STRUCTURAL STEEL DESIGN
AND CONSTRUCTION

by

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**GLOSSARY**

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GLOSSARY

This glossary defines some expressions that are commonplace to the entire construction industry, with a focus on the steel industry.

**Advanced Bill** – a preliminary bill of materials prepared using the Engineer of record’s contract drawings. From the advanced bill, a purchase order is usually prepared and provided to the steel mill or manufacturer to reserve a time slot (window) in which the steel order will be produced or to reserve a certain quantity of shapes produced by the mill.

**AISC** – The American Institute of Steel Construction.

**AISC Weight** – the weight of structural steel as defined by the AISC.

**Anchor Bolt** – an embedded bolt or threaded connection used to attach column bases and transfer loads to the foundation.

**ASTM** – The American Society of Testing and Materials and the organization that generally establishes the grades of structural steel.

**Beam** – a structural element that usually carries its primary loads in bending perpendicular to its axis.

**Bearing Area** – The part of the Beam, column or structural element that rests on a support.

**Blanks** – an assembly of identical or nearly identical multiple structural elements or built-ups fabricated prior to engineering or detailing being completed to take advantage of economies of scale in the shop or to gain time on the fabrication schedule.

**Brace** – a structural element used to stiffen or support a portion of a structure or frame.

**Built-up Member** – a structural element fabricated from a number of other structural elements connected by welding, bolts or other means.

**CAD** – Computer Aided Design using popular programs such as Autocad® that digitize (computerize) the geometry of the structure.

**Calculations** – structural analysis tabulations performed and documented by the structural Engineer of record to size all structural elements, braces, and stiffeners in accordance with the Code.

**Camber** – a curvature built into a Beam, truss or other structural element to offset anticipated deflection so that the element will not bow under dead load.

**Chamfer** – the result of cutting or grinding (beveling) the edge of a steel member or plate at other than a ninety-degree angle. This often occurs when welding two pieces of steel together.

Column – a structural element that usually carries its primary loads in compression or tension parallel its axis.

Column Base – usually a thick plate at the bottom of a column through which anchor bolts mechanically connect the column and transfer forces to the foundation.

Composite Beam – a structural element, usually a Beam that is connected to a concrete slab such that the steel and concrete act as one element.

Compression – the state, for example in a column or an element of a truss, whereby a member is being shortened by a force. Compression is an axial load that is the opposite of tension.

Connection – a joint or node of structural elements used to transfer forces between structural elements or members.

Dead Load – the weight of the structural frame (or element) itself plus any equipment permanently attached to it.

Decking – a structural element usually constructed from corrugated bent plate used to form an elevated slab.

Design Forces – the loads that act on the structural system, e.g. dead load, live load, and environmental influences such as wind load, snow load, seismic load, and other dynamic loads.

Detail Drawing – a shop drawing, usually produced by a detailer, that defines the exact shape, dimensions, bolt hole patterns, etc. of a single piece of steel (or more) that may stand alone in the structure or that is one of many pieces in an assembly or shipping piece.

Detailer – a person or entity that is charged with the production of the advanced bill of materials, final bill of materials, and the production of all shop drawings necessary to purchase, fabricate and erect structural steel. The detailer may be an independent contractor or on the staff of a fabrication or erection company.

Detail Piece – a single piece of steel that may stand alone in the structure or that is one of many pieces in an assembly or shipping piece.

Detailing – the production of different types of shop drawings needed to fabricate and erect structural steel.

Engineer of Record – a sole practitioner or member of a firm responsible for the structural engineering of the steel structure and that ultimately seals the drawings and specifications with his or her professional seal.
**Erection** - the act of assembling the shipping pieces in the field including material handling, safety, plumb and bolt, welding, and placing deck material.

**Erection Drawing** - a primary shop drawing that illustrates to the raising gang how to assemble the shipping pieces in the field. Ironworkers match piece marks on the actual shipping pieces to the piece marks noted on the erection drawings.

**Fabrication** - the act of changing steel from the mill or warehouse into the exact configuration needed for assembly into a shipping piece or directly into a structural frame. It includes material handling, template making, cutting, bending, punching, welding, and grinding.

**Force** - a reaction that develops in a member or structural element, e.g. axial loads, moments, shear and torsion.

**Frame** - a system of assembled structural elements.

**Geometry** - the configuration of all the structural elements noted on the engineering and shop drawings that depict the relationship of one structural element to the next. The geometry is controlled by the drawings produced by the Engineer of record from which the detailer uses working points and dimensions to produce erection, detail and other shop drawings. If the “geometry” does not “close” it means that one or more dimensions are wrong.

**Girder** - a large primary beam used to carry point loads along its length. Girders usually support beams and columns.

**Grade** - a designation of the ASTM that identifies the chemical composition and strength characteristics of structural steel, e.g. ASTM A50 which identifies the steel as having a yield (or failure) strength of 50,000 pounds per square inch.

**Live Load** - the loads imposed on a structure that are not permanently attached to the structure such as loads imposed by the weight of people, movable equipment, vehicles and furnishings. It does not include wind load, snow load or seismic load.

**Loads** - a force or systems of forces carried by the structure or any of its elements.

**Loading Combinations** - are the systematic application of composite design forces or loading conditions used to determine the maximum stresses in structural members. For example 100% dead load and 80% live load plus 50% wind load from the east plus 75% snow load all occurring in a designated seismic zone. These loads would all be applied to the computer model structure at the same time.

**Member** - a structural element such as a beam, column, girder or brace.
Mill Order – the actual final purchase order for the mill or manufacturer based on quantities derived from the production of certain steel shop drawings. This order replaces or confirms the advanced bill.

Moment – a force in of steel that is caused by an applied load causing a structural element to want to rotate at a given point causing a moment reaction at that point. The moment, in simple terms, is measured by multiplying the force times the distance that force is applied from the support.

Moment Connection – is a joint that resists and supports a moment such that the joint resists rotation.

Piece Mark – an identification number that distinguishes one piece of steel or assembly from another. Piece marks oftentimes follow a code that can tell the ironworker the exact area, level and location of the piece of steel.

