DESIGNING WITH STRUCTURAL

STEEL

A GUIDE FOR ARCHITECTS

SECOND EDITION

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PART II

PROTECTING STRUCTURAL STEEL

GUIDE TO COATINGS TECHNOLOGY

It is not always necessary to paint or coat structural steel; e.g., when the structure is hidden and protected from moisture, it is protected with spray-applied fire protection or aesthetics do not require it. These specific conditions will be clearly explained in this section.

There are many times, however, when the steel structure must be protected against corrosion; e.g., when it is architecturally exposed. Over the past few years, great strides have been made in the development of high-performance coatings leading to the increased use of exposed steel as a means of architectural expression. Steel's high strength-to-weight ratio allows thin and elegant forms to support large loads and span long distances. The ability to have long-term protection on exposed structural steel has allowed many of today's innovative architects to express a wide variety of ideas through the structure itself. Properly specified and applied coating systems can be expected to give 20 to 25 years of initial service life that can be extended almost indefinitely and with subsequent maintenance painting.

Coatings technology continues to evolve with paint systems being developed to meet more and more stringent requirements. This is a blessing in the sense that owners and architects can expect continually improving performance, but it also means that developing a proper specification for a given project requires keeping up with the most recent product developments.

Paint specifications for building structures should be performance-based to allow competition within a performance standard. Paint specifications should also be project specific and take into account the following three factors:

- Building end-use—Is it a factory where the structure will be exposed to corrosive processes or high humidity? Is it a public facility subject to abrasion and vandalism (graffiti)? Is it a swimming pool with high humidity and heat? Or, is it an office building that is well-protected and subject to benign usage?
- Environment—Is the building located on the coast in a saline atmosphere, at an inland location surrounded by industrial plants, or is it in a desert-dry climate but subjected to relentless attack by the ultraviolet rays of the sun?
- Is the structure to be exposed on the exterior, interior or both?

This portion of the guide is intended to inform architects of issues that should be considered in the development of a proper paint specification for building structures. In addition, there is considerable background information intended to help specifiers understand coating systems in general so that they can make informed and intelligent choices. Several coating references are provided at the end of this section.

BASICS OF PROTECTIVE COATINGS

The Corrosion Process

A clear understanding of the corrosion process is essential to understand the steps to inhibit corrosion with protective coatings.

Oxygen combines with iron, the major element in steel, to form rust. This electrochemical process returns the iron metal to the state that it existed in nature—iron oxide. The most common form of iron oxide or iron ore found in nature is hematite (Fe_20_3), which is equivalent to what we call rust. Iron in iron ore is separated from the oxide to yield usable forms of iron, steel and various other alloys through rigorous electrochemical reduction processes. Because the iron has a strong affinity for oxygen, it is necessary to deal with the ever-present tendency to form the more electrochemically stable iron oxides.

The process of combining iron and oxygen, called oxidation, is accompanied by the production of a measurable quantity of electrical current, which is why this is called an electrochemical reaction. For the reaction to proceed, an anode, a cathode and an electrolyte must be present. This is termed a corrosion cell. In a corrosion cell, the anode is the negative electrode where corrosion occurs (oxidation), the cathode is the positive electrode end, and the electrolyte is the medium through which an electrical current flows.

Coatings in Corrosion Control

A coating may be defined as a material which is applied to a surface as a fluid and which forms, by chemical and/or physical processes, a solid continuous film bonded to the surface.

Eliminating any of the reactants in the process can interrupt corrosion. If a barrier is put on to the iron that prevents oxygen and/or water from coming in contact with steel, the corrosion process can be prevented. Steel is not the only surface protected by such barriers. Other alloys and metals such as stainless steel, brass, aluminum and other materials such as concrete, wood, paper, and plastic are also protected from the environment with coatings. Protective coatings that serve as barriers are the principal means of protecting structures.

COMPOSITION OF COATINGS

Most coatings are made up of four principal parts: pigments; non-volatile vehicles (resins or binders); volatile vehicles (organic solvents, water or the combination of both); and additives (specialty chemicals which make the coating function). All of the components of a coating interact to accomplish the purpose for which the coating was designed.

Pigments

Pigments are included in coatings to perform any of the following functions:

- Add color
- Adjust the flow properties of wet coatings
- Resist light, heat, moisture, chemicals
- Inhibit corrosion
- Reflect light for opacity or hiding
- Contribute mechanical strength

Pigments whose prime function is to contribute opacity to coatings are called hiding or prime pigments. The principle white-hiding pigment is titanium dioxide. There are hundreds of colored-hiding pigments which, when used alone or combination with other pigments, give coatings their variety of colors. Hiding pigments can be very expensive. In order to make the paint less costly, non-hiding or extender pigments are used. Certain colors, such as light-stable reds, are more expensive. Determine costs from your coating supplier prior to writing the project specification.

Pigments are used to adjust the viscosity and flow properties of the paint in order to obtain paint that won't sag at high film builds. Using pigments with low oil absorption can decrease the amount of solvents in the paints. Pigments used to reduce or prevent corrosion of a coated surface are called inhibitive pigments.

Pigments help protect the resin in the film from degradation of solar radiation. Hiding pigments do the best job of protecting the resin from the harmful portion of solar radiation by blocking its penetration into a film. Pigments in the film also inhibit penetration of corrosive elements, thus protecting the substrate. Pigments also can add mechanical reinforcement to a film, adding strength, flexibility, and abrasion resistance.

Non-Volatile Vehicles (Binders)

The binder or resin portion (polyurethane, epoxy, etc.) of the coating is the "glue" that holds the coating together and onto the substrate. The physical properties of the coating are mainly derived from the physical properties of the solid resin, but pigments and additives can affect the final properties. Coatings are generally named after the type of resin used as the coating binder.

Resin binders change from the liquid to the solid state by several different dying curing mechanisms:

- Lacquer, dispersion and latex paints dry through the evaporation of solvent and/or water.
- Vegetable oil and alkyd paints harden through oxidative cure.
- Two-component chemically reactive paints harden through chemical cure, i.e., two components are mixed prior to application and polymerize on the substrate, e.g., epoxy or polyurethane.
- One-component chemically reactive paints harden through the reaction of a resin that has an active chemical group, with atmospheric moisture releasing a new chemical group that causes the resin to crosslink.

The simplest drying mechanism is evaporation of the volatile vehicle. Solventborne lacquers generally have very high solvent content because very hard resins needed for good film protection require a lot of solvent to reduce the paint viscosity to application consistency. Vinyl and chlorinated rubber coatings are examples of resins relying on solvent evaporation.

Another type of paint that dries through simple evaporation of the volatile vehicle is waterborne paint. Here a major portion of the volatile vehicle is water which acts to lower the viscosity of the paint. Acrylic and vinyl latexes, water-based epoxies and polyurethane dispersions are examples of this technology.

Coatings based on natural oils or alkyd binders modified with drying oils develop their film properties principally through oxidative curing. Atmospheric oxygen creates active crosslinking sites on vegetable oil or the drying oil portion of the synthetic resin. These sites connect to form a three dimensional, chemically bonded network. Linseed, alkyd and epoxy ester binders are examples of systems that cure by a combination of solvent evaporation and oxidation.

Two-component chemically reactive paint is manufactured and sold in two separate containers. The two multifunctional reactive resinous materials are mixed together just prior to use. The two resins immediately begin to react together to form a polymeric matrix. During polymerization, the paint viscosity will increase. This means that the paint has a specific use life before the paint will gel. Polyurethane and epoxy are examples of these coatings.

One-component chemically reactive paint utilizes polyisocyanate chemistry. The isocyanate group reacts with atmospheric moisture to yield an amine group. The amine reacts very rapidly with additional isocyanate to form a urea crosslink. This paint offers the ease of use of other one-component technologies with the performance of a two-component paint. Moisture-cured polyurethane technology is a rapidly growing example of this technology.

Volatile Vehicles (Solvents)

A solvent is used to dissolve the resins and additives in order to reduce the viscosity of the mixture to provide application consistency and allow the paint to flow out properly. In every case, it is designed to evaporate from the film during or after application.

Solvents are also used in waterborne dispersions and latexes. At some point in either the manufacture of the resin or the paint, solvents are added to soften the resin. During the drying of the paint film, the water evaporates. The dispersion of latex particles come into contact and flow together to form a continuous film. Finally the solvent evaporates from the film. This process, called coalescence, would not take place without the solvent. Resins that are hard enough to produce through tough films are too hard to coalesce without the solvent. Waterborne coatings are gaining interest by specifiers because they are perceived as being environmentally friendly. Although many waterborne coatings do have low levels of solvents, some waterborne paints contain solvent in amounts equivalent to those in high-solid, solventborne coatings.

Environmental concerns are forcing raw material suppliers and paint producers to lower the solvent content of the products they supply in order to reduce the amount of volatile organic compounds (VOCs) released into the atmosphere.

Coatings suppliers select the type of solvent suitable for each type of coating formulation. The choice of solvents is made based on the optimum paint viscosity and evaporation rate that result in proper paint flow and thus, the intended appearance and adhesion. Coating applicators may need to add solvents during application to control viscosity over the various temperature ranges encountered in the field.

The wrong choice of solvents can jeopardize an application. If the chosen solvent evaporates too fast, bubbles caused by the vapor pressure of the solvent may appear in the surface. If the coating is spray applied, the solvent may "flash out" of the spray mist before it reaches the surface, and the spray may become too dry for the paint particles to flow together. This effect is called dry spray. A solvent that is too slow to evaporate may remain in the film too long, causing sags and runs and resulting in a film that is soft and has other altered performance properties.

The applicator must also take care not to add thinning solvent beyond that recommended by the manufacturer, because the paint viscosity may be so slow that the wet films will sag and run. Over-thinned paint that is applied at too low a film build may result in films that are too thin and have no hiding power.

Additives

Additives make up only a small proportion of any paint. Yet without these chemicals the paint could not deliver all of its potential performance.

Paint additives are used to aid pigment grinding, stabilize resin and pigment dispersions, break foams, aid flow, prevent film surface defects, catalyze chemical reactions, prevent oxidation, enhance adhesion, provide slip and abrasion resistance to the film surface, prevent corrosion, and to improve weathering resistance and enhance color retention.

These additives can be inexpensive or can be the most expensive component on a per pound basis of any ingredient. In these days of cost competition, it is not unusual for a paint manufacturer to cut costs by leaving out one of these vital ingredients. Sometimes the effects may not be known until years after the paint application. For example, in a high performance polyurethane topcoat, it is usual practice to add antioxidants and UV absorbers to enhance the weathering resistance. If theses additives are left out of the formulation to lower cost, instead of the ten years of gloss and color retention, only one or two years might be expected. *It is imperative that expected paint performance be listed in the job specification.*

TYPES OF COATINGS

Zinc-Rich Primers

Zinc has been the most successful coating material for steel protection.

The English started with the idea of using zinc dust in organic vehicles to provide a zinc-rich coating. A completely different concept was started in Australia where the inorganic zinc-rich materials were developed. The idea of incorporating zinc dust into an organic vehicle coincided with the time that the more sophisticated synthetic resins became available.

Two categories of zinc-rich primers are available based on the binder chemistry. *Inorganic zinc* coatings are composed of powdered metallic zinc mixed into a reactive silicate solution. Those formed from sodium silicate, potassium silicate, lithium silicate, colloidal silica, the various organic silicates, and even galvanizing, are reactive materials from the time they are applied.

The second category is *organic zinc-rich* primers, the binders of which are based on organic or carbon-based compounds. Organic vehicles include phonoxies, catalyzed epoxies, urethanes, chlorinated rubbers, vinyls, and other suitable resinous binders.

One very important characteristic of inorganic zinc coatings is the electrical conductivity of the matrix. Electrons formed by ionization of zinc at any point within the coating can migrate to the steel substrate and provide cathodic protection to any steel area that may be exposed. Particle-to-particle contact of the zinc pigment is not required for conductivity in inorganic zinc coatings since it is in a conductive, organic zinc-rich matrix. Organic rich coatings generally require a higher zinc loading to develop the zinc particle contact necessary for protection.

Epoxy

Epoxy binders are available in three types: *epoxy ester; epoxy lacquer resin;* and *two-component epoxy.*

The two-component epoxies are most commonly used for painting structural steel. Epoxy resins of this type can cure by chemical reaction. The epoxy is generally combined with either of two types of hardeners (polyamine or polyamide) to form *epoxy-polyamine* and *epoxy-polyamide.*

Epoxy-polyamine blends are more resistant to chemicals and solvents and are often used for lining tanks. Epoxy-polyamide paints are the most popular of all epoxy binders for use on structural steel. When exposed to weathering, they chalk quickly, but retain excellent chemical and abrasion resistant properties.

Acrylics

Acrylics can be supplied as solvent- or water- based coatings with varying performance characteristics. They exhibit good color and gloss retention, are single package, relatively low in cost and easy to apply. Solvent and chemical resistance, however, is lacking. They are best for interior, non-corrosive environments.

Polyurethane

Polyurethane binders are available in two types for painting structural steel:

- Moisture-cure polyurethane
- Two-component polyurethane

Moisture-Cure Polyurethane

Reacts with air moisture to cure. They produce the hardest, toughest coatings available in one package, and are increasingly popular due to the wide range of application and productivity advantages:

- Can be applied to cold damp surfaces
- Can be applied at temperatures below freezing
- No dew point restriction
- Year round application season
- Excellent recoatability
- Single component

Two-Component Polyurethane

Polyurethanes can also be reacted with products such as polyols, polyethers, polyesters or acrylics to produce extremely hard, resistant durable coatings. These are commonly used as topcoats.

Alkyds

Alkyds are available in both water dispersion and solvent-based formulations. Alkyd-oil vehicles can be formulated in flat and semi-gloss finishes over a wide compositional range. Generally, alkyds have poor color and retention properties and tend to chalk when exposed to sunlight. Their primary advantage is low cost.

PAINTING GUIDES

Sample painting guide specifications have been included at the end of the coatings technology section. Other coatings technologies can be considered. Consult your painting supplier for recommendations based on specific project requirements.

SPECIAL PURPOSE COATING SYSTEMS

Intumescent Paint

Intumescent paints are examples of special purpose coating systems. They can provide fire ratings for exposed steel for up to three hours. See the later section called "FIRE PROTECTION" for additional information on intumescent paints.

Hot-Dip Galvanizing

There are several reasons for selecting galvanizing as a coating system. For light fabrications and some medium structural applications, galvanizing can be the lowest cost coating system. It is usually also one of the lowest long-term cost coating system alternatives. Galvanizing does not adhere to the steel, but is actually metallurgically bonded to the base steel—forming an alloy layer between the surface zinc and the underlying base metal. Galvanizing is a tough coating system, providing high resistance to mechanical damage in transport, erection and in service. Finally, galvanizing eliminates maintenance for relatively long periods of time. This can be a significant factor if maintenance of the facility requires shutdowns or the area to be maintained is not easily accessible.

There are several types of galvanizing processes that are used throughout the industry including electric, zinc plating, mechanical plating and hot dip galvanizing. Hot-dip galvanizing is one of the oldest and most common types and has been used to fight corrosion for more than 200 years.

Hot-dip galvanizing is a process in which a steel article is cleaned in acid (pickled) and then immersed in molten zinc that is heated to approximately 850° Fahrenheit. This results in formation of a zinc and a zinc-iron alloy coating that is metallurgically bonded to the steel. After the steel is removed from the galvanizing bath, excess zinc is drained or vibrated off the steel member. The galvanized member is then cooled in air or quenched in water. The zinc coating acts as a barrier that separates the steel from the environmental conditions that can cause corrosion. The galvanizing process precludes the possibility of coating improperly prepared steel surfaces, since the molten zinc will only react with clean steel. Due to the immersion process, galvanizing also provides complete protection of all galvanized parts—including recesses, sharp corners, and inaccessible areas.

Today, almost any size item can be galvanized. Most galvanizing facilities have galvanizing kettles that are at least 30 ft in length. Larger kettles of up to 50 ft long are becoming common. If an item is too long for total immersion at on time, it may still be possible to galvanize the item. If more than one half of the item will fit into the kettle, a process called "double dipping" may be incorporated. Double dipping is a process where one half of the item is dipped in the kettle filled with molten zinc and withdrawn, and then the other half is dipped. The double dipping process provides a constant thickness of zinc coating similar to the total immersion process. Consult a galvanizer before planning to use a "double dipping" process.

Sometimes it is necessary to prevent the zinc coating from bonding to a local portion of the steel article. An example of this situation would be where something needs to be welded to the galvanized article, since the zinc coating could contaminate the welds. This concept would also apply to galvanized beams where the top flange must remain ungalvanized to receive shear connectors for a composite beam. Today there is a technology that can incorporate the hot-dip galvanizing process while leaving predetermined areas of the article uncoated. This process can be applied in any location, on any size or shape of steel members. Consult a local galvanizer for more information on this topic.

If aesthetics are an important issue for the galvanized item, the architect should indicate suitable locations to the galvanizer. Since all of the material is immersed into the galvanizing kettles, chains, wires or other holding devices are needed to support the immersed articles. Holding devices usually leave marks on the finished galvanized product. These marks are not necessarily detrimental to the coating, but could affect the desired aesthetics.

