NAC Executive Insights

Design and Construction of Structural Steel Work

Key Points

- Structural steel construction offers economical bay sizes that are much larger compared to using concrete.
- Structural steel construction offers high seismic performance.
- Structural steel construction offers flexibility to match current architectural trends for "building statements."

The technical fundamentals described in this Executive Insight provide a foundation for an increased rate and depth of learning related to the design and construction of structural steel work.

Overview and Responsibilities for Structural Steel Construction

The scope of structural steel work typically consists of the steel elements of the building frame shown on the design drawings, which are essential to support the design loads. Contracts for steel erection typically require others to provide site access, prepare the overall schedule, and identify and manage interfaces with other construction trades.

Structural steel construction offers the following advantages as compared with concrete:

- Economical bay size of 42 x 30 feet, which is much larger than when using concrete
- High seismic performance
- Flexibility to match current architectural trends for "building statements."

Completion of a steel structures involves several key players. The *structural engineer* is responsible for the overall structural design. The *designer* sets design criteria, designs the structure, and produces specifications and drawings. The *detailer* prepares shop drawings using design drawings, standard details for connections, and, importantly, has knowledge of operations for fabrication and erection.

The *general contractor (GC)* is responsible for the overall construction of the project. The GC's responsibility also includes coordination of steel erection with the civil, concrete, mechanical, electrical, and plumbing (MEP), and architectural work.

The *field, project, or construction engineer* provides construction input, reviews shop drawings, designs temporary steel, and develops detailed erection plans and drawings. They typically also prepare the schedule for arrival of the steel and the equipment needed. Another of their key activities is checking the site for stability of lifting equipment and safety.

The *steel fabricator's* responsibility varies by region. In the U.S., fabrication is typically combined with a steel erector on the West Coast. The fabricator orders standard steel shapes from supplier, may design connections based on area practice, fabricates custom members for the project, and delivers fabricated members in a sequence that supports the erection plan.

The *steel erector* is responsible for the means, methods, and safety of erecting the structural steel frame. The erector prepares the erection plan, receives the steel, erects and connects (steel decking is typically by others in California), and provides temporary supports and safety protection.

1.0 Design of Steel Structures

1.1 Design requirements and process

The design process for structural steel includes the following major steps:

1) Design the building geometry (usually led by an architect), considering function, occupancy, adjacency, and massing.
2) Calculate gravity and lateral loads.
3) Select type of structure to resist the loads and size the member.
4) Design the connections considering American Institute of Steel Construction (AISC) standards, fabrication, shipment, and erection.
5) Detail members and connections.

Structural steel designers should have an in-depth knowledge of the OSHA Subpart R, Safety Regulations, as well as other applicable construction regulations. They should incorporate solutions for erection in their designs.

1.2 Types of connections for structural steel

Connections for structural steel have an interesting history. In the 1920s, the designs used all riveted connection. In the 1930s, bolting started. Shop welding became common in the 1950s, followed by field welding in the 1970s. Controlled field welding and alternate systems developed in the 1990s.

Two major types of connections are currently used. Bolted connections include the bearing type and the slip critical type. The major types of welded joint types are complete penetration groove, partial penetration groove, and fillet.

Shear connections, the most common type for structural steel members, transmit shear from one steel member to another. They are not able to resist moments at the connections, and therefore allow rotation at the connection under lateral loading.

Bearing type bolted connections (also termed shear connections) initially resist forces by friction, then bolt shear, then bearing, then tension on the net bolt section. The bolts are tightened only to a snug-tight condition. The *slip critical* type (friction) connection uses bolt tension to produce a clamping force and friction at the slip face. This slip critical type is used in joints that are subject to fatigue load and in joints that use slotted holes. The slip critical joint requires tightening the bolt to a full pre-tensioning load, which is greater than 70 percent of the minimum tensile strength of the bolt.