Pin Connection – is a joint that does not resist a moment and in the structural computer model allows the joint to rotate eliminating the moment in a structural member. Pin connections are common in the design of trusses.

Plate Girder – A typically large beam capable of supporting large loads built-up by welding various plates together. Sometimes referred to as a built-up member.

Point Load – is an applied force concentrated in a small area on a structural element. The load is usually measured in pounds. A heavy piece of machinery with a small footprint is an example of a point load.

Reaction – a force or system of forces that occur at a connection or support resulting from the application of loads to the structure. Reactions are needed to design every connection in a structural frame. Reactions are usually categorized as being axial (parallel), bending (perpendicular) and torsion (twisting).

Shear – the deformation force in a structural element, usually a beam, in which parallel planes tend to slide relative to each other.

Shipping Piece – Sometimes a single piece of steel or more typically an assembly of fabricated steel pieces that are transported to the field as a unit and that are erected into the structure as a single assembly.

Splice – a connection between two structural elements to form one structural element.

Standards – a set of engineering calculations that define the procedure submitted by a fabricator for designing certain elements in the structure, e.g. a procedure for designing moment connections, truss connections or simple beam shear connections. The Engineer of Record usually approves of these procedures in advance of the fabricator designing the connections.
**Stiffener** - a plate or structural element the assists in the distribution of loads to prevent failure of the element at certain points along the element.

**Structural Shapes** - standard steel configurations produced by steel mills such as wide flanges, channels, angles, pipe, tubes, etc.

**Structural Steel** - the structural elements that make up the frame that are essential to supporting the design loads, e.g. beams, columns, braces, plate, trusses, and fasteners. It does not include for example cables, ladders, chutes, grating, stairs, catwalks, handrails or ornamental metal.

**Stud** - a vertical cylindrical bar of steel with a larger cylindrical cap fastened to metal decking used to form a mechanical connection between the metal decking and the poured-in-place concrete slab such that the two form a composite structural element. Studs are also used to produce composite beams.

**Submittals** - deliverables made by the contractor inclusive of shop drawings, manufacturer cut sheets and material samples.

**Templates** - forms used by a fabricator to insure the exact fabrication of multiple identical detail pieces. Templates are usually made of a durable cardboard-like material or sheet metal and allow ironworkers in the shop to manufacture detail pieces without taking measurements or referring to detail drawings.

**Tension** - the state, for example in a column or an element of a truss, whereby a member is being lengthened by a force. Tension is an axial load that is the opposite of compression.

**Torsion** - the twisting of a structural element about its longitudinal axis by applied equal and opposite forces.

**Truss** - a structural frame of steel shapes connected into an assembly that can support loads far in excess of beams and girders due in large part to the depth or height of the assembly. A truss is composed of chords (main horizontal members), vertical members and diagonal members.

**Uniform Load** - is an applied load over a large area on a structural element or over many structural elements. The load is usually measured in pounds per square foot. The force caused by the build up of snow is an example of a uniform load.

**Welding** - the act of joining steel pieces using heat and filler metal. The welding of structural steel is governed by the American Welding Society (AWS) Structural Welding Code.

**Working Point** - a reference point on the contract drawings. On drawings depicting steel, the intersections of the centerlines of beams, girders, columns and braces are usually designated as working points.
I. INTRODUCTION TO STEEL DESIGN AND CONSTRUCTION

Steel is a common building material used throughout the construction industry. Its primary purpose is to form a skeleton for the building or structure – essentially the part of the structure that holds everything up and together. Steel has many advantages when compared to other structural building materials such as concrete, timber, plastics and the newer composite materials. Steel is one of the friendliest environmental building materials – steel is 100% recyclable and in fact, according to the American Iron and Steel Institute, steel is the most recycled material in the United States reducing the burden on today’s landfills. Steel, unlike wood, does not warp or twist and does not substantially expand and contract with the weather. Unlike concrete, steel does not need time to cure and is immediately at full strength. Steel is versatile, has more strength with less weight, has an attractive appearance, can be erected in most weather conditions, is of uniform quality, has proven durability and has low life cycle costs. These advantages make steel the building material of choice.

Steel as a building material has been studied and tested for many years. It might be said that we understand the behavior of steel better than any other building material. Steel is a predictable material and during the 1990’s the industry had implemented new procedures for designing steel structures. Structural design has evolved, mostly due to the necessity caused by earthquakes.
The evolution of steel design brought us from the theory that the stiffer the structure the better. Today, flexibility and ductility is key. Until the 1970’s, structures were designed using proven formulas, but the calculations were done by hand. Today, using software on your PC, you can literally design a structure in a day, something that could have taken a structural engineer months to do using paper and pencil. The new tools available today solve some old problems and create some new ones. One of the key ingredients of the evolution of steel structure design is CAD (Computer Aided Design). The days of drafting are almost gone and digitizing the structure in the computer saves time, ensures quality and usually results in a lower cost. However, like all innovations, technology breeds its own set of new problems.

With us knowing so much about steel one would question why this component of a project is often plagued with problems. The steel industry is well organized. There are codes provided by the steel industry, most local and national building codes address steel issues, academia is constantly studying steel design and construction, and we are constantly learning from structural steel failures. So why is it that structural steel, usually a critical path activity on any project, has associated with it so many problems?

The answer lies in the process from design through erection, the number and types of parties involved in the process, and the ease and speed at which changes can be accommodated. This chapter will present the basics of structural design, fabrication and erection and will provide the “non-technical”
attorney a better framework from which to understand their client’s issues and ask better questions.

II. THE STEEL PROCESS – FROM DESIGN THROUGH ERECTION

While the size and complexity of the project may drive and in some way change the process, the path of steel structural design and construction is predictable and proven. For the purposes of this chapter we will examine structural steel in the context of a building design requiring the services of an architect. However, there are many structures, constructed of steel, that do not require architectural input - these could include frames to mount equipment and machinery, offshore platforms, marine terminals, refineries, process plants and other non-aesthetic structures.

The production of conceptual, schematic and design development drawings are essential predecessor activities to finalizing the design of the structural framework. In theory, it is the structural engineer’s job to make the vision of the architect come true. While most architects can appreciate the complexity of the structural design of their vision, only the structural engineer can gauge what needs to be done to satisfy the architect’s requirements.