Best results for galvanizing will occur when the architect and fabricator keep the nature of the galvanizing process in mind at all stages. To minimize any warping that may result form the galvanizing process, the item to be galvanized should be fabricated so that it can be quickly and completely immersed in the kettle. Use of symmetrical sections in lieu of unusual angles or channels will minimize shape warping. For more information on galvanizing characteristics, consult a local galvanizing company.

In any building there are many areas susceptible to corrosion that warrant special protection through galvanizing. The two-page Figure 24 illustrates high potential corrosion areas on high-rise buildings where galvanized protection is advised. An example of a building design galvanizing checklist is also given in Figure 25. Additional information on galvanizing is available from the American Galvanizers Association (AGA). Contact information for AGA is given in the Appendix.

Galvanized Steel — Painted (Duplex System)

Sometimes it is desirable to provide a coating system for steel that includes both galvanizing and paint systems. There are several reasons why it would be desirable to combine these materials: aesthetics, color coding, safety markings, ease of repairing, and low life-cycle costs are just a few. This combination of galvanizing and paint systems is known as a duplex system.

The key to success of a duplex system is proper surface preparation and proper selection of a paint system. Simply stated, the galvanized system must be clean, and the paint system must be compatible with zinc. Previous difficulties with paint adhesion on hot-dipped galvanized surfaces were related to three factors:

- Lack of surface profile on newly galvanized surfaces
- Reaction between paint components and zinc (wrong choice of coatings)
- Surface contamination between painting and galvanizing

Today, these difficulties can be overcome. The lack of surface profile can be overcome by brush-blasting or chemical etching treatments of the galvanized surface. The reactions between components of paint can be overcome by properly specifying paints that do not contain vegetable oil-based vehicles (alkyds), which destroy the zinc bond. Finally, proper solvent washing prior to painting can control the surface contamination between galvanizing and paints.

In many cases, a piece of steel that has been galvanized and painted can provide synergistic benefits in protection to the steel. There is evidence that protection provided by painting galvanized steel is greater and lasts longer than the sum of the protection provided separately by zinc or paint alone. *The protection is typically 50 percent greater than the additive effects of zinc and paint topcoating.*

If steel is galvanized and painted, any corrosion resulting from the eventual broken barrier is limited to the surface of the exposed areas and does not cause undercutting, blistering or flaking of the paint. Actually, galvanized products retard further damage to the steel by sealing pores and cracks in the paint film. At the same time, paint actually extends the life of the underlying galvanized coating by postponing degradation of the zinc layer.

The selection of a suitable painting system is critical for the successful painting of galvanized steel. Loss of adhesion often occurs when incompatible systems, such as alkyd resin-based paints, epoxy resin-based paints or acrylate

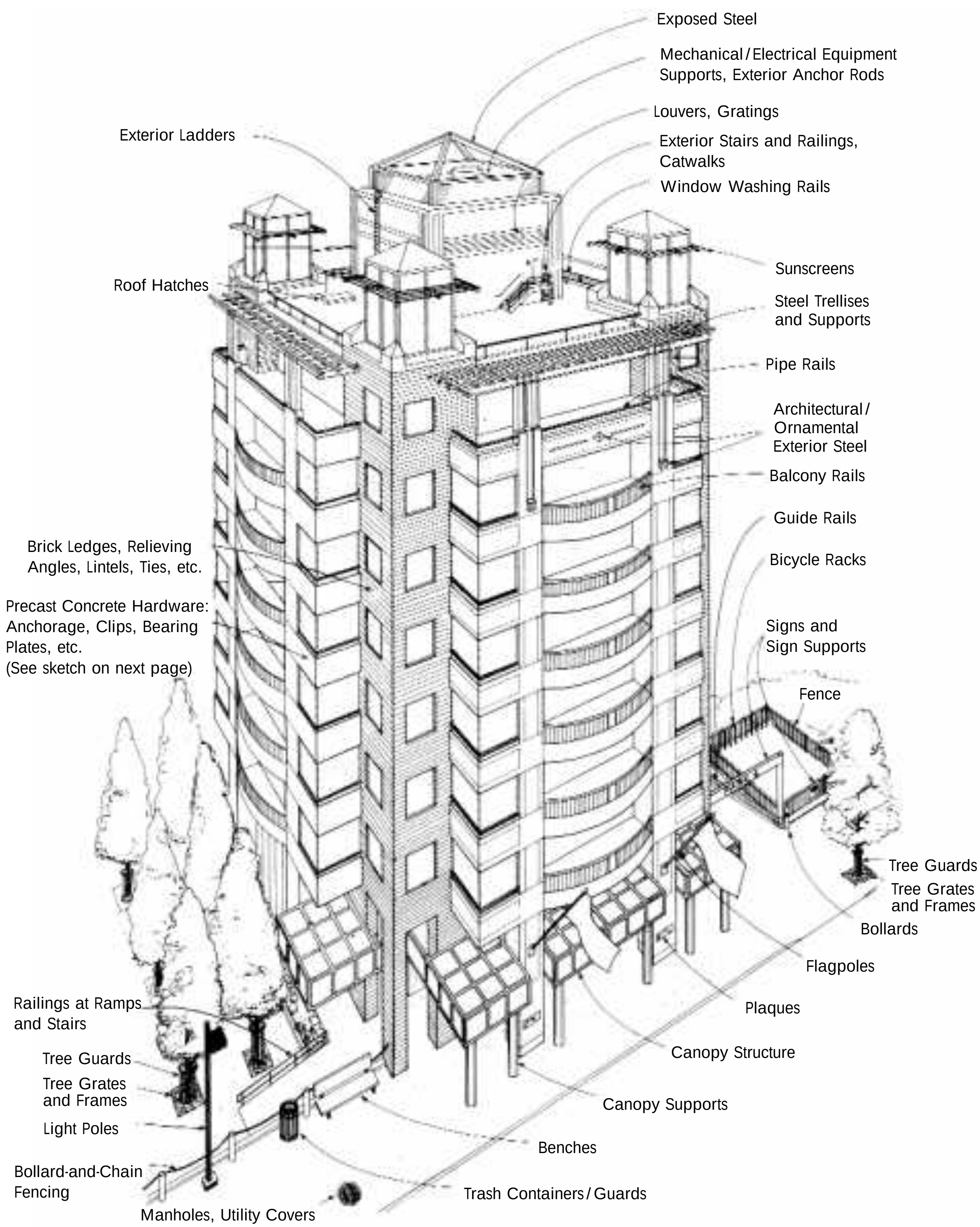
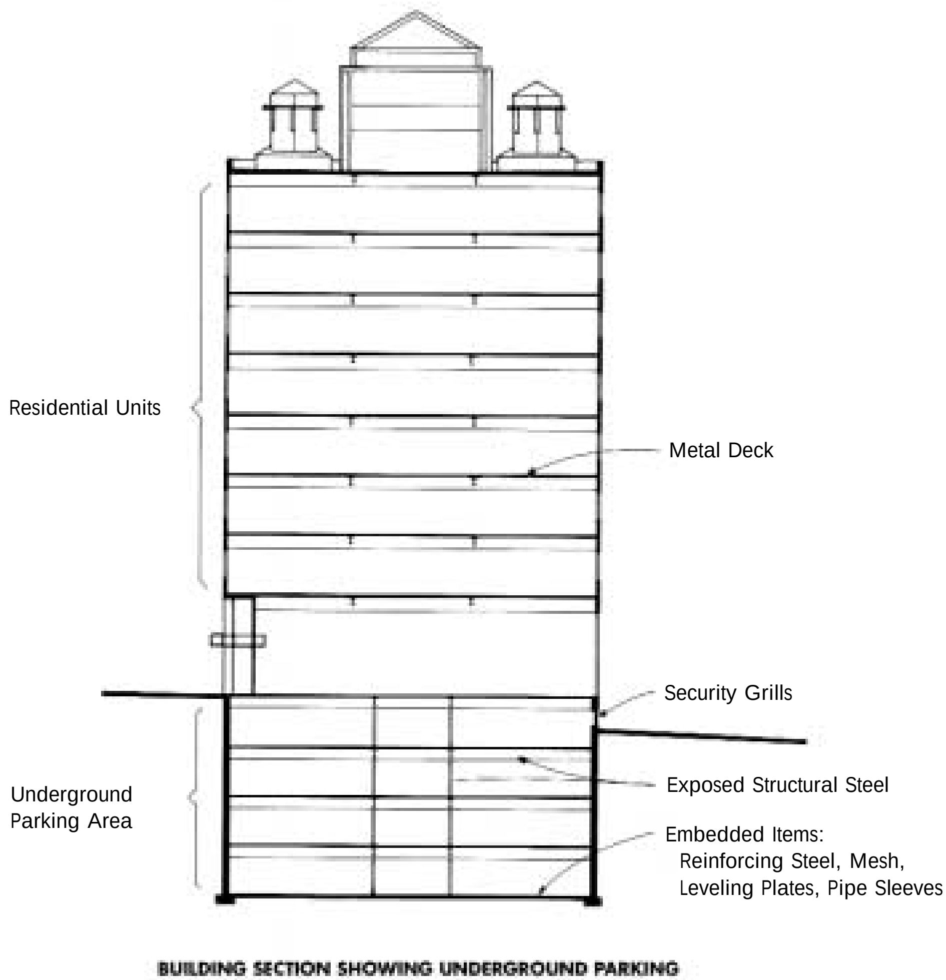


Figure 24. High potential corrosion areas of high-rise buildings



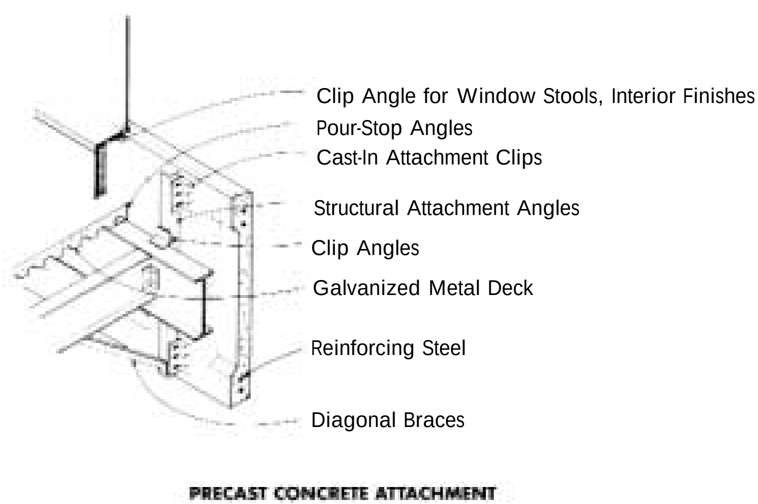


Figure 24. (Continued) High potential corrosion areas of high-rise buildings

Project Name ______________________ Date __________

Division 2 - Site Work
__ Railings
__ Fence/Gates
__ Fence
__ Guide Rail Signs/Sign Supports
__ Benches
__ Light Poles
__ Bike Racks
__ Trash Containers
__ Tree Guards
__ Manhole Covers Utility Covers
__ Post & Chain Fencing
__ Bollards
__ Fountain Accessories
__ Metal Sculptures Footbridges
__ Other

Division 3 - Concrete
__ Precast Hardware
__ Brick Ledges
__ Relieving Angles
__ Anchor Rods
__ Reinforcing Steel
__ Mesh/Embedded Items
__ Lintels
__ Other

Division 4 - Masonry
__ Anchor Rods
__ Lintels
__ Relieving Angles
__ Brick Ledges
__ Other

Division 5 - Structural/Misc. Steel
__ Window Washing Rails
__ Support Steel in Garage
__ Railings
__ Handicapped Rails
__ Fences and Gates
__ Fence
__ Anchor Rods
__ Relieving Angles
__ Lintels
__ Brick Ledges
__ Balcony Rails
__ Ladders
__ Trash Containers
__ Fire Escapes
__ Tree Guards
__ Catwalks
__ Gratings/Hatches Channel and Stringers for Exterior Stairs
__ Security Light Poles
__ Architectural/Ornamental Steel
__ Canopy Supports
__ Steel in Atrium Area
__ Steel in Laundry Area
__ Steel in Swimming Area
__ Sunscreens/Trellises
__ Flag Poles
__ Curb Angles
__ Pipe Stanchions
__ Other

Division 15 - Mechanical
__ Exterior Anchor Rods
__ Catwalks
__ Gratings
__ Supporting Steel for Mechanical/HVAC Equipment
__ Equipment Screens
__ Louvers
__ Other

Division 16 - Electrical
__ Exterior Anchor Rods
__ Gratings
__ Pipe Support
__ Supporting Steel for Mechanical/ HVAC Equipment
__ Light Poles
__ Other

Figure 25. High-rise building design checklist

resin-based paints applied over chlorinated rubber primers are used. It is important to use compatible products (primer, sealer and topcoat). There are a variety of manufactured paint systems that have unique characteristics and are appropriate for specific use with galvanized steel. Specific paint system characteristics, however, are beyond the scope of this guide. Comments here relate only to generic paint systems and are based on overall understanding of industry experience. Contact paint manufacturers for additional information of specific paint applications.

A paint system that is to be used over galvanized steel typically includes pretreatment, primers and topcoats. Pretreatments are commonly used to condition galvanized surfaces for proper paint adhesion. In many cases, a topcoat will not adhere to galvanized steel without a primer. Therefore, a primer coat is a critical component of the system. The primer acts as a tie coat to the galvanized steel, and provides other performance characteristics for the overall system. The topcoat must also resist dulling, fading, chalking, flaking, peeling and blistering in the environment in which the steel must function.

PAINT SYSTEMS

Government Standards

Over the past several years, environmental and worker protection regulations have been promulgated that have had a dramatic impact on the way painting can be conducted for both new and existing structural steel.

The 1990 Clean Air Act Amendment requires that volatile organic compound emissions be reduced for industrial maintenance coatings for field applications. The systems included herein have VOC levels up to 3.5 lbs per gallon (0.42 kg/liter).

Coating Systems

Paint systems used in the U.S. are listed in Table 1. Some of the systems are listed as "Newer Technology." This is because experience with these systems is generally less than ten years, but available information indicates the products to be effective and worth consideration—especially for unique situations. Tables 2a and 2b are an application guide showing the most effective use of the paint systems described in Table 1. These tables offer recommendations for the type of system that will be effective, based on the severity of the environment in which it will be used, and also indicate the systems that can be used to topcoat various types of existing paints.

Interior Structural Steel

Before an appropriate coatings systems for a specific application is determined, it must first be determined whether or not a coating system is actually required at all. Currently, many architects specify all interior steel that is not covered with spray-applied fire protection to be shop primed, even though the steel will not be exposed to view or subjected to corrosive environments. This specification is usually not appropriate and is generally not in the best interest of the owner.

An examination of a number of buildings that had been in use for more than 50 years indicated no corrosion of any significance whether or not the steel was painted. Some isolated locations of severe corrosion had been found in these buildings, but only at localized spots where water had been allowed to seep in and remain in contact with the steel for long periods of time. Results of this study led the American Institute of Steel Construction to conclude that *structural steel hidden between the exterior cladding of a building and the interior finish need not be painted.*

Appropriate protection of the steel should be determined by the end-use of the building and the exposure of the steel structure. The building's service requirements may determine that little or no protection of the steel is necessary at all. Steel does not rust except when exposed to atmospheres above approximately 70 percent relative humidity. Serious corrosion of steel occurs at normal temperatures only in the presence of both oxygen and water. In dry atmospheres (less than 70 percent relative humidity), non-painted steel can be exposed for extremely long periods of time with no evidence of rusting. If the steel is not painted, a thin transparent film of iron oxide forms on the non-painted steel, actually protecting the steel from further corrosion. Therefore, it is difficult to justify painting all interior steel members as a protective measure for the steel.

Table 1

Paint Systems

SYSTEM	PRIMER	INTERMEDIATE COAT	TOPCOAT
1	Inorganic Zinc-Rich Primer	Epoxy	Aliphatic Polyurethane
2	Waterborne Inorganic Zinc-Rich Primer	Acrylic Waterborne	Acrylic Waterborne
3	Polyurethane Organic Zinc-Rich	Polyurethane	Aliphatic Polyurethane
4	Epoxy Organic Zinc-Rich	Epoxy	Aliphatic Polyurethane
5	Epoxy	Epoxy	Aliphatic Polyurethane
6	Polyurethane Aluminum Primer***	Polyurethane	Aliphatic Polyurethane
7	Epoxy Mastic	Epoxy Mastic	Aliphatic Polyurethane
8	Oil and Alkyd*	Oil and Alkyd*	Oil and Alkyd*
9	Acrylic Waterborne**	Acrylic Waterborne**	Acrylic Waterborne**
10	Polyurethane Micaceous Iron Oxide***	Polyurethane Micaceous Iron Oxide***	Aliphatic Polyurethane
Newer Technology Paint Systems			
11	Polyurethane Organic Zinc-Rich	—	Polyurethane, High Build
12	Polyurethane Organic Zinc-Rich	Polyurethane, water-based	Aliphatic Polyurethane (Water Based)
13	Epoxy Organic Zinc-Rich	Acrylic Waterborne**	Acrylic Waterborne
14	Thermal Sprayed Zinc	—	Acrylic Waterborne
15	Thermal Sprayed Zinc	—	—
16	Low Viscosity, 100% Solids, Epoxy Penetrating Sealer or Polyurethane Penetrating Sealer	Epoxy Mastic or Polyurethane	Acrylic Epoxy or Polyurethane

Notes

* Oil and Alkyd paints include alternate inhibitive pigments to lead such as zinc oxide, barium metaborate, zinc hydroxy phosphate, calcium boro silicate, calcium sulphanate and zinc molybdate, which have been tested and are acceptable alternates.