2.0 Steel Materials

2.1 Properties of materials for structural steel

Steel offers many advantages for use in building structures. It has high resistance for basic stresses (tension, compression, shear) and non-directional stress response. Other advantages are uniform quality and dimensions, well understood properties, resistance to freezing and thawing, and the capacity to satisfy many special purposes. The design of steel structures should consider the potential for corrosion, such as salt in the atmosphere.

2.2 Rolled steel shapes

AISC sets standards for member dimensions and properties. These are designated by shape symbol, depth, and weight per foot. Properties defined by AISC are weight in pounds per foot, cross sectional area in square inches, depth in inches, width and thickness of flanges in inches, web thickness in inches, moment of inertia, section modulus, and radius of gyration. Members of the same nominal size vary in cross section for different values of weight per foot.

3.0 Detailing and Fabricating Steel for Building Structures

3.1 Detailing structural steel

Detailing of structural steel is now performed primarily in 2D AutoCAD with increasing use of 3D. Integrated software packages allow partially automated fabrication. Several sources and activities provide key design criteria for detailing. These include standards; coordination with structural, architectural, and MEP drawings; and the desire to maximize shop connections as limited by maximum shipping size of pieces and capacity of the crane planned for erection. Other important considerations include access to the site and space required for material laydown and equipment locations. States and cities may limit the length and load and impose other restrictions.

3.2 Fabricating structural steel

Fabrication of structural steel begins with standard shapes and lengths from the supplier. Custom steel components are shipped to the site for assembly without further processing. Fabrication typically requires a large and well-equipped shop and a range of operations. The duration of fabrication for a typical job varies from three to eight weeks depending on the complexity, amount of welding, and use of an automated beam line.

The major operations for fabrication are: 1) cutting with a special saw (produces a machined finish) or a cutting torch; 2) bending with hydraulic benders for camber; 3) hole punching up to 1 ½ inches; 4) drilling holes larger than 1 ½ inches; 5) fit-up and assembly; 6) welding (automatic or manual); and7) sandblasting and surface coating.

4.0 Preparation for Steel Erection

The typical overall sequence for steel buildings involves the core and shell. This is followed by tenant work. Completing a steel structure requires steel erection, bolting or welding, decking with edge forms for opening, and other related activities.

4.1 Logistics for steel work

Building zones or segments are typically determined by about 10 truck loads; each member is marked with its zone. State and local transportation requirements define the typical truck size. Structural members can be extremely long (see photo).

The delivery sequence and location for receiving steel at a project site is determined by the available laydown and shakeout space. Typically, steel is delivered at the project site first in the morning and then after lunch. Projects with a staging area allow shakeout and positioning for more efficient erection. These two factors create significant constraints for plans.

4.2 Anchor bolts and column base plates

Anchor bolts set in concrete footings or mat foundations form a critical interface between concrete and steel work. The AISC Code of Standard Practice requires anchor bolts to be installed such that the variation in dimension between any two bolts within a group is less than 1/8-inch (3mm). The Code also establishes the division of responsibility for installation of loose column base plates: those that can be set by hand are installed by the general contractor; those that require a crane are set by the steel erector.

The design for larger columns may include leveling nuts on each anchor bolt. These are located under the column base plates. They assist in plumbing the columns by allowing adjustment before tightening the bolts above the base plate.

4.3 Steel erection plans and methods

Erection plans for structural steel include the following key elements: contract requirements (sequence, coordination), regulations (safety, environment, labor), structure (stability), and site (space and access restrictions). Erection drawings show the erection mark and location of each piece, the separation of framing zones, the sequence of erection, the bolt schedule, and the required methods for bolt tightening.

Field engineering activities as a part of erection planning include: zoning the building; setting member size and CG; designing temporary steel; locating and sizing the crane; calculating construction loading and support requirements; identifying requirements to leave out steel (gut bay) for access to erect other portions; and locating personnel lifts and design supports.

The major criterion to select equipment for steel erection is the lifting requirement determined by **extreme load and reach**. Mobile cranes are typically used for steel erection up to 14 stories. Options include a setup in luffing mode for increased reach.