After the architecture of the building is determined, the design of the framework - beams, columns, bracing etc. - proceeds with engineering calculations.
A. **Engineering**

Structural engineering is the application of science and math to design a structure. With reference to the various building codes, the recommendations and codes of the American Institute of Steel Construction (AISC), and the empirical data derived from all the testing done on steel structures, the structural engineer understands and can adequately predict the behavior of steel.

In the United States and in some other countries, when the term “code” is used in the steel design and construction industry, it is usually in reference to the Code of Standard Practice for Steel Buildings and Bridges published by AISC. First published in 1924, the Code has been periodically updated to reflect new technology. In the year 2000, the September 1, 1986 version of the Code is still in effect.

The purpose of the Code is clearly stated in Section 1.:

"The practices defined herein have been adopted by the AISC as the commonly accepted standards of the structural steel fabricating industry. In the absence of other instructions in the contract documents,
the trade practices defined in this Code of Standard Practice, as revised to date, govern the fabrication and erection of structural steel.”

The Code provides the structural engineer, detailer, fabricator and erector with the framework from which to engineer, detail, fabricate and erect steel. In addition to the Code of Standard Practice, the AISC publishes a Commentary on the Code of Standard Practice that assists the users of the Code in understanding the background, basis and intent of its provisions. It is one of the few construction industry codes that has a detailed explanatory commentary.

Besides the Code of Standard Practice, AISC publishes other codes that more specifically cover other aspects of steel design and construction. They include the Specifications for Structural Joints Using ASTM A325 or A490 Bolts which also includes a commentary section, and the Manual of Steel Construction [which allow for two different design approaches to engineering steel – Allowable Stress Design and Load & Resistance Factor Design].

With reference to these Codes the structural engineer, using both the computer and hand calculations, produces the structural design of the building, bridge or other framework.

For clarity, one can categorize structural steel design of frameworks into three areas: main members, secondary members and connections. The structural engineering of main members may include beams,
columns, trusses, and girders. Main members are the skeleton of the framework and are the primary members that carry the loads imparted on the structure. Simply, it is the part of the structure that holds things up. The structural engineering of secondary members may include bracing, stairs, and decking. Secondary structural elements are designed to carry specific loads. For example, a brace is added to provide extra support in the area of a load thereby reducing the size of a member or the moment at a connection. Connections are joints or nodes of structural elements used to transfer forces between structural elements or members. The structural engineering of connections ensures that at the point (node) where the structural members meet (connect), sufficient steel area exists to resist the cumulative stresses at that node – axial loads (compression and tension), bending moments, and torsional loadings (torque).

1. Main Member Design

The actual structural engineering calculations for the main (primary) members takes place after a number of critical factors are determined. To start, the engineer uses the architectural drawings to determine the column locations from which the concrete foundation will be designed. The steel columns will connect to the concrete foundation through the use of anchor bolts embedded in the concrete
and connected to column base plates with nuts and washers. The location of the columns determines the configuration of the framework of members.

Concurrently, the engineer is obtaining other information from the architect on loads – dead load, live load, and special point loads. Initially, the structure must hold up its own weight (dead load) and must, in addition, hold up uniform and point loads (live loads) that anticipate how the
Typical Elevation of a Truss drawn by the Engineer of Record. Elevations describe the relative vertical position of structural elements to one another. Note the top of slab elevations of the various floors. Also note the column line designations and the fact that no dimensions are given for column lines — this information would be contained on a plan drawing. Note that member sizes are being called out and that loads are given for the diagonal members of the truss.

applied this live load to the design, the engineer does not have to calculate the cause and effect of every single piece of equipment that can stress the structure. However, in some cases, certain machinery is placed on the floor that is so heavy that point loads must be taken into consideration.
Other loads that cause stress on the structure, typically referred to as environmental loads, are wind, snow, rain, earthquakes, floods, vibration and loads caused by member failure due to fires. These loads, plus the dead and live loads, describe the loading conditions. The art in structural design,
for which some of the magic is taken away by the codes, is in applying the correct loading combinations of loading conditions to the structure to determine the highest stresses in the structural members that can reasonably be expected to occur.

For example, what are the stresses in a column when 100% of the dead load, 50% of the live load, 25% of the snow load, and 75% of the wind load are applied to the structural model? This application of concurrent loads is called a loading combination. There can be as few as one loading combination or there can be literally over a hundred. This is one of the problems computer analysis has caused. The ease at which we can program data, and the speed at which results are generated, has resulted in the undermining of the art of being able to determine through experience the critical types and numbers of loading combinations. In fact, because of the litigiousness of our industry, engineers too often run every possibility through the computer. Before the advent of PC based software, eight loading combinations were often deemed sufficient.

Using the example of the column described earlier, each loading combination may result in a different set of
stresses and reactions on the column. The computer or engineer then selects the best sizes and thicknesses of standard structural shapes produced by the steel mills. The engineer then evaluates a variety of factors to make sure the geometry of the structure works. For example, you would not want a thirty-six inch deep beam framing into a fourteen-inch girder. So the engineer makes these determinations and using either CAD or draftsmen prepares structural drawings – framing plans, elevation and details. But the important consideration sometimes overlooked by the Engineer of Record is what happens at the connections.

2. Secondary Member Design

After the main members have been located, sized and their reactions and loads are known, supporting secondary members must be designed for the structure. Secondary members include braces, stiffeners and other structural elements that typically support main members causing the main members to be smaller in size. Other secondary members that need to be designed include stairs, catwalks, grating, ladders and other miscellaneous appurtenances.
The dead weight of the secondary members may be significant enough to consider in the design of the main structural members. The total weight of secondary members can also be significant and must not be overlooked in calculating the weight of the structure.

3. Connection Design

It is often the case that the structural design of the connections is delegated contractually by the Engineer of record to the fabricator. The rationale is that no entity knows
This is an illustration of a simple shear connection. The figure on the left is an elevation and the figure on the right is a section cut right through the connection. The smaller beam is fabricated with bolt holes, while the larger girder is fabricated with a plate welded (note weld symbol) to it with bolt holes. In the field the bolt holes on the beam are lined up with the bolt holes on the plate and the beams are bolted together.