** Acrylic Waterborne paints are available with numerous resin systems and pigmentations.

*** Polyurethane Aluminum Primer and Polyurethane Micaceous Iron Oxide can be used as a primer on bare steel, or as a penetrating sealer on existing coatings. They should be specifically formulated for whichever use is intended.

It is reasonable to conclude that painting is not mandatory for interior steel framing in low humidity environments, provided the structure remains water tight.

The question then must be asked, why paint interior steel at all? If the steel of a building under construction is exposed to the elements for a normal period of time prior to enclosure, the minimal corrosion which occurs on the unpainted steel would not be considered to be structurally detrimental. The issue then becomes a matter of aesthetics. The appearance of "raw" steel may not be desirable. Customers and building owners usually prefer the appearance of a painted surface to a rusty surface on exposed steel framing.

Table 2a

Paint Systems in Table 1 Applicable to Maintenance Painting Involving Spot Repairs and Overcoating

EXISTING PAINT SYSTEM	HIGHLY CORROSIVE* ENVIRONMENT	MILDLY CORROSIVE ENVIRONMENT
Zinc-Rich	3,4,5,7,10 **11,12,13,16**	3,4,5,7,9,10 **11,12,13,16**
Oil/Alkyd	6,7,8,9,10 **16**	6,7,8,9,10 **16**
Vinyl and Chlorinated Rubber	6,9,10 **16** (Polyurethane Penetrating Sealer)	6,9,10 **16** (Polyurethane Penetrating Sealer)
Epoxy** or Polyurethane**	5,6,7,10 **16**	5,6,7,10 **16**

Table 2b

Paint Systems in Table 1 Applicable to New Construction or Maintenance Painting Where Existing Paints are Completely Removed

	HIGHLY CORROSIVE* ENVIRONMENT	MILDLY CORROSIVE ENVIRONMENT
	1,2,3,4,10 **11,13,14,15**	1,2,3,4,5,6,7,10 **11,12,13,14,15,16**

Paint systems reference numbers (see Table 1) shown in bold text are considered “Newer Technology” for either coating unpainted steels or topcoatings over existing paints.

* A highly corrosive environment may be a “macro” environment where high ambient chloride levels exist such as immediately over salt water, or a “micro” environment where only a portion of a structure is exposed to such things as manufacturing process chemicals or humidity or both. All other environments are considered at least “mildly” corrosive.

** Roughening of surface may be necessary

There are, however, disadvantages to painting interior steel that is not exposed to view. One disadvantage is the cost. Shop painting can be expensive, particularly if the steel fabrication shop does not have the appropriate painting facilities. For example, not including surface preparation by blasting or other means, a single coat of shop-applied primer can add 3-6 percent to the in-place cost of the structure. Touch-up painting in the field can also add substantial cost to the project, particularly if the required touch-up work is extensive and accessibility to the touch-up area is limited.

Painted surfaces can also be problematic if an item needs to be welded to the painted steel. The paint can contaminate a weld if all of the paint at the weld location is not completely removed.

The architect should determine the most appropriate coatings for the various types of steel members on the project. They should also educate the owner about the appearance and maintenance of various steel finishes specified for the owner's facility. The owner also needs to realize that interior coatings are not expected to protect the steel for extended periods of time prior to the enclosure of the building. This type of information will lead to greater client satisfaction. If an owner insists on painting interior steel, refer to the painting and cleaning specifications produced by the Society for Protective Coatings (formerly the Steel Structures Painting Council/SSPC) for additional painting and surface preparation information.

SURFACE PREPARATION

Clean Surfaces and Performance

Proper surface preparation is vital to maximize the service life of a coating. In fact, inadequate surface preparation is the biggest single cause of coating failures. No matter how carefully a coating is formulated and manufactured, how sound the research on which it was based or how sophisticated the technology, the coating will fail prematurely in service if the surface to which it is applied was inadequately prepared. No coating can form a strong bond to a surface if there is contamination under the coating that is weakly bound to the substrate. Peeling coatings, dirt, rust, mill scale, oil, wax, moisture or other foreign materials provide a poor foundation to hold a coating, sometimes even when the contamination is present in such small quantities as to be invisible to the eye. The eventual result will be loss of adhesion.

Surface preparation must be considered as an integral part of the coating specification. The coating specification must include the following:

- The generic description of the paint used for each coat
- The surface preparation
- The kind and number of the individual coats of paint and their film thickness

Specifications must be written for coatings systems that include these items as well as the expected performance properties of the entire system over the life of the protected steel.

Specifications

Specifications and pictorial standards for surface preparation have been published by SSPC and are considered to be the supreme reference for the architect and maintenance engineer. The complete specification for the above procedures may be found in Volume 2, "Systems and Specification", of the *Steel Structures Painting Manual.* Pictorial standards for these procedures are also available from this group. Following is a brief description of these specifications.

Solvent Cleaning (SSPC-SP1). Describes a method for removing all visible oil, grease, soil, drawing and cutting compounds, and other soluble contaminants from surfaces.

Solvent cleaning should be used prior to any of the other surface preparation methods for the removal of rust, mill scale or paint. If this is not done, containments such as oil or salt on the surface of rust or paint could be driven into the substrate and would be difficult, if not impossible, to remove.

Hand Tool Cleaning (SSPC-SP2). Describes a method of preparing surfaces by using non-power tools. Before hand tool cleaning, remove all visible oil, grease and soluble welding residues, and salts by the method outlined in SSPC-SP1. Hand tool cleaning is intended to remove all loose mill scale, rust and paint. It is not intended that this process remove tight mill scale, rust and paint. Materials are considered adherent if they cannot be lifted with a dull putty knife. Examples of hand tools are a wire brush and sandpaper.

Power Tool Cleaning (SSPC-SP3). A specification that describes a method of preparing steel surfaces by using power-assisted hand tools. Before power tool cleaning, remove all visible oil, grease and soluble welding residue, and salts by the method outlined in SSPC-SP1. Power tool cleaning is intended to remove all loose mill scale, rust, paint and other foreign matter. It is not intended that this process remove adherent mill scale, rust and paint. Materials are considered adherent if they cannot be lifted with a dull putty knife. Examples of power tools include a rotary abrader, grinder and needle gun. Vacuum power tools should be specified to comply with OSHA regulations regarding emissions.

White Metal Blast Cleaning (SSPC-SP5). Describes a method of cleaning surfaces by using abrasives. Before white metal cleaning, remove all visible oil, grease and soluble welding residue, and salts by the method outlined in SSPC-SP1. When white metal cleaned surfaces are viewed without magnification, they shall be completely free of all visible oil, grease, dirt, dust, mill scale, rust, paint, oxides, corrosion products and other foreign matter. Blast media can be metal shot or mineral grit.

Commercial Blast Cleaning (SSPC-SP6). Describes a method for cleaning surfaces by using abrasives. Before blast cleaning, visible deposits of oil or grease shall be removed by the method outlined in SSPC-SP1. When commercial blat cleaned surfaces are viewed without magnification, they shall be free of all visible oil, grease, dirt, durst, mill scale, rust, paint, oxides, corrosion products and other foreign matter, except for staining as described in Section 2.2 of that specification.

Brush-Off Blast Cleaning (SSPC-SP7). Describes a method of cleaning surfaces by using abrasives. Before blast cleaning, visible deposits of oil or grease shall be removed by the method outlined in SSPC-SP1. When brush-off cleaned surfaces are viewed without magnification, they shall be free of all visible oil, grease, dirt and dust. Tightly adherent mill scale, rust and paint may remain on the surfaces. Materials are considered tightly adherent if they cannot be lifted with a dull putty knife.

Pickling (SSPC-SP8). Describes a method of cleaning steel surfaces by means of chemical action, electrolysis or both. Before pickling, visible deposits of oil or grease shall be removed by the method outlined in SSPC-SP1. When pickled surfaces are viewed without magnification, they shall be free of visible mill scale or rust.

Near-White Metal Blast Cleaning (SSPC-SP10). Describes a method of cleaning surfaces by using abrasives. Before blast cleaning, visible deposits of oil or grease shall be removed by the method outlined in SSPC-SP1. When near-white cleaned surfaces are viewed without magnification, they shall be free of visible oil, grease, dirt, dust, mill scale, rust, paint, oxides, corrosion products and other foreign matter, except for staining as described in Section 2.2 of that specification.

Power Tool Cleaning (SSPC-SP11). Describes a method of cleaning surfaces to bare metal and retaining or producing a surface profile by using power tools. This method differs from SSPC-SP3 (Power Tool Cleaning) in that

SSPC-SP3 requires only the removal of loosely adherent material and does not require the production or retention of a surface profile. Before power tool cleaning, visible deposits of oil or grease shall be removed by the method outlined in SSPC-SP1. When SSPC-SP11 power tool cleaned surfaces are viewed without magnification, they shall be free of oil, grease, dirt, rust, mill scale, rust, paint, oxide and corrosion products and other foreign matter. Slight residues of rust and paint may be left in the lower portion of pits if the original surface is pitted.

OTHER SUBSTRATES

In addition to steel, there are other surfaces that must be coated for aesthetic, safety or corrosion inhibition purposes. These surfaces must also be prepared properly for coating.

***Concrete*.** Concrete should be coated for the protection from moisture penetration and the resulting physical damage of spalling. There are several factors to consider when preparing concrete to receive coating.

1. Laitance is a thin layer of fine particles on the surface of fresh concrete caused by the upward migration of water during the mixing and finishing process. Because this layer has poor adherence to the main body of concrete, it must be removed before coating. Abrasive blasting or acid etching can accomplish this. Failure to remove this laitance layer prior to coating is the biggest cause of failure on new concrete.
2. Efflorescence is the deposition of salts on the concrete surface caused by moisture release during curing or moisture migration through the concrete as it ages. These alkaline deposits act much like concrete laitance and must be removed.
3. Form oil is applied to concrete forms as a release agent prior to pouring the concrete, to ensure the easy removal of the forms after curing. Some form oils are transferred to the concrete surface as a contaminant and must be removed by detergent and water washing before acid etching or abrasive blasting.
4. Concrete hardeners are sometimes used to modify the strength and permeability of concrete. They tend to migrate to the surface and cannot be acid etched. They must be removed with abrasive blasting.

The surface of the concrete is usually treated to promote adhesion of the coating system. Either physical abrading or chemical cleaning methods are used. Physical abrading can be done with, for example, sandpaper or a power-abrading machine. Chemical cleaning can be done with various chemicals such as trisodium phosphate or muriatic (hydrochloric) acid. After treatment, the surface must be dry and free from grit.

Cast Iron. Cast iron is a porous material that is likely to absorb moisture or other liquids with which it comes in contact. These liquids must be removed prior to surface preparation and painting. The requirements of the paint system control the degree of blast cleaning.

Zinc. Zinc surfaces (galvanized or metal sprayed) should first receive a surface cleaning according to SSPC-SP1 (Solvent Cleaning). The surface should then be etched with materials like mild phosphoric acid or ammonium hydroxide to give a rough surface profile suitable for the specified coating. If the zinc is allowed to weather naturally, the zinc oxide will provide a profile suitable for many coatings.

Alkyd- or ester-based coatings must not be applied directly to zinc surfaces. Zinc oxide is an amphoteric material that is capable of acting as either an acid or base. The zinc oxide can destroy the integrity of an ester/alkyd coating by saponifying the ester link producing a zinc soap. The result can be deterioration of film properties and loss of adhesion of the coating to the zinc surface.

Copper and Brass. Copper and brass must be abrasive blasted according to SSPC-SP 7 (Brush-Off Blast Cleaning) in order to remove corrosion products and provide a surface profile.

USE OF PROTECTIVE COATINGS

Shop Painting Bare Steel

When constructing a new structure, an owner now benefits from a number of environmentally friendly coatings with greatly extended service file. It is expected that coating technology will continue to evolve, allowing the development of coating systems that are even longer lasting and more economical.

The use of metallic zinc pigmentation in today's coatings effectively eliminates under-cutting corrosion and sub-film corrosion through galvanic action. Abrasive blast removal of mill scale in the fabrication shop improves long-term adhesion and helps the original coating tolerate maintenance overcoating without costly surface preparation. With an intermediate coat and topcoat applied, the first required maintenance should occur after approximately 25 years of service. At that time, with spot cleaning, spot priming and the addition of another topcoat (approximately 2-3 mils), you could expect another 15-20 years of service life. At the end of that period, the same process would be repeated with the same anticipated results.

A shop may be either a permanent painting shop (which may be part of a steel fabricator's plant), a separate painting shop, or a temporary shop constructed at or near the building site to repaint the steel. A covered shelter does not necessarily constitute a "shop."

The shop-applied coating may include an initial coat or multiple coats as specified by the owner, or, if acceptable to the owner, as selected by the contractor.

New steel used as a construction item is the easiest to protect from corrosion because it probably has not been contaminated with salts that act as electrolytes for the corrosion cells. Because the salts may not be present, it will be easier to achieve the degree of surface preparation needed to protect steel. Older steel (and specifically corroded steel) may have soluble salts imbedded in the corroded pits and intergranular surfaces. Though the salts may be of a soluble type, they are difficult to remove even with the most rigorous cleaning procedures and tend to shorten the service life of coating systems when compared to the life of the same systems on new steel.

Mill scale is a hard, smooth, blue-black layer of iron oxide ($Fe_2 0_3$) that forms on steel during the hot-rolling process. Mill scale is very inert. When intact, it forms a very efficient barrier to protect steel from corrosion. Unfortunately it has a different coefficient of expansion than steel and is very brittle. Because of this, it cracks and chips. The remaining mill scale then becomes cathodic with respect to steel, forming very efficient corrosion cells. The result is that mill scale must be removed before painting.

Red rust, a form of mixed iron oxides, is a surface contaminant familiar to everyone. It varies in color form light red to dark brown and may be loose and powdery or hard and granular. Red rust provides a weak foundation for paint, contributes to the formation of corrosion cells, and contributes to the destruction of coatings. In the case of light superficial rust, there are surface-tolerant primers that can be used to provide future protection of the steel. For example, steel that has been prepared and cleaned in the fabrication shop may develop superficial rust on the jobsite prior to the building being enclosed may be adequately protected by such primers.

Generally, all new structural steel is specified for Near-White Metal Blast Clean, SSPC-SP10 or Commercial Blast Cleaning, SSPC-SP6.

Requirements for Preparation of Bare Metal

Surface preparation is the most critical procedure for successful performance of a coating system. Surface preparation consists of cleaning the bare steel or previously coated surface. It includes establishing an appropriate profile of bare steel and/or an acceptable surface condition of the previously coated surface. Cleaning and surface profile are both critical to the performance of the paint system.

Cleaning of the surface includes removal of all soluble salts, oils, grease, dirt, dust and any other contaminants, by whatever means necessary, that will adversely affect the adhesion of the paint coat to the surface. Ensuring that recontamination does not occur, such as from airborne dusts, is also critical to a successful recoating project.

When blast cleaning is used to prepare the surface, the compressed air used to propel the abrasive shall be tested periodically to ensure it is free from oil and moisture and sufficient volume and pressure to clean the surface in a productive manner to the required profile.

For inorganic zinc prime coatings, surfaces shall be cleaned to a level as obtained by SSPC-SP10 for new construction. For other primer coats, the surface preferably should be cleaned to SSPC-SP6 or SSPC-SP3 may be acceptable.

Preparation Methods and Specifications

Power washing. Consists of blasting the steel with water at a pressure of 800 psi to 5,000 psi with the nozzle not more than 12 in. from the surface. If residue containing hazardous substances is removed during the washing process, the water will have to be strained to remove the contaminants or disposed of as hazardous waste.

Abrasives. Any abrasives used shall be free of oil, moisture, hazardous substances (i.e., lead, chromium, mercury, etc.) and corrosive constituents (i.e., chlorides, sulfates, salts, etc.). Non-steel abrasives shall be in accordance with SSPC-AB1, *Specifications for Mineral and Slag Abrasives*. Abrasives with "free" silica contents in excess of one percent should not be used.

As surface profile is critical to paint system performance, it must be controlled at the time it is produced, i.e., when the blasting work is conducted. This can be accomplished by controlling the range of particle size and shape in the abrasive used for blasting. The SSPC has published a reference guide, *Visual Standard for Abrasive Blast Cleaned Steel SSPC-Vis1-89*.