Engineering and safety requirements may prompt a separate classification and additional planning for several types of crane lifts. For example, lifts greater than a specified portion of crane capacity may require additional planning. Other important criteria may result in classifying lifts as special or critical and require a written plan prepared by a qualified person. Examples of these criteria include: lifts requiring two or more cranes, lifts greater than a specified weight, lifting of personnel, lifts that require operation within a specified distance of power lines, and any lift that can create other risks.

Several conditions are necessary to begin steel erection. The general contractor should provide adequate access to and within the site to allow safe and unrestricted movement of crafts, materials, and equipment. Concrete that will bear any construction load during steel erection should reach a specified percentage of design strength prior to start of erection.

Steel erectors typically use one of two overall methods. The *tier erection method* involves setting all columns and beams at one floor level before continuing upward. This typically includes two or three floors per tier, as determined by column length. The perimeter is erected first, then the interior. Tier erection allows completing floors at one time. The steel erector will generally favor this method as the most productive.

The billboard erection method progresses the full height of a building, bay by bay. It is less efficient for the erector, but the general contractor may require this method to allow earlier start of work by other trades in specific parts of the building.

5.0 Erecting Structural Steel

Two main types of crews erect steel. The *raising crew* installs column base plates using shim packs and leveling nuts, verifies their position and grouts them in place.The crew then attaches slings and erects columns, followed by headers and beams.

The *fitting crew* fits beams into a column or other beams by using a spud wrench in the bolt holes. This crew installs a minimum of two erection bolts through columns and plates or one bolt through braces. Potential problems with fit-up of structural steel include inability to align bolt holes and obstructions from either the configuration of the individual member, adjacent members, or work by other trades. Standard practice allows reaming bolt holes a specified amount to allow fit-up.

Safety regulations typically require the sequence of column erection, beam erection, and then bolting within two floors or welding within eight floors. Other requirements may include a fully planked or decked floor and/or safety nets.

Regulations also usually require installation of steel decking prior to attaching shear connectors or reinforcing steel for a floor. Contractors install plumbing equipment for steel structures prior to loading with material. Field crews should review the latest applicable safety requirements and verify compliance.

Plumbing steel is aligning for compliance with erection tolerances, generally +/- 1 inch horizontal or 1 in 500 units of height. Crews typically use a transit, a two-foot offset, and diagonal guy cables with turnbuckles. QC programs normally require an independent check.

6.0 Bolted Connections

The steel bolt assembly for a bolted connection in structural steel includes the bolt, nut, and washer. Three main types of bolts are currently used: 1) *A307* designated unfinished, lowest capacity, used as erection bolts; 2) *A325* (heat treated, 120 ksi minimum tensile strength); and 3) *A490* (heat treated, 150 ksi minimum tensile strength), also designated high-strength.

Bolts are shipped to a site in lots with test certificates. At least three bolt, nut, and washer assemblies from each lot is tested to verify the bolts’ ability to develop the required tension. Bolt length must reach the plane of the nut or stick through. Reuse of A490 and galvanized A325 bolts is not allowed.

Bolting crews install the specified connection bolts and tension them with a pneumatic wrench. Specialized designs for bolts and washers, described in the following section on quality control for bolting, require changes in the tools and operations for bolt tensioning. Increased productivity and ease of quality control have prompted increased use of these methods.

Bearing type connections require snug-tight bolts, tightened by a few bursts from an impact wrench or the full effort of ironworkers with spud wrenchs. Slip-critical type connections require tensioning the bolt to a minimum value based on bolt diameter and type.

Three main methods are used in tension bolted connections to verify correct values. The *turn-of-nut method* requires bringing the nut to a snug-tight condition and then further tightening an additionally 1/3 to one full turn, depending on the length and diameter of the bolts. The amount of turn is defined by AISC tables. Contractors consider turn-of-the nut as the most reliable and preferred method. The *calibrated wrench method* uses wrenches set to provide bolt tension at least five percent greater than prescribed minimum bolt tension. This method requires returning to further torque after tensioning all bolts. A special calibration tool is used to verify correct set values for the wrench.