Either way, by taking this approach, the Engineer of record (EOR) in this process delegates to others the responsibility for completing the rest of the design of the structure. Arguably, all the EOR did was size the main and secondary members. Yet one can make a case that the
complexity in the design of the structural framework lies in the connections.

Connections cannot be designed without the input of the EOR. The connection designers need to obtain geometrical data from the structural drawings. This establishes the location and the sizes of members connecting at a node. Next the connection designers require knowledge of design intent, e.g. how did the EOR mean for this connection to act - did they want it to react like a moment connection or should it be designed as a pin connection. Without getting into the dynamics of structural theory, what is important is that the fixity of a connection must match what the EOR modeled when the main and secondary member sizes were determined in the computer analysis. The type of connection used in the structural computer model or hand calculation can easily be illustrated on the structural drawings for the connection designer’s use.
Next, the connection designers need to know the forces or reactions for each of the members connecting at the node. The connection designer is looking for reactions such as axial forces, bending moments, shear and torsion. The difficulty is that every member of the framework has
different reactions for each loading combination selected. The manner in which the EOR selects one set of reactions to supply to the connection designer is a complex issue and one that will be addressed below.

On the assumption that the connection designer has been given all the necessary criteria, the connections are designed using computer programs or hand calculations. These calculations must be prepared and stamped by a licensed professional engineer and are subject to the approval of the EOR. But, in some cases, there are thousands of connections. To alleviate the EOR’s burden of approving every connection design, standards or template designs are produced.

For example, a typical design procedure will be prepared for a cantilever beam whose connection is a moment type. Once the procedure is approved by the EOR, the connection designer follows this design procedure for every connection design meeting this criterion. At the end of the project, the connection designer certifies that it has followed the approved procedure, but it is good practice for the EOR to spot check for compliance.
Connections may be the most complex part of the structural engineering of a project. Besides figuring out how to physically weld or bolt the various members together, the engineers have to consider the need for various stiffening plates and bracing. The design of connections is not cookbook. However, once the true reactions are known at the connection, which is the real design challenge, the application of the structural formulas is routine.

At the completion of the structural engineering of the entire framework – main and secondary members and connections – a book of engineering calculations is prepared.

4. Engineering Calculations

Somewhat analogous to as-built drawings, the EOR should prepare a record of the final calculations used for determining the size and type of all members and their connection configuration. Later, this record can be used for many purposes, including to re-analyze the design after a failure or to check the structural integrity of the framework for new loads due to changes in the physical configuration of the structure such as a new floor or an addition.
Unfortunately, large and complex jobs rarely have the final structural calculations in order. Oftentimes, preliminary designs and the iterative design of structural elements are mixed up with final calculations.

Lastly, it is important that the results of the final design calculations match what was fabricated and erected in the field.

B. Detailing

Detailing is the process of converting the structural design drawings to shop drawings. These shop drawings are used by the fabricator to identify the size, shape, and material grade of every single piece of structural steel in the framework. On huge projects, those with over 40,000 tons of steel, it would not be unusual for the framework and connections to be comprised of literally 300,000 individual pieces of steel. Keep in mind however that to facilitate erection economy many of these detail pieces are fabricated into assemblies before being shipped to the field. On a huge project, as described above, it would not be unusual for a project of this magnitude to have more than 45,000 assemblies or shipping pieces.

Detailing is a step by step, arduous process, although technological advancements such as CAD and electronic mail
Typical Bill of Material prepared by the detailer to send to the mill. As an example, line 6 lists the type of member as a ‘W’ or wide-flange shape 14 inches tall weighing 370 pounds per foot being 25 feet 2 inches long made of Grade 28 steel.

1. Advanced Bill of Material
Whether the fabricator hires an outside person or firm to provide the detailing or utilizes in-house personnel, one of their first tasks is to produce the advanced bill of materials. Taken directly from the structural plans produced by the EOR, detailers prepare the steel orders (bill of material) to purchase steel from the mill. Steel is usually purchased in a series of phases or all at once. Steel purchased from a mill in a huge lot insures material availability, quality and a volume discount. Material not purchased from a mill, for example from a warehouse, is more costly and there is no guarantee that the sizes and grades will be available. Steel can be purchased domestically or abroad. U.S. manufacturers face stiff competition from countries such as Japan, Germany and England.

Steel mills in general do not produce all the various types of steel required on a project. Some mills only produce plate and some mills only produce shapes such as wide flanges, channels and angles, for example. Some mills produce all shapes, but they restrict the sizes of the shapes they manufacture. For example some mills are tooled to only
Common Steel Shapes

produce very large shapes such as heavy wide-flange beams and some mills may not produce wide-flanges shapes at all.

In fact, some mills only produce certain shapes at various times of the year. Therefore it is critical to know what shapes and sizes your project is going to utilize as early as possible. This will insure availability and a predictable schedule for delivery. If you miss a mill’s “window” for producing certain types of steel and the mill has already contracted for this year’s annual production, you will be forced to find another source.
The advanced bill of material is no more than a detailed quantity takeoff of the steel in the job. Besides ordering standard shapes, the detailers determine the quantities, sizes and thicknesses of flat plate that are required. These plates will be cut up to fabricate various assemblies including plate girders and stiffeners.

The next step after the advanced bill is produced is to prepare the erection drawings.

2. Erection Drawings

Erection drawings provide the field erection crew (raising gang) with the roadmap of how to erect (put together) the steel assemblies after they are delivered to the field. Essentially, they are a set of instructions on how to put the puzzle pieces together. The erection drawings look very similar to the structural drawings produced by the EOR with a few major distinctions. First, every assembly shipped to the field is given a shipping piece number to identify it. This number is noted on the drawing and is also stenciled onto the actual assembly of steel. Second, on the erection drawings, every assembly of steel is shown, no matter how insignificant or small. The erection crew must know where each assembly
fits into the structural framework. Also, unlike the structural drawings, the erection drawing illustrates how the connections will be fabricated in the field. In fact, because the erection drawings are produced first (before the detail drawings), the erection drawings need to exactly illustrate the
location of the members so that the geometry of the connections can be designed and detail drawings can be completed. For every assembly a detail drawing is produced illustrating the parts (elements) of the assembly.