When using automated recycling blasting equipment with steel shot or grit, it is important to consider that a working mix is developed through use, then maintained by addition of suitable quantities of steel abrasive of the correct size range. This mixture of sizes is commonly called the work mix or operating mix. It is important to emphasize that this is indeed a mixture of a range of particle sizes, shape and hardness that is necessary to produce the correct profile. Larger particle sizes are suitable for removing heavy build-ups of mill scale or rust. Smaller size ranges increase productivity of removal of corrosion products through an increased number of impacts. When using abrasives, the "right mix" can be obtained through consultation with the supplier of the abrasive.

Steel shot/steel grit abrasives, with maximum recycling, are strongly recommended when blasting steel. When recycled, the abrasives shall be visibly cleaned to meet SSPC Recyclable Abrasive Specification XRAX-92P.

Surface profiles. Profiles of steel surfaces shall be obtained using abrasive or equipment meeting the requirements herein. When repairs to previously applied coatings are required, the proper surface condition of the repair area shall be obtained by power tool cleaning, spot blasting or by other acceptable means. Surface profile is measured as the difference between the average depths of the bottom of the peaks to the average tops of the highest peaks created by the blasting.

The profile height is dependant upon the size, type and hardness of the abrasive, the particle velocity, and angle of impact and hardness of the surface. Surface profile provides the "tooth" needed for adhesion and long-term durability of coating systems. Too great a profile can result in inadequate coverage of the peaks by the first coat of paint, leading to premature rust-through of the coating. For most coatings up to about 8 mils (200 microns) thickness (note: all references to paint film thickness are based on dry film thickness [DFT] measurements), a surface profile of 1 mil (25 microns) minimum to 3 mils (76 microns) maximum is adequate for new surfaces. For maintenance painting, actual profiles may be substantially greater due to pitting caused by corrosion. Selection of a coating system must consider the actual profile present. The user is advised to follow the recommendations of the coating manufacturer for a particular product.

Surface profile measurements shall be determined in accordance with ASTM Specification D4417, *Standard Test Methods for Field Measurement of Surface Profile of Blast Cleaned Steel*. Methods A, B or C may be used. Method A is a visual comparison between the blasted surface and a standard. Method B entails actual measurement of the depth of profile and determining the arithmetic mean. Method C uses a replica tape and a micrometer and is generally considered the most reliable of the three methods.

Faying surfaces (new construction). The contract drawings indicate the surface preparation requirements, Classes A, B or C, for faying surfaces of slip-critical bolted connections. When approved by the owner, the contractor may redesign the connection to provide a different class of contact surface. For coated faying surfaces, the contractor shall supply the owner with a certification that the coating proposed to be used has been tested by an independent laboratory, and meets the slip coefficient requirements used in the design of the connection for the thickness to be applied. Testing shall be in accordance with the "Testing Method to Determine the Slip Coefficient for Coatings Used in Bolted Joints" as adopted by the Research Council on Structural Connections and located in Appendix A of the 2000 Edition of the *Specification for Structural Joints Using ASTM A325 or A490 Bolts*.

Edge grinding. The idea of edges of beams being ground to a $^{1}/_{16}$-in. radius prior to shop painting is probably rooted in the traditional belief that coatings draw thin on sharp edges due to the forces of surface tension during drying. Reduced thickness would then lead to corrosion failure. This is not true for paints commonly specified today.

Rolled edges, such as with hot-rolled structural shapes, have rarely been shown to require any additional preparation for painting as the rolling process leaves a rounded edge, although it may not be a $^{1}/_{16}$-in. radius. Even when edges are sheared or burned, grinding to a $^{1}/_{16}$-in. radius is not necessary for paint performance.

Highly pigmented zinc-rich paints do not flow away from the edge and, in addition, provide galvanic throwing power to protect any edges or areas not coated. Also, these materials resist corrosion undercutting. Therefore, the requirement that burned edges always be ground to a minimum $^{1}/_{16}$-in. radius is questionable. Edge radiusing requirements in fabrication specifications are not only very expensive, but offer undetectable improvements in corrosion resistance.

Improved specification language should include provisions that reflect the following:

- Sharp edges, such as those created by flame cutting and shearing, shall be broken prior to surface preparation. (Breaking the edge can be accomplished by a single pass of a grinder in order to flatten the edge.)
- Usually the rolled edges of angles, channels, webs, and I-beams are presumed to need no further rounding. (If sharp edges occur, they can be broken by a single pass of a grinder in order to flatten the edge.)
- Machine fillet welds are considered a paintable surface with no further treatment required. Only weld spatter need be removed.

Surface imperfections. Another common myth is that surface imperfections such as ridges, slivers, fins or hackles must be ground flush since they also are sharp edges. Such anomalies are surface imperfections on rolled sections and plates. They result when small (usually less than ½ in.) areas of the steel surface are not bonded to the surrounding surface and are bent upward during the blast cleaning, usually by a metallic abrasive. It is typically only necessary to cut off the head of the isolated hackles, with no further grinding. An exception could occur if there were extensive hackles in a small area. In such an instance, some further attention may be warranted.

Re-profiling of blast cleaned surfaces. Blast cleaned surfaces that are subsequently ground do not need to be re-profiled to achieve effective coating performance. A small study undertaken by the SSPC has shown that steel which has been blast cleaned, ground and recoated performed as well in salt fog tests as steel that had been re-profiled and recoated.

Maintenance painting. Maintenance painting can consist of four options:

- Spot painting
- Spot painting and full topcoat
- Total removal and repaint
- Zone painting

Where the surface is contaminated with marine salts or other contaminants, the surface to be coated should be washed or, if necessary, power washed to remove all contaminants before any other cleaning operations are begun.

At the beginning of the surface cleaning preparation stage of the project, the paint applicator shall clean and prepare a minimum two foot by two foot area to demonstrate that the proposed methods will obtain the specified surface preparation requirements. This area shall be preserved for reference purposes during the surface preparation stage for the remainder of the project.

Spot painting. Where only spot painting of corroded areas is specified, all areas of loose paint shall be removed and the bare steel cleaned to the condition specified or required by the manufacturer and equivalent to SSPC-SP1, Solvent Cleaning, SP6 for abrasive blast cleaning, SP2 for hand tool cleaning, SP3 for conventional power tool cleaning, and/or SP11 for special power tool cleaning. Primers requiring a bare metal profile may be cleaned by abrasive blast cleaning SSPC-SP6 or by needle guns and rotary peening tools to SSPC-SP11. Care must be exercised when spot blasting to avoid damaging the intact coating around the blasted areas. This may require use of low-angle blasting and small particle size abrasives. Interfaces (edges) between the existing intact coating and the cleaned area may be feathered to provide a smooth coating for spot priming. Several coating systems do not require feathering (such as polyurethane moisture-cured systems). The bare steel areas shall have an ideal surface profile of 1 mil (25 microns) to 3 mils (76 microns). However, corroded areas will generally be rougher than this, which must be considered in selection of the paint system to prevent early rust-through at the profile peaks. Surface preparation procedures may need to be modified to prevent early rust breakthrough. Paint that is to remain in place around the corroded areas shall be thoroughly cleaned by washing, and roughened, if necessary, by sandpaper or power tools to ensure adhesion of the new paint. The surface of each coat to receive a subsequent coating shall be clean, dry and prepared in accordance with the manufacturer's recommendations.

Spot painting and total topcoating. Damaged or corroded areas of the existing coating shall be prepared in accordance with that for spot painting. Roughening of the entire surface may be necessary to achieve proper adhesion. The surface shall be thoroughly washed to remove all contaminants that will adversely affect paint adhesion. As a minimum, the manufacturer's recommendations should be followed.

Zone painting. Intact coatings in zones of the structure specified to be painted shall be prepared in accordance with the above procedures and manufacturer's recommendations. Deteriorated areas shall be prepared in accordance with spot painting and total topcoating.

Recleaning. Prepared surface shall be coated before any visible rusting occurs and, preferable, within 24 hours after preparation. The occurrence of rusting or contamination from any source will require the recleaning of the surface.

EVALUATION OF EXISTING COATING FOR OVERCOATING

Overcoating is defined as the process of applying a surface tolerant coating to a minimally prepared surface and existing layer of lead-containing coating. It is not implied that lead particles are neutralized, totally surrounded by or otherwise rendered harmless.

Overcoat Paint Process

The overcoat painting approach calls for thorough cleaning, using a power water wash, of all exterior structural steel or interior steel when conditions permit. This removes dirt and some embedded chlorides in the surface. In isolated areas of corrosion and/or paint breakdown, loose rust and old coatings are removed by a combination of SSPC-SP2, SP3 or SP11 surface preparation. Project plans must provide for containment and disposal of all generated waste and debris in compliance with applicable environmental regulations. Also, initial air monitoring may be necessary to determine the emission levels of lead and other airborne particulates.

Overcoating eliminates open air blasting so pollution containment and waste disposal costs are reduced. In addition, non-corroded lead-containing paints are left intact after water blasting. This reduces surface preparation costs and allows for these paints to continue providing protection.

During the overcoating process, exposed steel surfaces are spot primed followed by a spot/full intermediate and full topcoat.

Coating Evaluation

The most important factor in determining if a structure is a candidate for overcoating is to determine the condition of the existing coating system. This evaluation is conducted to assess the condition of the coating and the base metal at representative areas of the structure.

The following factors must be evaluated:

- Approximate percentage of rusted areas
- Character of rust area: light, moderate or severe corrosion
- Compatibility of the existing coating system/systems (test patch areas)
- Condition of steel under the coating (Does mill scale exist?)
- Adhesion of existing coating to the steel
- Adhesion between layers of the coating system
- Determination of paint type and dry film thickness (DFT) of coating. In the case of aluminum-pigmented alkyds, it must be determined whether existing coating, to be painted over, contains leafing or non-leafing aluminum pigments. It may be difficult to develop proper adhesion between leafing pigmented paints and the new coating system.
- Serviceability or expected remaining life of coating and/or ability of the coating to be repaired

Degree of corrosion. The determination of the existing condition should be made based on rating the percentage of the surface that is deteriorated (requiring mechanical preparation). The procedures contained in ASTM

D610, *Standard Method for Evaluating Degree of Rusting on Painted Steel Surfaces*, can be used as a guide for a visual assessment of the condition of the surface. If more than 15-20 percent of the total surface is visually corroded, total removal of the existing coating is recommended. This is because the work requirements for preparation of an area of this extent will not be significantly different than for total removal, and the likelihood of obtaining a longer lasting system is greater.

Adhesion testing of existing coating. In addition to determining the degree of corrosion, the adhesion of the remainder of the existing coatings to the steel substrate (or between coatings of the existing system) must be determined in accordance with ASTM standard methods. Two test areas representative of the other apparently "intact" coating conditions on the structure should be selected with at least five measurements for every 10,000 sq. ft of painted surface.

If 20 percent of the test areas exhibit condition 3A (jagged removal along incisions up to $^{1}/_{16}$-in. on either side) or worse, or a combination of visually corroded conditions and lack of adhesion of 20 percent or more is present, complete removal and recoating is recommended.

COATING TEST METHODS AND PROCEDURES

The following test methods may be used to evaluate the coating:

Method 1: Adhesion Testing of Coating to the Steel

The adhesion test may consist of one or more of the following:

1. *SSPC Steel Structures Painting Manual*, Vol. 1, Chapter 2, pp. 204, Pen knife subjective coating adhesion evaluation.
2. ASTM D4541: *Standard method for pull-off strength of coatings using portable adhesion testers*. Test for adhesion of organic coatings. Elcometer adhesion test. Instrumentation testing of the tensile adhesion to the substrate. The inspector determines location and frequency of testing.
3. ASTM D3359: *Standard methods for measuring adhesion by tape test.*

   Method A: X-cut Tape Test

   Method B: Cross-cut Tape Test

   Shear Adhesion Test, measuring adhesion by tape test. Location and frequency of testing is determined by the inspector.

Method 2: Coating Cohesion and Adhesion Test

Evaluation of coating cohesion and adhesion between coats is accomplished as outlined in Method 1.

Method 3: Substrate Examination and Evaluation

The test methods are as described in the *Steel Structures Painting Manual*.

1. Vol. 1, Chapter 6, pp.201-202, Tooke gage examination through a 50X internal microscope.
2. Vol. 1, Chapter 6, pp.200. Coating inspection requirements specify use of a minimum 30X power pocket-sized microscope to examine the coating field evaluations.

Method 4: Dry Film Thickness Testing

The gages that may be employed include:

1. SSPC-PA 2 (Type 1 gages), SSPC Method for Measurement of Dry Film Thickness with Magnetic Gages; *Steel Structures Painting Manual*, Vol. 1, Chapter 6, pp.198-200.
2. SSPC-PA 2 (Type 2 gages), SSPC fixed probe or magnetic flux gages; *Steel Structures Painting Manual*, Vol. 1, Chapter 6, pp.201-202.

Method 5: Coatings Cure Evaluation

ASTM D1640, *Test Methods for Drying, Curing, or Film Formation of Organic Coatings*, is specified as a recommended field method. Field evaluation of coating cure is generally difficult because there are no universally reliable filed tests for such purposes. Solvent rub tests, sandpaper tests and microscopic examinations can be utilized in field testing. If field testing results are inconclusive, coating samples can be taken for extensive laboratory analysis.

Compatibility of Overcoating System

Prior to selection of materials to overcoat existing coatings, the recommendations of the manufacturers of proposed overcoatings should be solicited. Paints that will cause "lifting" of the existing coating must not be allowed. The compatibility testing of the competitive materials shall be conducted in accordance with ASTM D5064, *Standard Practice for Conducting a Patch Test to Assess Coating Compatibility*, and the following (if different systems are present on different parts of the structure, each system must be tested):

A 12-in. diameter section in the middle of the test area shall have the existing coating removed to bare steel (SSPC-SP 11). The edges of the bared area are to be feathered using power tools. This area shall be primed with the selected paint(s) to determine if the primer lifts the edges off the existing paints.

Apply candidate coatings by proposed method of application to the entire test panel area. (The top coat(s) should be applied to the primed area in accordance with the manufacturer's recommendations.)

Inspect surface after the coating is fully cured (7 days or 2 weeks at 77° Fahrenheit [25°C] and 50 percent relative humidity) for signs of lifting, wrinkling, cracking or other film defects. If time permits. The evaluation period should be extended beyond exposure to the first "deep freeze" to ensure compatibility of the topcoat.

Only coatings exhibiting no peeling or removal (Scale 5A of ASTM D3359) will be allowed.

Degradation—Because existing paint systems may degrade rather rapidly, the tests specified above should be conducted no more than 180 days prior to the beginning of work to ensure that the decision on scope of work (e.g., spot painting versus total removal) is still valid.

Table 3 is a listing of known incompatibilities. This information is the result of actual experiences of bridge owners and should be used as a beginning point in determining system selection when topcoating existing steel.

SURFACE PREPARATION FOR OVERCOATING SYSTEMS

Method A: High-Pressure Water Wash

High-pressure water wash can be used to remove dirt and contaminants from existing sound paint surfaces and corroded areas. There is no SSPC specification reference.

Table 3

Coating Incompatibility

EXISTING PAINT TO BE COATED	KNOWN INCOMPATIBLE COATINGS	SYMPTOM OF INCOMPATIBILITY
Zinc	Alkyds	Blisters or Delaminates
Oil/Alkyd	Solvent Based Vinyls; Epoxies	Softening, Lifting or Shriveling
Vinyl	Epoxies	Softens or Dissolves Coating

Note: with the proper formulations, even the above incompatibilities may be overcome.

All exposed areas of existing steel members are cleaned by high-pressure water to remove chalking, dirt, dust, oil or other deleterious material, so that new paint will adhere to the surface.

There are several schools of thought regarding water pressure. One calls for hydrant pressures of 80-150 psi with large volumes of water. Another requires higher pressures (500-5,000 psi) and less water. The source and types of contaminant and degree of cleanliness will dictate the specification. Also, a non-sudsing, biodegradable detergent may be added to the water to optimize the cleaning operation. However, a rinse operation must follow and various environmental regulations may apply. In general, the purpose of the water wash is to remove loose chalk, paint, rust and dirt prior to the more extensive final surface preparation necessary to the painting operation. Slight chalking may remain as evidenced by rubbing a hand over the existing coating surface.

Method B: Hand and Power Tool Cleaning

Another method of surface cleaning is Solvent (SSPC-SP1), Hand Tool (SSPC-SP2), Power Tool (SSPC-SP3), and Power Tool Cleaning to Bare Metal Cleaning (SSPC-SP11). All exposed areas of existing steel members (the entire exposed steel structure) are cleaned by approved methods, in accordance with SSPC-SP1, to remove dirt, dust, oil film, or other deleterious material, so that new paint will adhere to the surface. Solvent cleaning may be supplemented by scrubbing with water and mild detergent. Small areas of the structure that show pinhole corrosion, stone damage from traffic or minor scratches are cleaned in accordance with SSPC-SP2, SSPC-SP3 or SSPC-SP11.

Smaller surface areas where the topcoats are peeling or are badly deteriorated are scraped and cleaned by these methods. It is not the intent that large surfaces of corroded metal be prepared by SP2 or SP3 cleaning. Small containment areas that utilize abrasive blasting may be more economical.