To assist in field operations for bolted connections, other special types of bolting systems use tension control bolts or load indicator washers to confirm correct tensioning. *Tension control bolts* (ASTM F1852) are made with either hex or button heads and include a splined shaft attached to the threaded end of the bolt. Tightened with a special electric wrench, these bolts are designed so that the splined end shears off when the bolt reaches the required tension. Load indicator washers (ASTM F959), also termed direct tension indicators, provide another method of verifying correct tension. They include a protrusion that is flattened to a prescribed gap during bolt tensioning.

7.0 Overview of Welding Technology and Processes

A properly completed welded joint has the potential for the same strength properties as the metal of the parts. Other processes such as soldering, brazing, or adhesive bonding do not duplicate the mechanical properties of the base materials at the joint. Consumable electrode arc welding processes deposit filler metal more efficiently and at higher rates than other welding processes.

7.1 Physics of welding

Welding is the application of heat or pressure to produce a localized coalescence of materials and a suitable bond, with or without filler metals. Welding produces a molecular bond of materials, not a mechanical connection such as bolts.

Shielding is required during the welding process to prevent high temperature metals from reacting with oxygen and nitrogen. It is typically provided by an electrode covering, a shielding gas, or a powder.

7.2 Welding processes and properties of materials

Welding processes differ by base metals, method of shielding, filler metal type and form of input, heat input, and feasible deposition rate (pounds of filler metal per hour).

7.3 Heat flow in welding

Quality welding requires maintaining the specified thermal conditions in and near weld metal within specific limits to control metallurgical structure, mechanical properties, residual stresses, and distortions that result from a welding operation.

The rate of heat input to the workpiece during welding is governed by magnitude and rate of energy input at the weld, the distribution of heat input, and the weld travel speed. Heat transfer in a weldment forms a time-dependent temperature distribution. The weld undergoes a thermal cycle that varies from location to location depending on the heat input, weldment geometry, and material properties.

7.4 Types of arc shielding

Metals at high temperature react chemically with oxygen and nitrogen in air to form harmful oxides and nitrides. Arc welding processes must provide a means to cover the arc and the molten metal with gas, vapor, or slag to prevent contact of molten metal with air.

The covering for “stick” electrodes in certain arc welding processes, under the heat of the arc, generates a gaseous shield. The arc covering also supplies ingredients that react with deleterious substances on the metals, such as oxides and salts, and tie up these substances chemically in a slag that rises to the top of the pool and crusts over newly solidified metal. Other welding processes use a shielding gas supplied to the point of welding.

8.0 Metallurgy of Welding

Weldability of base metal is the capacity of the material to be welded under the imposed fabrication conditions into a specific, suitably designed structure for satisfactory performance of its intended purpose. It is primarily determined by chemical composition. Most common engineering alloys are weldable, but some are more difficult.

Weld metal differs in microstructure based on different thermal and mechanical histories. It depends heavily on the sequence of events when the weld metal solidifies, including reactions with gases and slag or flux. Weld metal is strengthened by solidification grain structure, solid solution strengthening by alloying additions, transformation hardening by different cooling rates, or precipitation hardening by aging heat treatment.

9.0 Welding Processes Most Frequently Used in Construction

All arc welding processes require an electrical circuit that consists of an AC or DC power supply, an electrode (hot) cable from the power supply to a holder for the electrode, an arc producing a temperature of about 6500° F formed by the electric current and the gap between the electrode, the welded piece that receives the heat generated by the arc, and a work cable from the piece back to the power supply. Safe practice also requires grounding of the power supply and the work piece.

The design of the electrode, typically a consumable material that becomes the filler metal for the weld, and the method of shielding the molten metal until it cools are the two main variables that differentiate the major welding processes used for structural work.