3. **Detail drawings**

Detail drawings are what most people in the construction industry would categorize as the official shop
drawings. Detail drawings depict the components of each assembly; remember those 300,000 individual pieces of steel. On these drawings, the detailers give the fabricator step by step instructions on how to fabricate each piece. Fabrication involves material handling, cutting, burning, drilling, grinding, welding, punching, bending, shearing, and sawing the components of the assembly. Each detail piece is given a distinct number so that the fitters in the shop know how to put the assembly of detail pieces together into shipping pieces.

Detail drawings usually depict a final bill of material for the steel shown on a particular drawing. Any additional pieces not contained in the advanced bill of material are either added to the original purchase order(s) or are bought from sources other than the mill.

On the huge project described earlier it would not be unusual to have more than 15,000 detail drawings and approximately 2,000 erection drawings. Administratively, it is a nightmare for the fabricator, detailer, EOR, architect and erector to track changes. To assure the EOR that the detailer and fabricator have followed their instructions as to design and design intent, the fabricator is required to submit its erection and detail drawings for approval, like any typical
shop drawing. The only difference here is the substantial quantity of steel detail drawings.

4. Submittals and Approvals

The only way the EOR will know what is being fabricated and erected is to review the drawings produced by the detailer. Periodically, it is important for the EOR to make site inspections of the fabrication plant to assure adherence to the requirements set forth in the structural design. Fortunately, many details on how to bolt, weld, camber and chamfer steel are controlled by the AISC in its Code of Standard Practice for Steel Building and Bridges.

To reduce the thousands of shop drawings needing review by the EOR, certain standard drawings are produced. These drawings depict how typical assemblies will be put together and include details on bolting, shop and field welding, and configuration.

Like any shop drawing, the EOR reviews the details of these drawings for conformance to the standards and its design intent, e.g. to verify that a connection intended to be a moment connection will function as one if the steel is assembled in conformance with the detail drawing.
Soon after some of the steel has arrived at the fabricator and some of the detail drawings are complete, fabrication begins. The phasing and coordination of the advanced bill of materials and the detail drawings is critical to the success of the project.

Detailing also involves the production of a number of other specialty drawings. These include anchor bolts plans, bolt placement drawings, column schedules, stair and handrail drawings, and specialty connection drawings.

C. Fabrication

Fabrication is the process of cutting, burning, welding, drilling, grinding, punching, bending and generally producing the steel detail pieces shown on the detail drawings. The process of fabrication is systematic.

The process starts with coordinating the first steel to be fabricated with the steel inventory. Separate material handling laborers make sure that the fitters have the correct steel at various fitting stations when the steel is needed. Concurrently, template makers are producing disposable cardboard-like templates used for cutting steel. These templates take the guesswork out of the shop worker’s hands. They just fabricate the steel to match the template and, in theory, a perfect detail piece is produced.
With the right steel at their location and templates in hand, the fitters begin the process of producing the detail pieces.

Later in the process, fitters or a separate welding crew will attach a series of detail pieces together to form the assemblies or shipping pieces. There are many techniques used in welding metal together.

The two most common welding processes in the construction industry fall under the categories of gas welding and arc welding. Gas welding is a process in which heat is produced with an electric arc formed between a metal electrode and the metal being welded. An inert gas, usually helium or argon shields the arc from contamination. Common gas techniques are MIG (metal-inert-gas) and TIG (tungsten-inert-gas) welding.

Carbon arc welding is a puddling process in which the heat from an electric arc creates a small pool of molten metal that can be added to using metal from a filler rod. This is sometimes referred to as stick welding.
welding. Welding techniques for shop fabrication or field erection of steel are similar.

After the fabricated assembly is transported to the field, the only work remaining is unloading, sorting (shakeout), temporary storage and erection.

D. Erection

Erection is the process of erecting or connecting together the shipping pieces in the field at the project site. Generally columns get
erected first, then trusses and major girders, then beams, bracing, stairs and other miscellaneous steel.

The success of erection is dependent on a few important factors. The first and most critical element is the erection of the columns. Column base plates are connected to the foundation using anchor bolts placed in the concrete by the foundation contractor. The location of the anchor bolts (usually four or more) for a single column in the foundation must match exactly the pattern of bolt holes in the base plate of a single column.

Moreover, because it is more economical to erect frames comprised of multiple columns held together with beams and braces, rather than individual columns, the spacing between anchor bolt groupings must line-up exactly with the location of the columns. In the real world bolt hole patterns in base plates often do not match the anchor bolt locations. Also, the centerlines of columns often do not line up with the centerline of the anchor bolt grouping. To prevent these errors, fabricators usually insist on a survey of the anchor bolt locations prior to fabricating base plates and frames. Another method of mitigating the tight tolerances is for the foundation contractor and the fabricator to use templates to insure an exact match.

Another critical element of erection is crane access and movement. Steel is erected using one or more cranes, usually more than
one. Typically a few different types of cranes are used for steel erection -
tower cranes, crawler cranes and hydraulic cranes. Tower cranes are
those large T-shaped, counterbalanced configurations used to erect
multi-story structures and capable of heavy lifts. These cranes rotate
about a single point and are capable of lifting steel anywhere within the
radius of the tower arm. Crawler cranes are mobile and move around the
site to make the necessary steel “picks.” Hydraulic cranes tend to be
smaller, more mobile, and are used for lighter loads.

Crane movement is an important consideration in the
constructibility review of a project. Erectors usually divide the job into
phases based on the anticipated movements of the cranes. For the sake
of efficiency the fabricator usually fabricates the job in these same phases
so that the erector has the necessary steel for a single phase (or area)¹.
One or more of these cranes may be designated for unloading steel
when it shows up at the jobsite.

On most projects, the erection process starts with unloading the
shipping pieces using one of several cranes usually on the site. Sometimes
shipping pieces are erected into the framework directly from the truck;
othertimes pieces must be placed first in a staging area for later erection.