In recognition of the economic advantages of overcoating the Federal Highway Administration (FHWA) has been testing the coatings described in Table 4. The on-going test program has been underway for several years, with some results available from FHWA.

QUALITY ASSURANCE

The goal of the contract is to ensure that a durable paint system, applied in accordance with all the local and national regulations and specifications included herein, is obtained. To achieve this there are responsibilities that the owner, paint manufacturer and contractor must meet. The owner must ensure that contract documents adequately cover the regulatory requirements that the bidders will be asked to cover by their proposal. The owner must also ensure the paint system(s) specified is compatible with existing coatings, if applicable, and the system(s) is proper for the site environment in which it will be located.

Table 4

FHWA Test Program: Coating Systems for Minimally Prepared Surfaces

SYSTEM NO.	GENERIC COATING TYPE
1	Waterborne Acrylic (3 Coats)
2	Moisture-Cured Urethane (3 Coats)
3	Epoxymastic/Aliphatic Urethane
4	Surface Sealer Epoxy/Urethane/Urethane
5	Surface Sealer Urethane/Urethane/Urethane
6	Low VOC Alkyd Primer (2 Coats) Low VOC Silicone Alkyd Topcoat Waterborne Acrylic (3 Coats)
7	Surface Sealer Epoxy/Urethane/Urethane

The contractor is responsible for properly preparing the surface, supplying only acceptable materials and trained workers, supplying properly maintained equipment whether the paint is applied in a shop or the field, and full compliance with the regulatory requirements contained in the contract documents. The paint manufacturer is responsible to supply only the level of quality of materials that meet the contract requirements, including adequate instructions to the contractor and owner of the environmental and application requirements to safely obtain a long-lasting coating.

EVALUATION OF PERFORMANCE REQUIREMENTS FOR COATING SYSTEMS

The key to selecting paint is to know the performance criteria. For maintenance paint, whether painting the walls of a home or the I-beams of a bridge, there are test methods available whose results can guide in the selection of the paint.

Performance data are available from paint suppliers. A comparison of the different types of paint performance, the cost and the years of service will lead to the best economical decision.

During paint development, performance is measured on paint that is applied under standard conditions. For example, laboratory conditions are held closely around 77° Fahrenheit and 50 percent relative humidity. In addition, surface preparation of the substrate, film thickness, spray conditions, etc. can be very carefully controlled. This leads to very reproducible results and the possibilities of good comparisons between generic types of paint and even between formulations within a type of paint.

Paint is seldom applied in the field under the same carefully controlled conditions used during laboratory cure and testing. This means that field performance may not duplicate exactly laboratory performance. Although the same performance trends seen in the laboratory between generic types of paint and formulations of the same type usually are seen in the field, most researchers will admit that it is very difficult to predict field life expectancies from laboratory data.

There are several ways in which performance information can be gathered:

- Case histories
- Outdoor panel exposures
- Accelerated laboratory tests

In assessing performance, case history documentation for structures in a similar environment is probably the best method for approving a coating system. However, after waiting for five years to determine field performance, it is not unusual to find that paint raw materials have changed or that paint formulations have been improved with state-of-the-art technology. When this is the case, other methods of assessing performance are needed. Four of these methods are described below.

Field and laboratory testing procedures used to judge the performance characteristics of paints:

1. ***Field application and exposure.*** Paint is applied to test panels and dried in the environment for which the paint is designed. The panels remain in the environment for the duration of the test.
2. ***Lab application with field exposure.*** Paint is applied to test panels and dried under standard laboratory conditions. The panels then are placed in the field in the actual environment where the paint is to be used. The panels remain in this environment for the duration of the test.
3. ***Lab application with test fence exposure.*** Paint is applied to test panels and dried under standard laboratory conditions. The panels then are placed on a test fence in an environment that simulates one where the paint will be used. The panels remain on the test fence for the duration of the test.
4. ***Lab application and testing.*** Paint is applied to test panels and dried under standard laboratory conditions. The panels then are tested under accelerated conditions in a test cabinet that accelerates the deterioration of the paint and substrate.

Paint manufacturers, as well as third-party organizations such as universities, state and federal agencies and technical organizations, run a variety of performance tests to characterize their paints. For example, paint is tested to determine how it:

- Resists corrosive attack to the substrate
- Resists chalking, checking, cracking and loss of gloss and color
- Resists solvents and chemicals
- Resists abrasion from traffic or wind-driven debris

The next sections describe how two performance requirements—substrate protection from corrosion and weathering resistance of the topcoats—are used to judge the suitability of different paints.

PROTECTING SUBSTRATES FROM CORROSION

Corrosive Environments

Steel structures may be exposed to a variety of corrosive elements:

- Water, moisture and humidity
- Salt-laden air and rain
- Chemicals from the atmosphere, splashes or spills
- Graffiti-removal agents

An intact paint film will resist these elements. However, a coating that has defects such as pinholes or has been physically damaged from abrasion or impact will allow these elements to attack and corrode the metal directly. In addition, the effect of ultraviolet degradation from sunlight can deteriorate the paint film, causing chalking and film thickness loss. This can contribute further to the breakdown of the paint film and allow these elements to attack and corrode the steel structures.

The environment in which the structure stands determines how quickly a metal will erode. Environments can be termed benign, mildly corrosive, moderately corrosive or severely corrosive.

- A ***benign environment*** may result in little or no loss of metal, even when the metal has no protective coating. An example of this might be an arid climate, such as a desert, where there is no moisture or salt.
- A ***mild environment*** may result in one mil of metal loss per year. An example of this environment may be a Midwest climate where the steel structure might be exposed to rainfall, but probably not to salts or chemicals.
- A ***moderate environment*** may result in several mils of metal loss per year. An example of this environment may be near a city or a region of light industry. In addition to rain, the steel structure may be exposed to chemical fallout from power and industrial plants.
- A ***severe environment*** may result in many mils of metal loss per year. An example of this environment might be one in close proximity to seawater, with constant splashing or even immersion, or a heavy industrial area where corrosive acids might be splashed onto the structure.

Corrosion Performance Testing

The best performance information is data from actual experience and is available from paint manufacturers. However, paint formulations change, so it is often difficult to obtain the original formulations after several years of testing.

The alternative is to evaluate paint systems in a variety of accelerated test methods. Organizations such as the Steel Structures Painting Council (SSPC) and the National Association of Corrosion Engineers (NACE) spend considerable time exposing paint systems in accelerated and field tests and then evaluating correlations between the two.

Next to performance data from an actual application, field test data is the most reliable source of information to judge paint system performance. Test panels routinely are placed on racks on ocean beaches in North Carolina and Texas and on racks in medium and heavy industrial areas in Pittsburgh and Houston to judge performance and estimate service lives.

Paint companies rely on a variety of accelerated test methods to judge the performance of their corrosion-prevention systems. Two pieces of apparatus that have been traditionally used are the Salt Spray Cabinet and the Cleveland Humidity Cabinet™. In recent years, cyclic test methods have been introduced which use the Prohesion Cabinet™ and the Envirotest Cabinet™.

The Salt Spray Cabinet uses a salt solution to create a salt air mist. The panels are exposed continuously to this mist. Tests are run for hundreds to thousands of hours. This test originally was developed to determine corrosion rates for metals and was adopted by paint companies to judge paint performance. Although it is difficult to correlate to field performance, this test is most relied upon of all laboratory paint corrosion tests.

The Cleveland Humidity Cabinet uses condensing moisture (dew) to attack the paint system. Dew is chemically very clean and is a powerful agent for the formation of blisters in poorer performing paint systems. However, correlation to field performance is difficult.

The Prohesion Cabinet is used in a cyclic laboratory test where a salt spray episode is alternated with dry and light episodes. Corrosion mechanisms are similar to those seen in outdoor field exposures. Correlations are being developed between cabinet results and field tests.

The Envirotest Cabinet is another cyclic laboratory test apparatus. In this test, the panels are immersed in salt solutions and subsequently are exposed to dry and light episodes. Correlations also are being developed between these cabinet results and field tests.

Test Panels as Substitutes for Structures

Whichever test method is employed, field or laboratory, paint performance is judged by using steel test panels to simulate the substrates of actual structures. Panels are usually 4 in. × 12 in. and ¼ in. thick, and are made from hot- or cold-rolled steel. Panels can be new or rusted.

The panels are cleaned according to the requirements of the paint system being evaluated—hand tool cleaned, blasted, etc. The coating system is applied and cured per the manufacturer's instructions, sometimes under controlled laboratory conditions and sometimes under actual field conditions. The coating on the panel usually is cut, so that metal is exposed for oxidation. The panel then is exposed according to one of the test procedures.

After the exposure, two areas on the panel are evaluated—the face and the scribe cut. Each region is evaluated for the number and size of blisters. At the scribe cut, the amount of under-cutting is evaluated. In this manner, different coating systems can be compared in order to select the one that meets the requirements for resisting the environment in which your structure stands.

Weathering Environments

The topcoat on a structure not only provides additional coating thickness to help prevent corrosion, it also offers the opportunity to make the structure aesthetically pleasing. The original gloss and color of the coating should not change, so that the structure looks newly painted for the life of the coating system.

The technology of the topcoat must be chosen with the environment in mind. The weathering stresses of a given environment will lead to deterioration of the original gloss and color—the more severe the environment, the faster the appearance will degrade.

Field evaluations have shown that exposure to heat, humidity and sunlight causes coatings to fade, lose their gloss, crack and check. The speed of topcoat deterioration is directly related to the degree of exposure and to the sensitivity of a technology to that exposure.

Weathering Performance Testing

Cans of paint with "polyurethane" on the label do not all have the same weathering performance. Formulation variables, such as the type of polyurethane resin, the type of pigment, the ratio of resin and pigment and the amount of UV-absorbing additives, all determine the weathering properties.

Weathering performance information, like corrosion performance information, is best determined by field testing of laboratory-applied coatings, but the test methods are different. Test fences most often are situated in hot, sometimes humid, regions such as Florida, Arizona or Australia, but it is not unusual to see test fences on paint manufacturing sites in all parts of the country.

Usually field tests are run for a minimum of two years. By this time, a good understanding of weathering life can be estimated. Because developing new paint is a continuous activity, two-year paint data may not be available for newly introduced coatings. If this is the case, one-year data coupled with accelerated laboratory methods may be used.

Two accelerated lab methods are relied on—Weather-O-Meter™ or Q-UV™ weathering apparatus. Both methods use cycles of light and dark, dry and wet. The Weather-O-Meter typically uses a Xinon arc that generates an intense light to accelerate coating deterioration. Six months' exposure in the Weather-O-Meter is similar to two years in Florida. The Q-UV uses a special fluorescent type of light bulb. Three months in an instrument using a Q-UV-A bulb is about the same as two years in Florida.

Accelerated lab methods should only be used in combination with outdoor exposure information—for example, if only one year of Florida data is available. The correlation between accelerated weathering and Florida weathering does not allow for an accurate comparison of different types of paint. It is most suitable for examining minor formulation variations and as a screening tool. This information is a routine part of topcoat performance analysis. Ask for it!

Other Types of Performance Environments

The above sections describe in detail different environments and test methods for evaluating resistance to corrosion and weathering. Other types of environments could be identified. These include, for example, chemical and solvent environments, abrasive environments or immersion—water or soil—environments.

To make things more complicated, one environment often influences paint performance for another environment. For example, if a coating does not resist the effects of the weather, erosion of the coating could lead to premature failure due to corrosion. Similarly, if a coating does not resist chemicals, the coating could dissolve and lead to premature failure of the desired gloss retention.

Specifying Paint to Meet Performance Needs

To achieve the best cost-performance of a paint system, an owner or specifier first must determine the performance required for the structures' environment and then request cost bids based on paint of similar performance.

A low-performance paint, which would be suitable in a benign environment, would not be suitable for use in a more severe environment. For any given performance environment, if a paint has lower-than-required performance, it will fail early.

ECONOMICS

Cost of Materials

Coatings decisions often based on the cost per gallon or liter of paint as supplied. Instead, the cost of the solids portions of the paint should be considered. For example, paint at $15/gallon with only 50 percent solids is really more expensive than paint which costs $20/gallon and has 75 percent solids. This is because the real cost must be based on the amount of surface that can be covered. In this example the second paint will cover 50 percent more surface at only 33 percent more cost.

Typically, 10 to 30 percent more material is required than calculated. This additional material is used to wet and fill brushes, roller and spray equipment, is used to fill the profile caused by blast cleaning or is lost in over-spray. The proportional paint loss due to filling application equipment is greatest when small surfaces areas are to be painted and smallest for large jobs. Paint lost due to over-spray is highest when spray painting small diameter pipes, railing and catwalks and is lowest when painting large flat surfaces, such as walls or large tanks.

Life Cycle Cost

The paint raw material cost is only a small portion of the cost attributed to corrosion prevention through coating. A specifier must look at the cost of protection throughout the life of the coating cycle. The coating specifier must consider costs associated with painting such as inspection, surface preparation, the paint, application labor, containment and disposal. Paint costs can vary between 5 and 15 percent of the total cost. Since more expensive coatings systems usually last longer, they lead to lower lifetime costs than do low cost coatings that do not last as long.

Transfer Rates

Another factor that must be considered is the amount of material lost during the application process. For example, application by brush will result in a 4-8 percent loss; by roller, 4-8 percent; by conventional spray, 20-40 percent; or by airless spray, 10-20 percent. In addition, the amount of loss will vary with the size and shape of the surface being coated and the environmental conditions. For example, under adverse conditions of high wind and small surfaces, spray loss can be as high as 50 percent or more.

Estimating Paint Requirements

When the amount of surface to be painted is known, the amount of paint to order can be calculated by taking into account the surface area, the solids of the paint, the dry-film-thickness and the application loss.

INSPECTION

An inspector is a major factor in achieving a successful paint job. The inspector assists the engineer in the writing of the specification, acts as arbitrator with the contractor, oversees surface preparation and paint application and, overall, acts as the quality control expert. After the job the inspector can act as troubleshooter for failing systems. To obtain planned economics and realize the maximum potential of a coating system, it is essential that the system be installed exactly as designed. The employment of a qualified inspector is a means of increasing the probability of a successful application.

COATING REFERENCES

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FIRE PROTECTION

Fire protection is a major consideration in the design of most modern buildings. In its simplest terms, the means of fire protection for steel structures involves either of the following:

- Prescriptive methods with pre-approved construction assemblies based upon results from a "standard" American Society for Testing and Materials (ASTM) fire test (ASTM E119)
- Methods based upon fire engineering often referred to as rational fire design

What follows is an explanation of the rationale and practical considerations for both approaches.

GENERAL FACTORS

Three issues involved in fire protection include *life safety, protection of the structure*, and *fire suppression*. The need to fire protect a structure is a matter of compliance with the building codes that specify the number of hours of fire exposure that a building structure must withstand, within specific temperature limits. This is determined by such factors as the building use, occupancy, number of stories, building height, total floor area, area of each floor, and building separation.

Both the building codes and the insurance underwriters determine fire suppression requirements. For example, the building codes specify that high-rise buildings, large shopping malls and large industrial storage buildings be equipped with sprinkler systems. The insurance underwriters prefer that the structure be of noncombustible materials but, beyond that, their main concern is for the building contents whose value may far exceed the value of the structure itself. The requirements of the insurance underwriters for fire suppression devices can affect insurance premiums or whether or not the owner can obtain insurance coverage at all. In addition, the underwriters may provide insurance incentives in the form of reduced premiums for certain fire suppression measures such as modern Early Suppression Fast Response (ESFR) sprinkler systems. These may exceed the building code requirements and in turn, may allow for reductions in the amount of required fire protection on the structure itself or may liberalize building use restrictions.

Building Codes

Building codes determine the level of fire protection expected. Therefore, a working knowledge of the various building codes is essential. With the exception of some large cities that maintain their own codes, most areas in the United States enforce one of the following national model codes:

- *National Building Code*, published by the Building Officials and Code Administrators International, www.bocai.org.
- *Standard Building Code*, published by the Southern Building Code Congress International, www.sbcci.org.
- *Uniform Building Code*, published by the International Conference of Building Officials, www.icbo.org.

More recently, in 2000, a coordinated effort by the three model code bodies has resulted in the development of a single national code, the *International Building Code* (also known as IBC 2000). This was done to eliminate differences and inconsistencies among the three current codes and to simplify the task of building design. IBC 2000 acceptance is slowly growing across the country. Also, the reader should be aware that the National Fire Protection Agency is in the process of drafting yet another national model code.

Two building code issues that affect the selection and design of structural systems include the combustibility of the structural materials and the fire resistance of the structural system, as discussed in the next sections.

Combustibility of the Structural Materials

Fires usually start small and require fuel in order to grow. In fact, most fires either self-extinguish because of a lack of fuel or are quickly extinguished by building occupants or fire suppression systems such as sprinklers. Furthermore, even though most fires involve building contents, in the case of buildings built of combustible materials, the structure itself may represent the greatest potential source of fuel.

