.0 m

B=8-16a

MAIN SYSTEM
Diagonals

\[ a = 1.5 \rightarrow 2.0 \text{m} \]

\[ B = 8 - 16a \]

N-Truss
\( B = 8 - 16a \)

\( h \rightarrow H \)

\( a = 1.5 \rightarrow 2.0\text{m} \)

W-Truss
Cladding

h

\[ a = 1.5 \rightarrow 2.0 \text{m} \]

\[ B = 8 - 16a \]

MAIN SYSTEM
Roof Purlins

\[ B \]

\[ L = 7.0 \text{m} \]

\[ S = 5.0 \rightarrow 7.0 \text{m} \]
Horizontal Bracing

(1)

(2) MAIN SYSTEM (SEC 3-3)

(3)

(4)

VERTICAL BRACING (SEC 1-1)
- longitudinal bracing (vertically)
- horizontal bracing
LONGITUDINAL BRACING (SEC 2-2)

VERTICAL BRACING (SEC 1-1)

PLAN \( S = 5.0 \rightarrow 7.0 \text{m} \)
- Longitudinal bracing (vertically)
- Horizontal bracing