¹ When preparing an as-built schedule for steel activities, one can usually ascertain the actual dates for the
erection of steel by analyzing crane movement - a description of which should be detailed on a daily
construction report or log.
Other erection activities include plumb and bolt, safety, welding, decking, and buttoning-up. Plumb and bolt is the process of placing the steel assemblies in their proper location, aligning them and temporarily bolting them in place (bolts are not typically torqued to their final state until a majority of the area or frame has been erected). Safety is an activity performed by a separate crew that installs cable handrails and other safety devices in an area before the ironworkers begin to work. This allows the ironworkers to move freely from one area to another without interruption. A welding crew or multiple welding crews are then responsible for final welding of all the assemblies in accordance with the erection drawings. A bolting crew may also be utilized.

Decking is the process of placing corrugated bent plate on the structural frame to later accept cast-in-place concrete to form a slab. Decking is a structural element formed by bending plate into a corrugated shape. The height or deepness of the corrugations and the length and frequency of the corrugations determine the decking’s strength. Oftentimes the erector will contract with a second tier contractor to design, detail, fabricate and erect the deck. Included in the decking erection activity is the installation of studs that weld to the deck for the purpose of mechanically fastening the poured-in-place concrete to the deck forming a monolithic (composite) structural element.
The final torquing of bolts, welding of deck, installation of stairs, and installation of studs is an activity commonly referred to as buttoning-up. Buttoning-up the structure is one of the final structural erection activities.

Erection is a process that is dependent on the accuracy of the erection drawings and the accuracy of the fabricated steel. If steel is not
fabricated according to the detail drawings or if the detail drawings are in error, erection is disrupted. Field engineers, working for the erector, are responsible for the design of the fix. The field engineers produce field work, commonly referred to as FW drawings, to indicate the fix. Either these drawings are sent back to the fabricator to produce the steel or the fabrication is done in the field. Either way, the process takes time.

Another aspect of erection that is error prone involves steel stairs. No matter what precautions are taken by the EOR, the erector seems to always discover two common errors: 1) the stairs do not fit as intended and/or 2) some sort of interference is discovered. Stair problems are usually corrected in the field without input from the EOR, detailer, or fabricator.

III. THE IMPACT OF ERRORS, OMissions AND CHANGES ON THE PROCESS OF DESIGNING AND CONSTRUCTing STRUCTURAL STEEL

Problems in the design and construction of structural steel are, for the most part, caused by change. The change can result from an error, omission, or just the desire by one of the parties to change an element of the work, which then affects the structural design and geometry. As discussed earlier, the entire process involves four primary events—engineering, detailing, fabrication and erection. As a general rule the
earlier in this four phase process the change is identified and modifications implemented, the less the impact on the project.

A. Engineering

The best time to discover an error or omission or enact a change is usually during the structural engineering phase of steel design and construction. By way of example changes might include the placement of new steel not anticipated, the changing of steel already in the model, or the deletion of steel. Any one of these changes may impact engineering. They may cause the EOR to rework calculations, perform additional structural calculations, or even rerun the analysis performed by the computer. Fortunately, the impact is usually small in terms of time and cost because the change is known and implemented long before any steel is fabricated.

B. Detailing

Even minor changes during the detailing phase may have a large impact on the project, depending upon the nature of the change. Conversely, the change might be significant, but have little impact. It depends on the type and timing of the change. Their impact is best understood by dividing the detailing activities into four distinct tasks -
advanced bill of materials, erection drawings, detail drawings and submittals/approvals.

Since the information needed to prepare the advanced bill is derived from the EOR’s structural drawings, changes at this stage will not affect the detail or erection drawings. If the change occurs early enough it can be accounted for in the advanced bill. If the change occurs after the mill purchase order is prepared, two impacts occur.

First, the new or replaced steel caused by the change is not contained in the purchase order and sometimes the mill cannot accommodate changes to the order. Therefore, the changed steel will need to be purchased separately, which is more work, and for which a premium cost may be paid. Second, if the change replaced steel, the originally ordered steel specified in the advanced bill will not be needed on the project. The impact to the fabricator is that steel bought and paid for will now be put into the fabricator’s inventory. This is costly – material handling and storage is a huge labor expense for fabricators, the fabricator is out of pocket real dollars, and if the mill order was for odd lengths, the fabricator may only be able to sell the unnecessary steel for scrap value (about 4 to 10% of its original cost). If the change occurs during or after the shop drawings are produced another set of issues emerge.
Detailers coordinate the sequence of drawings produced with the fabricator and erector. The steel process, on most projects, is a “fast-track” process, meaning that fabrication and erection are taking place on elements of the structure for which the design is complete while the design of the other elements of the structure are still in process. The detailing of the entire structure need not be complete to get a jump-start on fabrication, and likewise on erection. In a perfect world an assembly can be detailed, fabricated, shipped and erected in as little as two to three days at a minimum, but the maximum time can take weeks, if not months depending on the complexity of the assembly.

Once a drawing sequence is determined (this matches the fabrication and erection sequence), any change will impact the production of drawings. For example, if a change occurred before a detailer began drawing an assembly, the impact will be minimal depending on the actual change. Some changes only require a change in dimensions, but some changes involve the addition of more detail pieces or even new assemblies. The later changes may cause more drawings to be necessary. It would not be unthinkable for a series of late changes on the huge job described earlier to cause the number of shop drawings to escalate from an anticipated 12,000 (all drawing types) to as many as 18,000.
If the detailer has completed a detail drawing, and it has already been transmitted to the fabricator’s shop office, a change may require that the work be put on hold and may affect a recall of the shop drawings. This event will now disrupt the detailer because they now have to re-detail a drawing they had thought was done. Likewise, fabrication is also disrupted. The resulting extra demands on steel handling, coordination, project management to track changes, and quality control is costly and difficult. Once a drawing has been released to the shop for fabrication more serious impacts occur.

C. Fabrication

The detailer sends the shop drawings to the fabricator’s shop office for processing. This processing includes: checking the drawing to insure all pieces are detailed, making templates, deciding which pieces will be fabricated first, deciding on gaining economies of scale by fabricating like pieces simultaneously, and checking the shop drawings against the latest set of structural drawing prepared and issued by the EOR.