Noncombustible materials such as stone, brick, concrete and steel do not burn and therefore are not a source of fuel. Although the physical properties of noncombustible materials may be adversely affected at elevated temperatures, these materials do not contribute to either the duration or intensity of a fire. Conversely, combustible materials such as wood, paper and plastic do increase the intensity and/or duration of a fire.

Tests conducted by the National Institute for Standards and Technology have indicated that an approximate relationship exists between the amount of available combustible material (fire loading expressed as pounds of wood equivalent per square foot of floor area), and fire severity (expressed as hours of equivalent fire exposure based upon the standard ASTM fire test). This relationship is illustrated in Figure 26. Subsequent field surveys measured the fire loads typically found in buildings with different occupancies and are listed in Table 5 (*Fire Protection Through Modern Building Codes*), produced by the American Iron and Steel Institute.

For noncombustible framing there is no assigned fire load. However, for conventional wood framing, a reasonable estimate of fire load for the structure is 7.5 to 10 psf. For heavy timber construction, the corresponding structural fire load might be on the order of 12.5 to 17.5 psf. As a result, building codes generally limit permitted size (allowable height and area) of combustible buildings much more than for noncombustible buildings.

Fire Resistance of the Structure

In addition to regulating buildings according to the combustibility or noncombustibility of the structure, building codes also specify fire resistance requirements

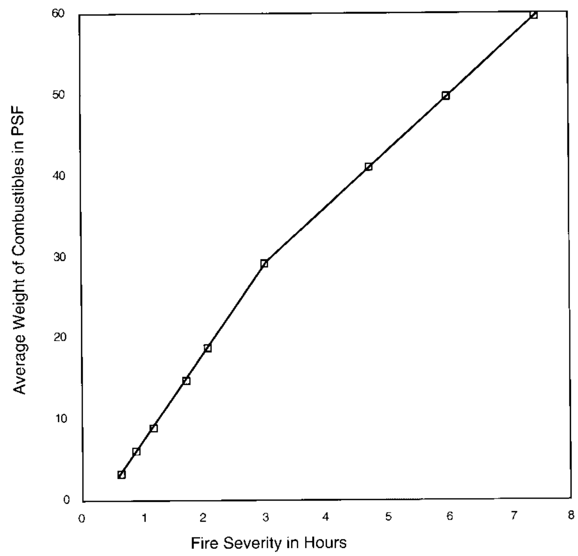

Figure 26. NIST graph illustrating the relationship of fire severity to the average weight of combustibles in a building

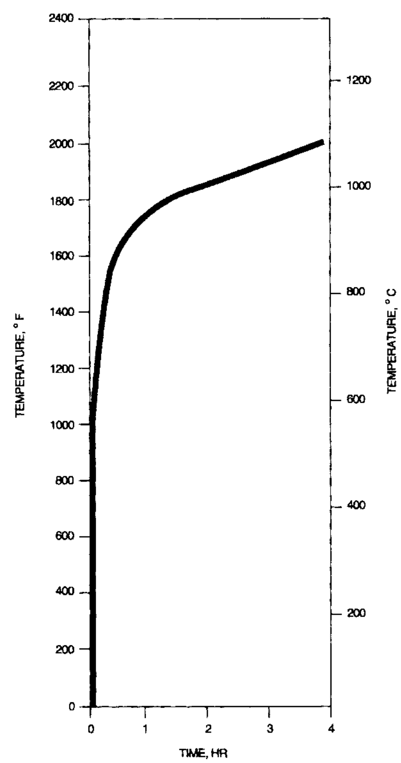

Figure 27. Graph from ASTM E119 test showing relationship of time to fire resistance temperature requirements

Table 5

Typical Occupancy Fire Loads and Fire Severity

OCCUPANCY DESIGNATION	OCCUPANCY FIRE LOAD (psf)	EQUIVALENT FIRE SEVERITY (hours)
Assembly	5 to 10	0 to 1
Business	5 to 10	0 to 1
Educational	5 to 10	0 to 1
Hazardous	Variable	Variable
Industrial		
Low Hazard	0 to 10	0 to 1
Moderate Hazard	10 to 25	1 to 2½
Institutional	5 to 10	0 to 1
Mercantile	10 to 20	1 to 2
Residential	5 to 10	0 to 1
Storage		
Low Hazard	1 to 10	0 to 1
Moderate Hazard	10 to 30	1 to 3

according to building size (height and area) and type of occupancy. Generally, fire resistance is defined as the relative ability of construction assemblies (floors, walls, partitions, beams, girders and columns) to prevent the spread of fire to adjacent spaces and/or to continue to perform structurally when exposed to fire. Fire resistance requirements are generally based upon standard tests in accordance with ASTM E119.

The ASTM E119 test method specifies a "standard" fire exposure that is used to evaluate the fire resistance of construction assemblies (Figure 27). Fire resistance requirements are specified in terms of the time during which an assembly continues to prevent the spread of fire and/or perform structurally when exposed to the "standard" fire. Thus, fire resistance requirements are expressed in periods of time in increments of whole or half hours. The design of the fire resistant buildings is typically accomplished in a very prescriptive fashion by selecting tested construction assemblies that meet specific building code requirements. Listings of fire resistance ratings for tested construction assemblies are available from the following sources:

- *Fire-Resistance Directory*, Underwriters Laboratories (UL), Northbrook, Illinois.
- *Fire-Resistance Ratings*, American Insurance Services Group, New York, New York.
- *Fire-Resistance Design Manual*, Gypsum Association, Washington, D.C.

The term "fireproof" is often used to describe fire-resistant buildings. Some manufacturers use this term to describe fire protection materials. The use of "fireproof" and "fireproofing" is improper because it connotes absolute protection; experience has clearly shown that large-loss fires can occur in fire-resistant buildings. No building is truly fireproof.

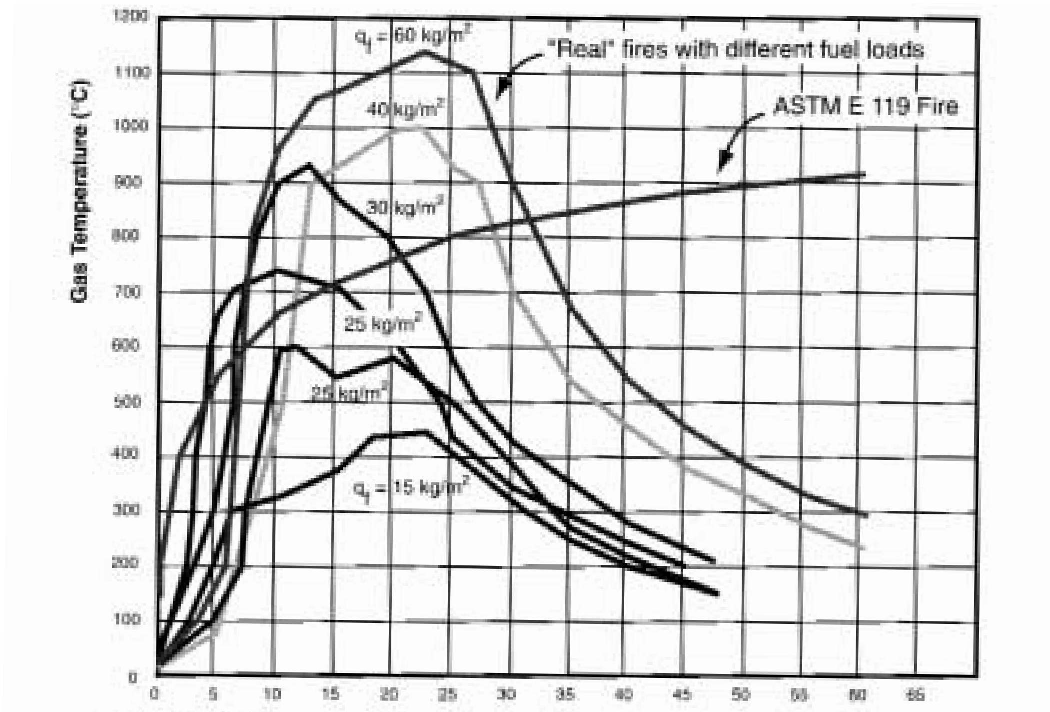

Figure 28. Time/temperature curves for various fire exposures

Effect of Temperature on Steel

The elevated temperatures developed during standard fire tests adversely affect the properties of virtually all materials, even noncombustible ones such as steel. In general, structural steel retains 60 percent of its ambient temperature yield strength at 1,000° Fahrenheit. During most building fires, temperatures in excess of 1,000° Fahrenheit are developed for relatively brief periods of time. Additionally, the structural elements are generally not loaded to their full design strength. Consequently, even bare steel may have sufficient load carrying capacity to withstand the effects of fire.

The "standard" ASTM fire test is conducted so that temperatures continuously increase, assuming an inexhaustible fire load, and the members are loaded to full design load. Figure 28 shows the time/temperature curves for fires under the standard ASTM test compared with "real" fires with different fire loads. As a result of the "standard" fire tests, when building codes specify fire-resistant construction, fire protection materials are required to "insulate" structural steel elements.

Fire casualty statistics indicate that occupant safety is threatened much more by toxic smoke than structural collapse.

Temperatures of Fire Exposed Structural Steel Elements

Basic heat transfer principles indicate that the rate of temperature change of a steel beam or column will vary inversely with mass and directly with the surface area through which heat is transferred to the member. Thus, the weight-to-heated-perimeter ratio (*W/D*) of a structural steel member significantly influences the temperature that the member will experience when exposed to fire. As used in this expression, *W* is the weight per unit length of the member (lbs/ft) and *D* is the inside perimeter of the fire protection material (inches). Expressions for calculating *D* are illustrated in Figure 29 for both columns and beams with either contour or box protection. In short, the weight-to-heated-perimeter ratio defines the "thermal size" of a structural member.

Since the temperature of a structural steel member is strongly influenced by the *W/D* ratio, it follows that the required thickness of fire protection material is also strongly influenced by *W/D* ratios. This interrelationship is clearly illustrated in Figure 30 that gives the fire resistance of steel columns protected with different thicknesses of gypsum wallboard as a function of *W/D* ratios. Clearly the *W/D* ratio is almost as important as the thickness of the fire protection material. *W/D* ratios are given in the Materials Section of the Guide.

In recognition of this basic principle, a number of semi-empirical design equations have been developed for determining the thickness of fire protection for structural steel elements as a function of *W/D* for specific fire resist-

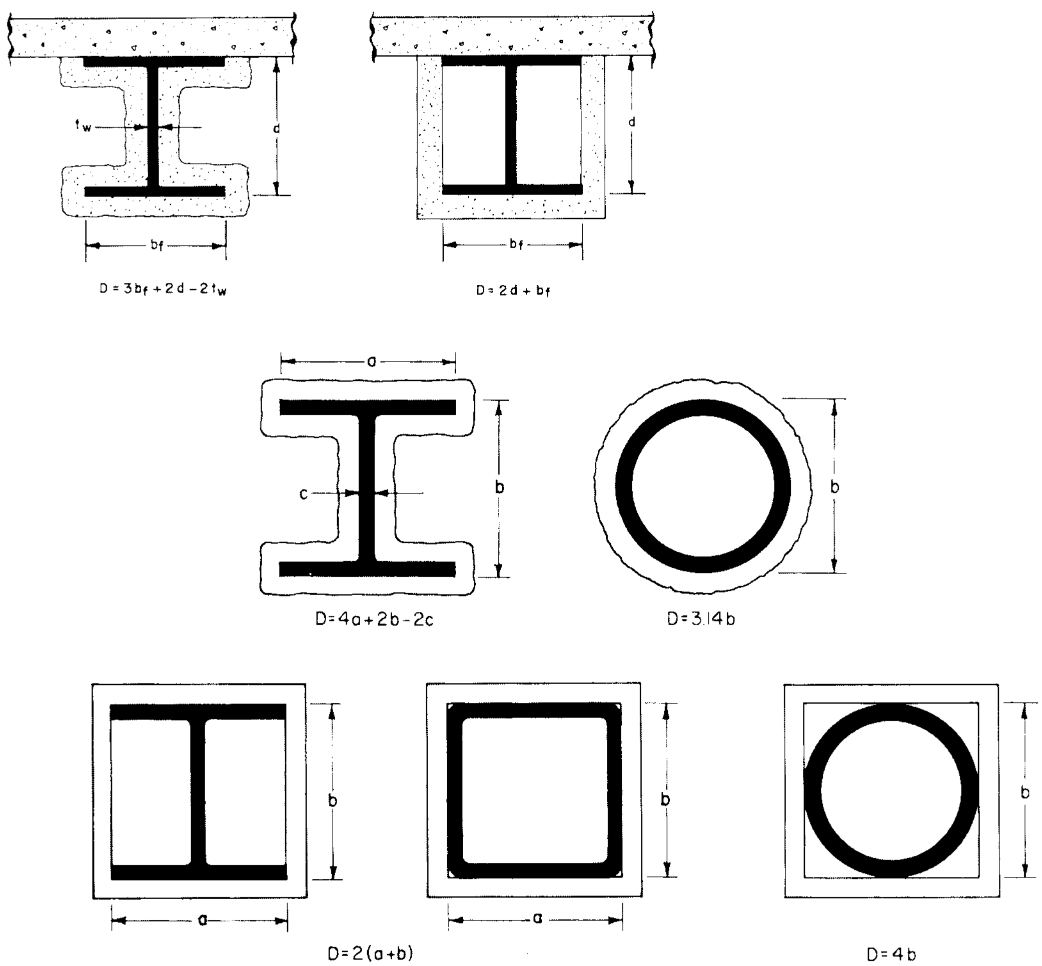

Figure 29. Determination of the heated perimeter of columns and beams. American Iron and Steel Institute; *Designing Fire Protection for Steel Columns*, *Designing Fire Protection for Steel Beams*

ance ratings. These equations have been incorporated into the UL Fire Resistance Directory, and are described in the following publications available from AISI:

- *Designing Fire Protection For Steel Columns*
- *Designing Fire Protection For Steel Beams*
- *Designing Fire Protection For Steel Trusses*

These calculation methods are also incorporated in ASCE/SFPE 29-99 *Standard Calculation Methods for Structural Fire Protection*, published by the American Society of Civil Engineers and in IBC 2000.

FIRE PROTECTION MATERIALS

A variety of materials and systems are available to protect (insulate) structural steel. The performance of these materials is evaluated during actual tests. In addition to insulating characteristics, the physical integrity of the materials is very important and care must be taken to ensure that they are installed according to the applicable fire-resistant designs.

Gypsum

Gypsum in several forms is widely used as a fire protection material (Figure 31). As a plaster it is applied over metal or gypsum lath. As wallboard it is typically installed

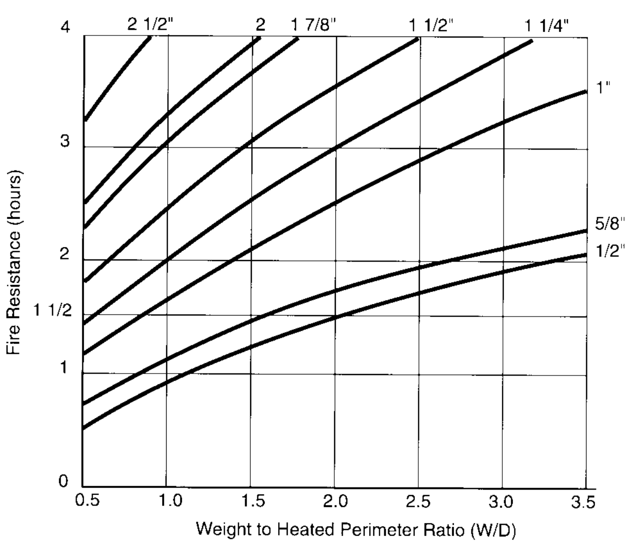

Figure 30. Variation in fire resistance of structural steel columns with weight to heated perimeter ratios and various gypsum wallboards. Illustration courtesy of the American Iron and Steel Institute, *Designing Fire Protection for Steel Columns.*

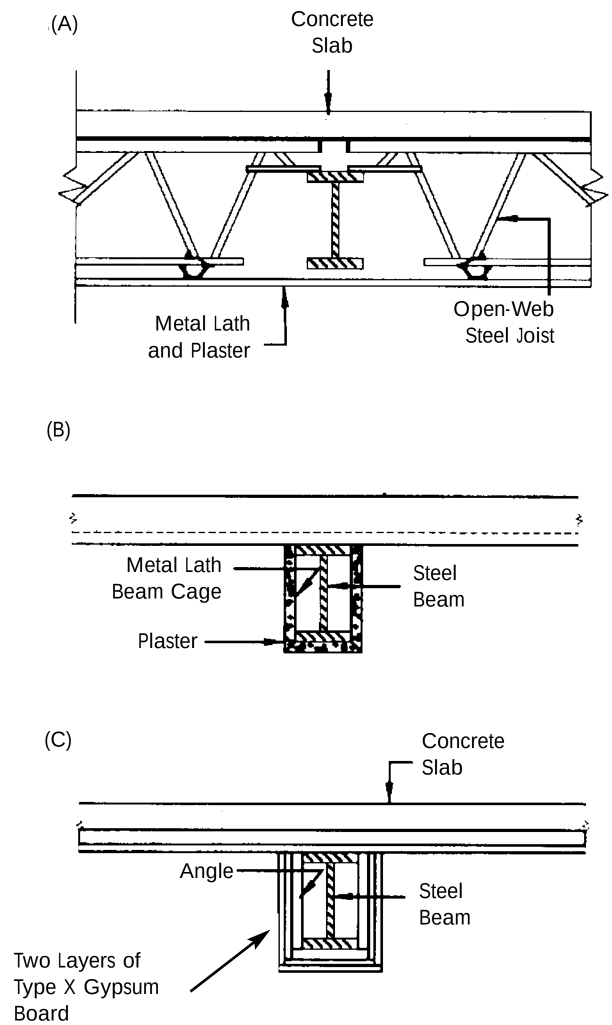

Figure 31. Some methods for applying gypsum as fire protection for structural steel: (a) open-web joist with plaster ceiling; (b) beam enclosed in a plaster cage; (c) beam boxed with wallboard. Illustration courtesy of the Gypsum Association, *Fire Resistance Design Manual.*

over cold-formed steel framing or furring. Detailed information on using this material for fire protection is available from the Gypsum Association.