The size, thickness, and position of the weld are important criteria for selection of the specific welding process. Fast fill joints require a large volume and high rate of deposition of weld metal. Fast freeze joints are out of position (such as vertical or overhead) and therefore require rapid solidification of the molten metal. Fast follow welds require the molten metal to follow the arc at rapid travel speed to produce a smooth bead. Penetration is the depth of the joint.

9.1 Shielded metal arc welding (SMAW)

The most widely used welding process for carbon and low alloy steels as well as stainless steel is shielded metal arc welding (SMAW), also known as stick welding. SMAW is simple, versatile, and applicable to the shop or field. This process uses a covered solid or powered metal electrode (1/16- to 5/16-inch diameter or 2 to 8 mm) to provide filler metal. The covering over the electrode provides shielding gas and slag. In this process the electrode rod provides its own shielding and is quickly consumed.

The main advantages of SMAW include: flexibility to handle many welding applications at many locations and in many welding positions, simplicity and lightness of the equipment, and low cost. Deposition rates vary from 2 to 17 lb/day, with a normal rate of 10 lb/day for a mix of welding access restrictions and positions.

The operator's skill is an extremely important factor in the quality of stick welds. Potential problems include: arc blow, arc stability, excessive splatter, incorrect weld profile, porosity, and surface roughness.

9.2 Flux cored arc welding (FCAW)

Flux cored arc welding (FCAW) uses a continuous filler metal electrode that is automatically fed as wire from a role. The tubular electrode contains core ingredients that supply some or all the shielding gas needed. Gas-shielded flux core processes include an external gas supply to supplement shielding from the core. Self-shielded electrodes provide full shielding from protective gases and slag.

The major variables for the FCAW process are: arc voltage, current, electrode wire type, wire feed speed, electrode angles and extension, travel speed, and shielding gas composition if used.

Because of its high speed and portability, FCAW is widely used in construction. It has a high deposition rate and can be used in all positions. Potential problems include melted contact tip, irregular wire feed, and porosity. Self-shielded FCAW emits highly toxic fumes.

9.3 Gas metal arc or metal inert gas welding

Gas metal arc (GMAW) or metal inert gas (MIG) welding processes use a continuous filler metal electrode supplied by solid wire on a reel. These are considered semi-automatic and are relatively easy to learn. Shielding is provided by externally supplied gas. Advantages are high versatility, unlimited electrode length, welding in all positions, slag-free weld bead, and high deposition rates.

Potential problems during MIG welding include: burnback, metal hardening, reduction in fatigue strength of the base metal, cracks and porosity, reduction in corrosion resistance of the welding zone, porosity, and unstable arc.

Conclusion

The design and construction of structural steel play key roles in many types of facilities, including buildings, infrastructure, equipment and piping supports, and many other miscellaneous support requirements. The resources and the operations involved in structural steel presented in this Executive Insight cover two important elements in structural steel technical fundamentals.

Sources

- American Institute for Steel Construction (AISC) sets standards for design of steel structures; AISC Code of Standard Practice gives overall requirements for design drawings, shop and erection drawings, fabrication, erection, QA, and contracts.
- American Society Testing Materials (ASTM) sets standards for steel materials and for testing.
- American Welding Society (AWS) sets standards for structural welding.
- Occupational Safety and Health Administration (OSHA), Subpart R, Safety Regulations

About the Authors

Bob Tatum was elected to the National Academy of Construction in 2002. His field experience began with serving in the U.S. Army Corps of Engineers on infrastructure projects in Vietnam. He worked as a field engineer and area superintendent on two large power plant projects. He joined the Stanford University construction faculty in 1983. His teaching and research focus on construction engineering, integration, and innovation.

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Joe Hunt was elected to the National Academy of Construction in 2013. He served as general president of the Association of Bridge, Structural, Ornamental and Reinfircing Iron Wokers from 2001 until his retirement in 2011. He has been involved in the ironworker industry his entire career, which spans more than 50 years. He is an active advisor to labor groups in Washington, D.C., and was instrumental in launching the IMPACT program to improve relationships with contractors, management, and customers.