If a change comes in during fabrication it will inherently impact both detailing and fabrication. The impacts are huge when an assembly is fifty percent complete and a change is issued revising a structural element. This disruption may cause a partially completed assembly to be
discarded in its entirety or set-aside on hold. Both cause more work and create inefficiencies.

If a change is sent to the fabricator after the assembly is completely fabricated the impact is similar. But if the assembly has already been shipped to the field and the erection crew has already installed it, the impacts are very expensive and may have a significant time impact on the project.

D. Erection

Changes that occur during erection are the most costly and disruptive. First, after so many months of engineering and detailing, fabricators and erectors get frustrated that all the bugs haven’t been worked out sooner, and that frustration often impedes the level of communication and coordination that is necessary and timely to implement a change with minimal impact to project cost and schedule. Second, any changes that occur after steel is erected will reversibly impact erection, fabrication, detailing and engineering.

Assemblies already erected must either be dismantled or additional engineering will be required to make what is erected work (with new steel) according to the design. Erection proceeds in a logical sequence. Changes made after erection of the assembly is complete invariably impact erection equipment, primarily cranes, safety and manlifts. They
may require the moving of some big cranes and may require the moving or additional rental of equipment. Disruptions caused by these changes require ironworkers to remobilize in an area already completed. In short, changes cause the erector more work, which takes more time and drives up costs.

Changes can occur during detailing, fabrication or erection. Complicated field changes discovered during erection are usually sent back to the detailer to implement and then get transmitted to the shop for fabrication. In the field, the erector's field engineer can sometimes detail (work out the geometry and design) simple changes. Fabrication of this changed or new piece or assembly can take place back in the shop or the ironworkers in the field can fabricate the new work.

V. SPECIAL CONSIDERATIONS IN STRUCTURAL STEEL DESIGN AND CONSTRUCTION

Problems in the steel industry share many of the same characteristics as sister industries: HVAC, plumbing, electrical, concrete, instrumentation, life safety and more. But, steel has some unique characteristics of its own which give rise to special considerations in its design and construction.

A. Weight
Steel is heavy and people associate weight with money and that is true. But the real cost of the steel framework is in the design of the connections. For example, depending on the project, steel could be bought for about $400 per ton, fabricated for about $450 per ton and erected for $550 per ton. Adding these components up brings the cost of installed steel to approximately $1,400 per ton. The equivalent cost of connections could cost anywhere from $2,000 to as much as $6,000 per ton or more. Efficiently designed connections translate into cost savings during fabrication and erection.

Many people in the construction industry think that the way to reduce the cost of the structural contract is by reducing the weight of the main members. While this does reduce the structure's weight, it causes the connections to become heavier and more complex. Connections must contain enough steel material to resist axial forces, bi-directional bending moments, torsion, and shear. Reducing member sizes reduces the amount of steel at the connection without changing the loads. The only place this can be made up is by the addition of various gusset and stiffening plates to add to the steel area at the node.

A simple example is that a wide flange shape beam that is eighteen inches tall and weighs one hundred and thirty pounds per foot (W18 x 130) has similar structural characteristics as a W27 x 84. The latter weighs forty-six pounds per foot less, and thus its use will lighten the main
member weight. However, the cost impact on fabrication and erection at the connections could totally offset any cost savings associated with the use of the lighter beam. Weight savings do not always translate into cost savings.

B. Connections

As discussed earlier, the connection designer needs full information on loads and design intent from the EOR in order to design efficient and constructable connections. Unfortunately, given the increasingly litigious nature of the industry, structural engineers are reluctant to give out this information. Their reluctance stems from a concern that their structural modeling and analysis may not accurately have calculated the correct loads. As a consequence, engineers have reverted to a design procedure that falls somewhere in the middle of the spectrum between good and bad design practice.

Rather than supplying the “real” loads, the EOR requires connection designers to design connections based on the member’s (primary or secondary) ultimate strength. That means that the connection designer must design for the largest load possible in the member just before the member collapses or fails. Because these large loads have an inherently large safety factor,
the resultant connection will be severely over-designed, very heavy, complex to fabricate and costly.

The impact of this will be an increase in detailing, fabrication and erection costs. But which party is going to pay for this extra work? Is it the fabricator providing connection designs or is it the EOR? Has the fabricator provided a lump-sum price or a GMP? Is this a predictable and reasonable risk for the fabricator to take? These are some of the key issues plaguing the steel construction industry today. Does the EOR have the right to reduce member weight at the expense of more complex connections without the input from the connection designer and fabricator? Industry participants regularly grapple with these troubling questions.

C. Quality

If one thing can be said about the steel construction industry it is that we can detect the differences between good steel and bad, and good workmanship and bad. Fabricators get to verify the chemistry and metallurgical characteristics of every piece of steel manufactured and delivered; quality control and assurance in the fabrication shop is easily seen visually and is easily tested using a number of different destructive and non-destructive tests. Essentially, we can microscopically determine if the steel is good,
whether the welds and bolts are good, and if the characteristics of the steel have changed. Macroskopically we can visually inspect the steel, inspect the bolts and inspect the welds and we can visually examine the steel for abnormalities. In fact, fabricators and erectors have some of the best quality controls programs in the construction industry.

Sample Mill Report certifying the mechanical properties of the steel, including yield and tensile strength, used to manufacture the shape. Also included are the chemical properties of the steel, based on the customary chemical composition of steel, including carbon, manganese, phosphorus, sulfur, silicon, copper, nickel, chromium, molybdenum, and vanadium.
el design and construction is a systematic process. From engineering through erection all the steps are purposeful and necessary. Shortcuts are not tolerated, and when taken predictably result in unintended consequences.

Since the steel activities are usually on the critical path of the project schedule, any disruption can have an impact on the project finish date. Because of the assembly line nature of steel – in detailing, fabrication and erection – little float is available to absorb disruptions that cause delays. A key concept in steel design and construction is to always work one piece of steel or assembly one time. Once a piece is engineered, it gets detailed, then fabricated and then erected. There is usually no allowance for rework in any schedule.