The effectiveness of gypsum-based fire protection materials can be increased significantly by the addition of lightweight mineral aggregates such as vermiculite and perlite. For plaster applications, it is important that the mix is properly proportioned, applied in the required thickness, and that the lath is properly installed. In the case of gypsum wallboard, three types are readily available; regular, Type X and proprietary. Type X wallboards have specially formulated cores that provide greater fire resistance than regular wallboard of the same thickness. In addition many manufacturers produce proprietary wallboards with even greater fire-resistance characteristics. It is important to verify that the wallboard used is that specified for a particular design. In addition, special types and spacing of fasteners and furring channels may be required.

Spray-applied Fire Resistive Material

The most widely used fire protection materials for structural steel are mineral fiber and cementitious materials that are spray-applied directly to the contours of beams, columns, girders and floor/roof decks (see Figure 32). These materials are based upon proprietary formulations and it is imperative that the manufacturers' requirements be followed with regard to mixing and application. Fire-resistant designs as to type and thickness of material are published by UL.

Because these materials are applied directly to the steel, adhesion is an important consideration. Prior to application, the structural steel should be free of dirt, oil and loose scale. Light corrosion will not adversely affect adhesion.

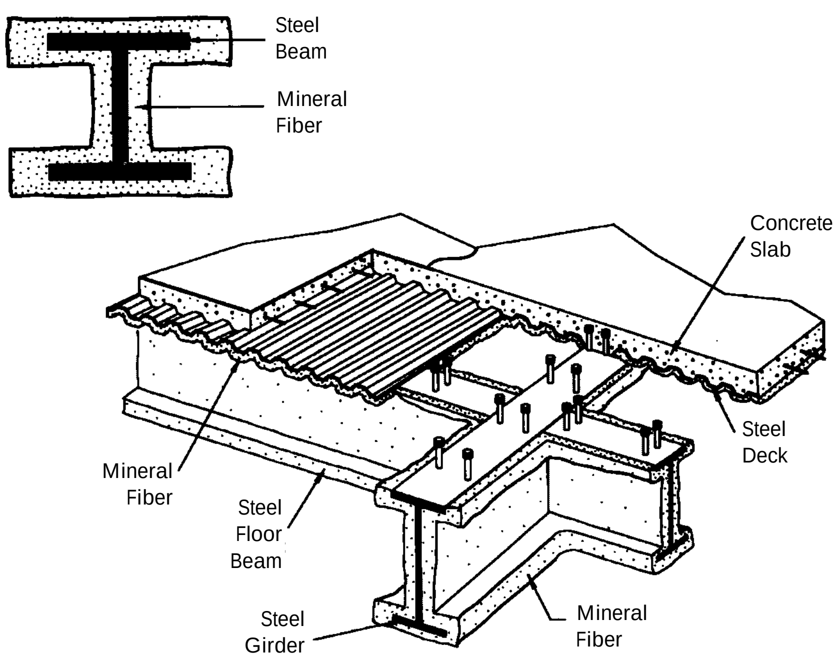

Figure 32. Mineral fiber spray applied to beam and girder floor system with steel floor deck supporting a concrete slab. Illustration courtesy of the American Iron and Steel Institute, *Designing Fire Protection for Steel Beams.*

Steel that is to be fire protected with spray-applied material should not be painted or primed unless it is in a corrosive environment, in which case, the bond between primer coat and fire-protective layer must be verified by UL. There are a number of primers that have this certification. In addition, research has found that it is not necessary to paint structural steel when it is fully enclosed between the inside and outside walls of a building, or otherwise protected, such as with spray-applied fire protection materials.

Suspended Ceiling Systems

A wide variety of proprietary suspended ceiling systems are available for protecting floors, beams and girders (see Figure 33). Fire resistance ratings are published by UL. These systems are specifically designed for fire protection purposes and require the careful integration of ceiling tile, grid and suspension systems. Also, openings for light fixtures, air diffusers and similar accessories must be adequately protected. As a consequence, manufacturer's installation instructions must be closely followed. In case of load transfer trusses and/or girders that support loads from more than one floor, building codes may require individual protection and, as a consequence, suspended ceiling systems may not be permitted for this specific application.

Concrete and Masonry

In past decades, concrete was the most widely used material for structural steel fire protection. It is not, however, particularly efficient for this purpose due to its relatively high thermal conductivity. As a result, concrete is no longer widely used solely for this purpose. A notable exception is the growing use of composite construction, such as concrete encased steel columns. Concrete and masonry are also sometimes used to protect steel columns for

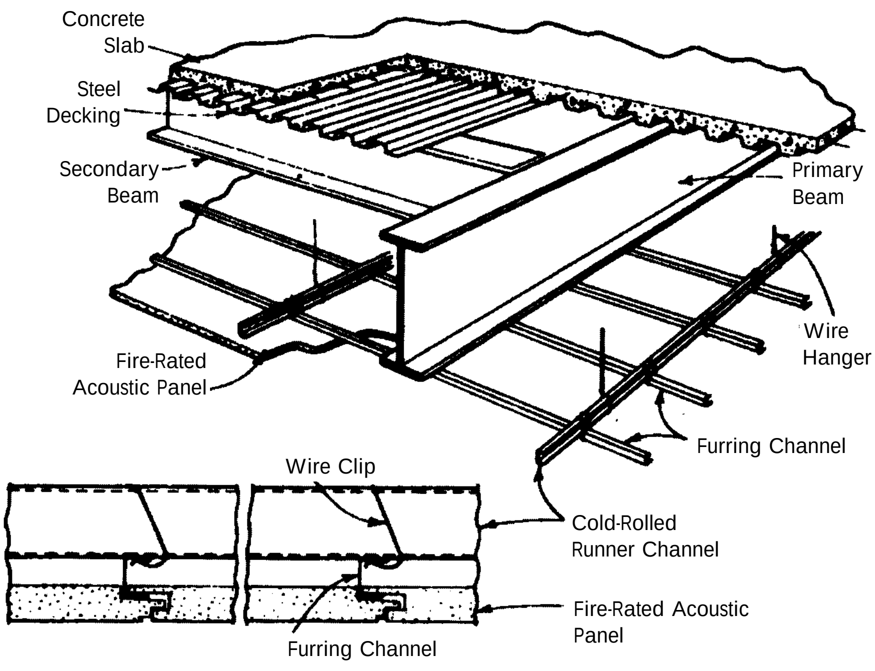

Figure 33. Steel floor system fire protected on the underside by a suspended ceiling. Illustration courtesy of the American Iron and Steel Institute, *Designing Fire Protection for Steel Beams*.

architectural purposes or when substantial resistance to physical damage is required. Design information on fire resistance of steel columns encased in concrete or protected with precast concrete columns covers is available from AISI. Information on using concrete masonry or brick is available from the National Concrete Masonry Association (NCMA), Herndon, VA, and the Brick Institute of America, Reston, VA, respectively.

Intumescent Coatings

Intumescent coatings are a unique product that can be used to achieve the required fire rating while still architecturally exposing the steel framing. Intumescent coatings are epoxy based paint-like mixtures applied to the primed steel surface, which at elevated temperatures expand to many times their applied thickness. They form an insulating blanket around the steel member protecting the member from further heat. In the past, the time of protection provided by these coatings was fairly limited but with continued improvements, fire ratings of almost three hours are now possible.

Intumescent coatings are not inexpensive, however, costing several times that of common spray-applied systems. The cost of intumescent coatings increases as the required fire rating increases. Therefore, their use is generally limited to exposed steel applications. It is not uncommon to see single members with a combination of systems; spray-applied fibrous systems on hidden portions and intumescent coatings on exposed portions.

UNDERWRITERS LABORATORIES (UL) ASSEMBLIES

A summary of UL assemblies that are commonly applicable in structural steel building design and construction is provided in Tables 6-10. These tables should be used in conjunction with the criteria and information contained in the latest UL Fire Resistance Directory. However, the inclusion of these assemblies in this Guide should not preclude the use of other UL assemblies or any other rational approach.

The ratings for the assemblies discussed in Tables 6-10 are given for a minimum member size that can be related to other larger member sizes. For W-shapes and similar members, this relationship can be made by the ratio of the weight to the heated perimeter (*W/D*). For HSS and steel pipe, the ratio of the area to the heated perimeter (*A/P*) defines the relation. *W/D* and *A/P* ratios are given in the Materials Section of this Guide.

Note that certain UL assemblies can also be used with members with smaller *W/D* and *A/P* ratios, provided certain criteria as outlined in the specific UL design are met. Also keep in mind that the equations for columns and braces are generally different because the heated perimeter of a beam differs from that for a column or brace.

Table 6 lists some fire protection systems for roof-ceiling assemblies. Table 7 covers floor-ceiling assemblies. Table 8 lists protection systems for beam-only designs for the roof and Table 9 lists beam-only designs for the floor. Finally, Table 10 shows protection for some common column assemblies. These tables make reference to "restrained" and "unrestrained" ratings, discussed in the next section.

RESTRAINED AND UNRESTRAINED CONSTRUCTION

In the context of fire resistance, the use of the terms "restrained" or "unrestrained" construction refers to the ability of the structural members and the surrounding construction to resist thermal expansion during elevated temperatures. This is often confused with structural restraint that has to do with the fixity or rigidity of supporting members at their connections. Thermal restraint is an important consideration because most materials tend to expand when heated.

The restrained condition as defined by the codes applies when an assembly (floor system, roof system and its supporting members) is surrounded by construction that is capable of resisting substantial thermal expansion

Table 6

Roof-Ceiling Assemblies

Assembly Rating: Restrained (hr)	Assembly Rating: Unrestrained (hr)	Type of Protection System	Roof Insulation Type	Metal Deck Depth (in.)	UL Design Number
1	3/4	Acoustical Ceiling Membrane	Rigid	1-1/2	P254
1	1		Rigid	1-1/2	P214
			Insulating Fill	9/16, 15/16, 1-5/16	P246, P255
				9/16	P261
1, 1-1/2	1, 1-1/2		Rigid	1, 1-1/2	P250
				1-1/2	P230
				1, 1-1/2, 2, 3	P225
			Insulating Fill	15/16, 1-5/16, 1-1/2	P231
1, 1-1/2, 2	1, 1-1/2, 2		Insulating Fill	9/16, 3/4, 1-1/4	P251
2	2		Rigid	1, 1-1/2	P237
1-1/2, 2	1-1/2, 2	Plaster w/ Metal Lath Membrane	Rigid	1-1/2	P404
1	1	Gypsum Wallboard Ceiling Membrane	Insulating Fill	1-5/16	P509
2	2		Rigid	1-1/2	P514
3/4, 1, 1-1/2, 2	3/4, 1, 1-1/2, 2	Spray-applied Fire Resistive Material	Rigid	1-1/2, 3	P701
1, 1-1/2, 2	1, 1-1/2, 2		Rigid	1-1/2	P711, P740, P741
				1-1/2, 3	P714, P717, P725, P739, P819
			Insulating Fill	9/16, 15/16,1-5/16, 1-1/2	P921
1, 1-1/2, 2	1-1/2, 2		Insulating Fill	9/16, 15/16, 1-5/16, 1-1/2	P927
1, 1-1/2, 2, 3	1, 1-1/2, 2		Rigid	1-1/2, 3	P719
1, 1-1/2, 2, 3	1, 1-1/2, 2, 3		Rigid	1-1/2	P723, P733
				1-1/2, 3	P732
2	1-1/2		Rigid	1-1/2	P718

NOTES

* The referenced assemblies are some commonly used Underwriters Laboratories (UL) assemblies used for conventional steel framed structures. For additional assemblies the reader should reference the UL Fire Resistance Directory.

* For additional design requirements such as beam spacing, concrete strength, density, reinforcing and clear cover, minimum metal deck gage, maximum deck span, shear connector requirements, design stress limitations, etc. see the specific referenced assembly in the UL directory.

* For roof designs that incorporate structural concrete slabs, D-series assemblies can be used provided that the roof insulation type, density and the appropriate D-series assembly modifications are in accordance with the UL directory published requirements.

* Metal deck depth for some assemblies is shown as a minimum and deeper decks may be substituted. Refer to the specific UL assembly for additional information.

Table 7

Floor-Ceiling Assemblies

Assembly Rating		Type of Protection System	Concrete		Metal Deck Depth (in.)	UL Design Number
Restrained (hr)	Unrestrained (hr)		Min. Thickness above deck flutes (in.)	Type		
1, 1-1/2, 2, 3	1, 1-1/2, 2, 3	Acoustical Ceiling Membrane	based upon required rating	NW or LW	1-1/2, 2, 3	D216
2, 3	2, 3			NW	1-1/2	D218
1-1/2, 2	1-1/2, 2	Gypsum Wallboard Ceiling Membrane	2-1/2	NW	1-1/2, 2, 3	D502
2	1-1/2		2	LW	3, 4-1/2, 6, 7-1/2	D501
1, 1-1/2, 2, 3	1, 1-1/2, 2, 3	Spray-Applied Fire Resistive Material	2	NW or LW	2, 3	D743
			2-1/2	NW or LW	9/16, 15/16, 1-5/16	D780
					1-1/2, 2, 3	D759, D832
1, 1-1/2, 2, 3, 4	1, 1-1/2, 2, 3, 4		2-1/2	NW or LW	1-1/2, 2, 3	D739, D767, D779, D858
			3-1/4	LW	1-1/2, 2, 3	D782
2	1, 1-1/2		2-1/2	LW	1-1/2, 2, 3	D752
2, 3, 4	1, 1-1/2, 2, 3		2-1/2	NW	1-1/2, 1-5/8	D744
3, 4	1-1/2, 2		3-1/4	LW	1-1/2, 2, 3	D754
1, 1-1/2, 2, 3	1, 1-1/2, 2, 3	Spray-Applied Fire Resistive Material w/ Unprotected Deck	based upon required rating	NW or LW	1-1/2, 1-5/8, 2, 3	D902
					1-1/2, 2, 3	D916, D925

NOTES

* The referenced assemblies are some commonly used Underwriters Laboratories (UL) assemblies used for conventional steel framed structures. For additional assemblies the reader should reference the UL Fire Resistance Directory.

* For additional design requirements such as beam spacing, concrete strength, density, reinforcing and clear cover, minimum metal deck gage, maximum deck span, shear connector requirements, design stress limitations, etc. see the specific referenced assembly in the Underwriters Laboratories (UL) directory.

Table 8

Beam-Only Designs for Roofs

Assembly Rating: Restrained (hr)	Assembly Rating: Unrestrained (hr)	Type of Protection System	Roof Insulation Type	Metal Deck Depth (in.)	UL Design Number
1, 1-1/2, 2, 3	1, 1-1/2, 2, 3	Spray-applied Fire Resistive Material	Rigid	1-1/2	S715, S733
1, 1-1/2, 2, 3, 4	1, 1-1/2, 2, 3, 4		Rigid	1-1/2	S701, S721, S724, S729, S734, S805
			Rigid or Insulating Fill	1-1/2	S735

NOTES

* The referenced assemblies are some commonly used Underwriters Laboratories (UL) assemblies used for conventional steel framed structures. For additional assemblies the reader should reference the UL Fire Resistance Directory.

* For additional design requirements such as beam spacing, concrete strength, density, reinforcing and clear cover, minimum metal deck gage, maximum deck span, shear connector requirements, design stress limitations, etc. see the specific referenced assembly in the Underwriters Laboratories (UL) directory.

* Metal deck depth for some assemblies is shown as a minimum and deeper decks may be substituted. Refer to the specific UL assembly for additional information.

Table 9

Beam-Only Designs for Floors

Assembly Rating: Restrained (hr)	Assembly Rating: Unrestrained (hr)	Type of Protection System	Concrete: Min. Thickness Above Deck Flutes (in.)	Concrete: Type	Metal Deck Depth (in.)	UL Design Number
2	2	Gypsum Wallboard	2-1/2	NW	1-1/2	N501, N502
3	2		2-1/2	NW	1-1/2	N505
1, 1-1/2, 2, 3, 4	1, 1-1/2, 2, 3, 4	Spray-applied Fire Resistive Material	2-1/2	NW or LW	1-1/2, 2, 3	N706, N734, N739, N823
					1-5/16, 1-1/2, 2, 3	N708, N772, N782

NOTES

• The referenced assemblies are some commonly used Underwriters Laboratories (UL) assemblies used for conventional steel framed structures. For additional assemblies the reader should reference the UL Fire Resistance Directory.