E. Changes

As discussed earlier, changes generated for whatever reason are the structural steel industry's nemesis. The AISC Code of Standard Practice for Steel Buildings and Bridges deals effectively with this issue. From SECTION ¶4.1 of the Commentary it states:

On phased construction projects, to insure the orderly flow of material procurement, detailing, fabrication and erection activities, it is essential that designs are not continuously revised after progressive releases for construction are made. In essence, once a portion of a design is released for construction, the essential elements of that design should be “frozen” to assure
adherence to the construction schedule or all parties should reach an understanding on the effects of future changes [change orders and claims] as they affect scheduled deliveries and added costs, if any.

In defense of the EOR, their work is dependent on getting the programmatic requirements from the architect and owner. If they do not have timely information, or if the information is changing, the steel contract will surely be negatively impacted.

F. Cost Estimates

We know so much about the design and construction of steel structures that cost estimates are reliable and accurate. Detailers, fabricators and erectors prepare cost estimates that meticulously reflect the work required during engineering, detailing, fabrication and erection. Engineering estimates during design development may be the most difficult to perform because little is known about the structure. Based on having “released for construction” structural drawings, detailing hours and the number of drawings can be accurately predicted. Knowing the major and secondary steel-framing members provides the fabric for estimating material and fabrication. Since connection design is not completed, nor are miscellaneous parts of the structure, the fabricator must put an allowance in its bid to cover that work. The cost of connection
fabrication and erection is usually estimated using allowances as low as 10% or as high as 20% of a structure’s weight. Connections are oftentimes estimated by making assumptions as to the number of anticipated shear, moment and complex connections assigning a unit cost and weight to each type. Lastly, erection may be the easiest to estimate accurately. Erectors understand and know how many tons of steel and shipping pieces a raising gang can erect in a day. They know the rate at which bolts are installed, welding is performed and decking is applied.

The more the engineer, detailer, fabricator and erector know about the design, the better and more competitive the estimates. Some fabricators and erectors are asked to give lump-sum prices based on allowances. While commonplace, agreeing to this places a substantial risk on the fabricator and erector. As an extreme example, two structures with an allowance of 10,000 tons can have either 40,000 small pieces of steel to be fabricated and welded or, as an extreme, the 10,000 tons can be comprised of two large pieces of steel. Clearly, the associated costs of engineering, detailing, fabrication and erection will differ dramatically. This admittedly extreme example highlights the problem with basing cost estimates on weight. Estimates should be based on the labor,
material and equipment associated with detail pieces, shipping pieces and special requirements.

G. Other Disciplines

The AISC Code requires that all data needed for the fabrication and erection of steel be located on the structural drawings. However, often times it is not. The EOR often records details and dimensions on architectural, electrical and mechanical drawings. The fabricator has to literally search for the information and must review every iteration of every drawing of every discipline to assure itself that changes to steel have not been made. Although most steel contracts clearly state that the fabricator has the obligation to review the drawings of other disciplines, this is ineffective and constitutes an erosion of good engineering practice and a waste of time. A detailer should not be forced to wade through scores of architectural drawings to find the top of steel elevation of a horizontal beam, or find out the size of a beam penetration by reviewing an electrical or mechanical drawing. While accepted, this is clearly in conflict with the AISC Code and good engineering practice. The AISC Code indicates that other disciplines drawings are to be used to supplement the structural drawings, not replace them.
H. Structural Drawings

In any discipline there is a convention for preparing plans.

The protocol for steel is well known, agreed to, and it works. A

Partial plan with drawing revision block. Revision block indicates that Issue No. 4 was issued for Construction and since that issue this drawing had been re-issued twelve times. The drawing illustrates changes, with clouds around the affected area, with the appropriate revision number noted. Drawings are clouded to show the latest changes and are removed on subsequent re-issues - the revision marks in the triangles always remain on the drawing.
convention in preparing steel plans is to note a change\(^2\) on a
drawing by drawing a cloud around the change and to note the
revision number. Unfortunately too often the EOR neglects to follow
this convention. The result is that changes may not be clearly
communicated to the detailer/fabricator.

On large, complex, troubled projects, line checking is the
answer. Detailers review the latest structural drawing with the
revision previously issued – line by line, dimension by dimension,
note by note. In fact, at the end of a line checking exercise, the
drawing being checked looks like a rainbow – yellow denoting
areas that have not changed, green denoting steel that has been
deleted, and red indicating new steel. If the EOR always clouded
the changes, the labor of line checking, which is very expensive,
would not be necessary.

I. Failure

Even though so much is known about steel and structures are
designed with conservative safety factors, structural failures occur.
Structural failures can be forensically studied to determine their
cause. Failures may result from bad design, poor assumptions,
unanticipated loadings or combinations, bad material, poor workmanship, or microscopic anomalies. Material science is such today that with more than reasonable certainty we are able to determine the cause of any particular failure. With this information, the AISC collects and analyzes this information and periodically updates the Code.

J. Economies of Scale

Steel detailers strive to draw similar detail pieces and assemblies on single shop drawings to save time and money. Consider a project that has thirty-nine built-up columns (four plates welded together to form a box), all having the same end conditions and differing only in their length. Typically, the detailer might elect to show one illustration of the column on one shop drawing and use a column schedule to depict the lengths of each column giving each a shipping piece number. Thirty-nine shop drawings are clearly not needed and detailers, when putting together their proposals, count on such economies of scale.

Likewise, fabricators count on this same economy of scale during the fabrication of detail pieces and the preparation of assemblies. Using the example above, a fabricator might elect to fabricate thirty-nine identical columns or “blanks” and cut them to
final dimensions when the exact lengths are known. Because much of the plate cutting in large shops is computerized, fabricators can save substantial time and cost by pre-fabricating assemblies.

Whether in the detailer’s office or in the fabrication plant, changes disrupt planned-for economies of scale. If for example a change submitted by the architect alters the length of one of the beams, the blank might be too short and may need to be scrapped. Most fabricators count on economies of scale in their bid and count on the time and cost savings. If a change disrupts the fabricator’s plan, the fabricator clearly loses the benefit.

If designed with fabrication in mind, structures can be configured to have repetitious members in type, size, material and end conditions. Even if that means that some beams may be heavier than required, the labor hours saved in fabrication may easily pay for the added cost of material.

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