• For additional design requirements such as beam spacing, concrete strength, density, reinforcing and clear cover, minimum metal deck gage, maximum deck span, shear connector requirements, design stress limitations, etc. see the specific referenced assembly in the Underwriters Laboratories (UL) directory.

Table 10

Column Assemblies

Assembly Rating (hr)	Type of Protection	Column Types	UL Design Number
1, 2, 3	Gypsum Wallboard	W, HSS	X528
2		W	X516, X518, X520
3			X509, X510, X513
3/4, 1, 1-1/2, 2, 3, 4	Spray-applied Fire Resistive Material	HSS, Pipe	X771, Y707
1, 1-1/2, 2, 3, 4		W	X772, X829, Y708, Y725
		W, HSS, Pipe	X790, X795
		HSS, Pipe	X827

NOTES

* The referenced assemblies are some commonly used Underwriters Laboratories (UL) assemblies used for conventional steel framed structures. For additional assemblies the reader should reference the UL Fire Resistance Directory.

* For additional design requirements such as beam spacing, concrete strength, density, reinforcing and clear cover, minimum metal deck gage, maximum deck span, shear connector requirements, design stress limitations, etc. see the specific referenced assembly in the UL directory.

throughout the range of anticipated elevated temperatures. Extensive research in the 1960s showed that restraint improves the fire resistance of many types of common floor system types of common floor systems. For example, when a beam is heated from below, the lower flange tries to expand while the top flange, which is topped with concrete, remains cooler and does not expand at the same rate. When the bottom flange expansion is resisted (restrained) by the surrounding construction (columns, beams on the other side of the columns, the concrete floor slab or roof deck), the resulting forces (compression similar to prestressing) in the beam give it additional capacity to withstand stresses during the fire. This additional capacity to resist the effects of elevated temperatures is reflected in the codes by the fact that "restrained" construction requires significantly less fire protection than "unrestrained."

Table X3.1 of the Appendix to ASTM E119 (see the Partial Extract of the Appendix to ASTM E119 later in this section) defines various forms of bolted, riveted, or welded steel construction as restrained, and has been incorporated into the Standard Building Code (SBCCI) in 1996 as a supplement. This same table continues to be part of the National Building Code (BOCA) by reference. Thus, under these two national model building codes, designers are permitted to treat structural steel framing as restrained per the definition in the table.

Under the Uniform Building Code (ICBO), all assemblies (including steel and concrete) continue to be considered unrestrained unless the engineer of record can substantiate a restrained rating. Until recently there has not been a straightforward method for structural engineers to do this. The result is that steel structures designed according to the Uniform Building Code have usually been classified as "unrestrained" with the resulting higher costs for fire protection.

Recent developments now provide engineers with a ready method for substantiating thermal restraint in their designs. It is available in the following references:

- Ioannides, S.A. and Mehta, S. "Restrained Versus Unrestrained ratings for Steel Structures—A Practical Approach", *Proceedings of the National Steel Construction Conference*, pp. 17.1-17.20, AISC, Chicago, IL, 1997.
- Gewain, Richard and Troup, Emile. "Restrained Fire Resistance Ratings in Structural Steel Buildings" *Engineering Journal*, Vol. 38, No. 2, 2001.

Even though substantiating a restrained rating may require some additional design time on the part of the engineer of record, the costs are usually far outweighed by savings in fire protection.

Partial Extract of the Appendix to ASTM E119-00a: Standard Test Methods for Fire Tests of Building Construction and Materials

X3. Guide for Determining Conditions of Restraint for Floor and Roof Assemblies and for Individual Beams

One of the major changes in the new rating criteria was the establishment of restrained and unrestrained ratings. To help determine the appropriate rating to use in a particular building situation, the following Guide is presented. It is Appendix C from the Standard for Fire Tests of Building Construction and Materials, UL263. Paragraphs X3.1 through X3.5 provide general information with respect to the concept of restraint against thermal expansion of building elements as it relates to restrained and unrestrained ratings. Table X3.1 gives examples of restrained and unrestrained conditions for certain common construction types. It should be understood that the information provided in Table X3.1 is to be used as a guide and that the concept of restraint against thermal expansion addressed in paragraphs X3.2 through X3.5 should be carefully considered in assessing the condition of restraint in building structures.

X3.1 The revisions adopted in 1970 introduced the concept of fire endurance classifications based on two conditions of support: restrained and unrestrained. As a result, specimens can be fire tested in such a manner as to derive these two classifications.

X3.2 A restrained condition in fire tests, as used in this test method, is one in which expansion at the supports of a load carrying element resulting from the effects of the fire is resisted by forces external to the element. An unrestrained condition is one in which the load carrying element is free to expand and rotate at its supports.

X3.3 This guide is based on knowledge currently available and recommends that all constructions be classified as either restrained or unrestrained. This classification will enable the architect, engineer, or building official to correlate the fire endurance classification, based on conditions of restraint, with the construction type under consideration. While it has been shown that certain conditions of restraint will improve fire endurance, methodologies for establishing the presence of sufficient restraint in actual constructions have not been standardized.

X3.4 For the purpose of this guide, restraint in buildings is defined as follows: "Floor and roof assemblies and individual beams in buildings shall be considered restrained when the surrounding or supporting structure is capable of resisting substantial thermal expansion throughout the range of anticipated elevated temperatures. Construction not complying with this definition are assumed to be free to rotate and expand and shall therefore be considered as unrestrained."

X3.5 This definition requires the exercise of engineering judgment to determine what constitutes restraint to "substantial thermal expansion." Restraint may be provided by the lateral stiffness of supports for floor and roof assemblies and intermediate beams forming part of the assembly. In order to develop restraint, connections must adequately transfer thermal thrusts to such supports. The rigidity of adjoining panels or structures should be considered in assessing the capability of a structure to resist thermal expansion. Continuity, such as that occurring in beams acting continuously over more than two supports, will induce rotational restraint which will usually add to the fire resistance of structural members.

X3.6 In Table X3.1 only the common types of constructions are listed. Having these examples in mind as well as the philosophy expressed in the preamble, the user should be able to rationalize the less common types of construction.

Table X3.1

Construction Classification, Restrained and Unrestrained (ASTM E119-00a)

I. Wall bearing:	
Single span and simply supported end spans of multiple bays:[A]	
(1) Open-web steel joists or steel beams, supporting concrete slab, precast units, or metal decking	unrestrained
(2) Concrete slabs, precast units, or metal decking unrestrained	unrestrained
Interior spans of multiple bays:	
(1) Open-web steel joists, steel beams or metal decking, supporting continuous concrete slab	restrained
(2) Open-web steel joists or steel beams, supporting precast units or metal decking	unrestrained
(3) Cast-in-place concrete slab systems	restrained
(4) Precast concrete where the potential thermal expansion is resisted by adjacent construction[B]	restrained
II. Steel framing:	
(1) Steel beams welded, riveted, or bolted to the framing members	restrained
(2) All types of cast-in-place floor and roof systems (such as beam-and-slabs, flat slabs, pan joists, and waffle slabs) where the floor or roof system is secured to the framing members	restrained
(3) All types of prefabricated floor or roof systems where the structural members are secured to the framing members and the potential thermal expansion of the floor or roof system is resisted by the framing system or the adjoining floor or roof construction[B]	restrained
III. Concrete framing:	
(1) Beams securely fastened to the framing members	restrained
(2) All types of cast-in-place floor or roof systems (such as beam-and-slabs, flat slabs, pan joists, and waffle slabs) where the floor system is cast with the framing members	restrained
(3) Interior and exterior spans of precast systems with cast-in-place joints resulting in restraint equivalent to that which would exist in condition III *(1)*	restrained
(4) All types of prefabricated floor or roof systems where the structural members are secured to such systems and the potential thermal expansion of the floor or roof systems is resisted by the framing system or the adjoining floor or roof construction[B]	restrained
IV. Wood construction:	
All types	unrestrained

[A] Floor and roof systems can be considered restrained when they are tied into walls with or without tie beams, the walls being designed and detailed to resist thermal thrust from the floor or roof system.

[B] For example, resistance to potential thermal expansion is considered to be achieved when:

(1) Continuous structural concrete topping is used,

(2) The space between the ends of precast units or between the ends of units and the vertical face of supports is filled with concrete or mortar, or

(3) The space between the ends of precast units and the vertical faces of supports, or between the ends of solid or hollow core slab units does not exceed 0.25 % of the length for normal weight concrete members or 0.1 % of the length for structural lightweight concrete members.

ARCHITECTURALLY EXPOSED STEEL

Exterior Applications

As a result of recent innovations with respect to structural fire protection, the concept of externally exposed structural steel deserves special mention. This allows for direct architectural expression rather than hiding the structure behind a decorative façade. Obviously, building code requirements for fire resistant construction strongly influence the design of architecturally exposed steel. A conventional approach for providing structural fire protection for structurally exposed steel is illustrated in Figure 34. Variations of this approach have been used in many buildings.

Another technique involves the use of water-filled columns (see Figures 35 and 36). Originally patented in 1884, this method was first used in the United States in the late 1960s for the 64-story US Steel Building in Pittsburgh, PA. Since then the system has been used in a number of buildings both here and in Europe. Although requiring careful and sophisticated engineering, the principles are well established and documented. Virtually any level of fire resistance can be achieved. In general, corrosion inhibitors should be used and, in colder climates, an anti-freeze solution should be used for exterior columns.

Another innovation involves the use of flame-shielded spandrel girder as illustrated in Figure 37. As shown, girder is protected on the interior in a conventional manner. Sheet steel covers are used to provide weather protection for the flanges and to deflect flames away from the exposed exterior web of the girder. This concept was first used for the construction of a 54-story office building in New York City. The design was verified by a wood crib burnout test of a full-scale mockup of one bay of this building. In addition, a second test was conducted by UL using a gas-fired furnace designed to simulate the spandrel girder configuration. Representative fire, flame and girder temperatures are illustrated in Figure 38.

As clearly illustrated by the flame-shielded spandrel girder concept, the "standard" ASTM fire test is not representative of the exposure that would be experienced

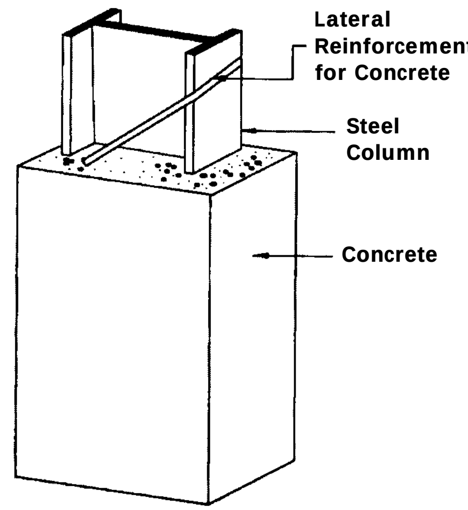

Figure 34. Fire protected exterior steel column with exposed metal column covers. Illustration courtesy of the American Iron and Steel Institute, *Fire Protection Through Modern Building Codes.*

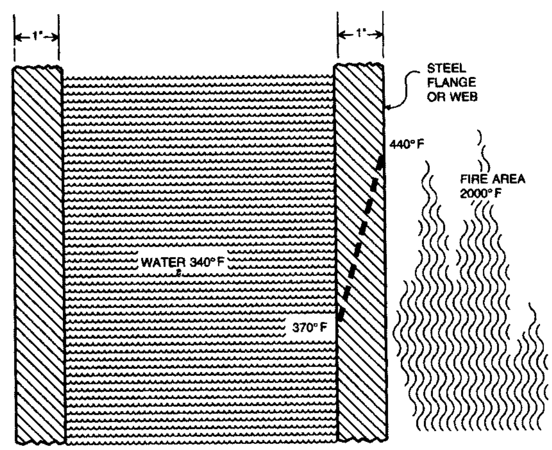

Figure 35. Tubular steel columns filled with water for fire resistance with temperature variation during exposure to fire. Illustration courtesy of the American Iron and Steel Institute, *Fire Protection Through Modern Building Codes.*

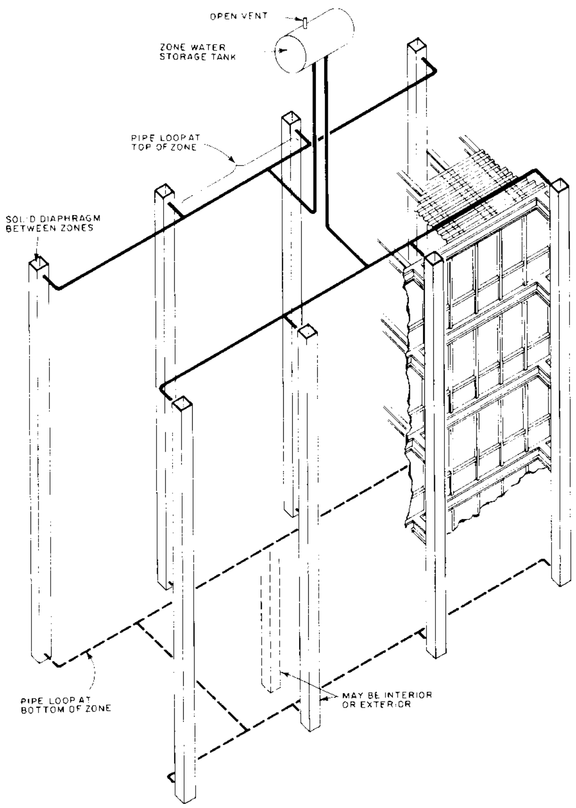

Figure 36. Schematic representation of a liquid-filled column fire protection system. Illustration courtesy of U.S. Steel, *Influence of Fire on Exposed Exterior Steel.*

by exterior columns and girders. Research has been conducted worldwide over the last two decades to better define the appropriate exposure for exterior structural elements. A comprehensive design guide is available from AISI (*Design Guide For Fire-Safe Structural Steel*).

Interior Applications

Each building code defines conditions (occupancy, area and height) when unprotected bare steel framing is permitted. If fire protection is required by the building code, structural steel exposed in the interior of a building may be protected with intumescent paint as described above. In other cases, a requirement to fire protect may be minimized or eliminated by a fire-engineered solution described in a following section.

Another method for fire protecting architecturally exposed columns for both interior and exterior applications involves encasing the members in a concrete-based insulating material that is then protected by an exterior steel jacket. This method is illustrated in Figures 39 and 40.

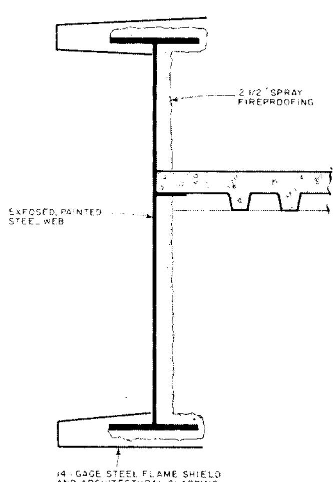

Figure 37. Fire-resistive flame shielding on spandrel girder. Illustration courtesy of U.S. Steel, *Influence of Fire on Exposed Exterior Steel.*

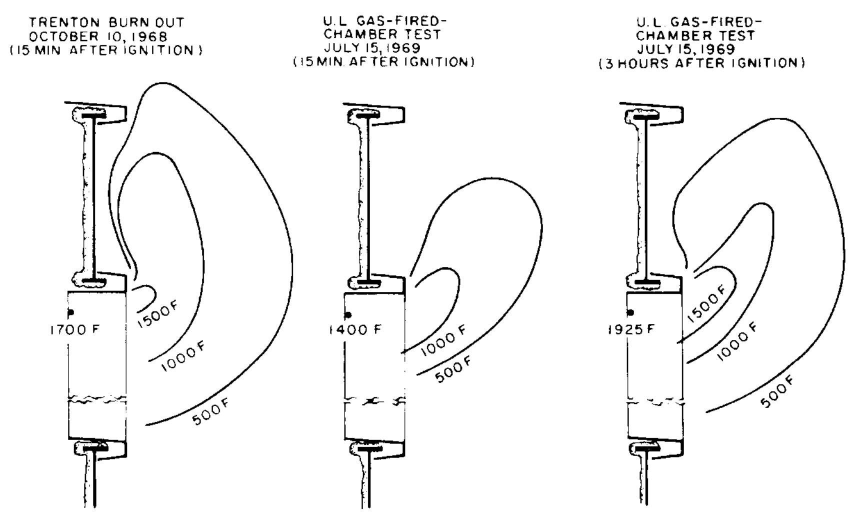

Figure 38. Flame patterns and temperatures during two tests on the load-carrying steel plate girder. Illustration courtesy of U.S. Steel, *Influence of Fire on Exposed Exterior Steel.*

RATIONAL FIRE DESIGN BASED ON FIRE ENGINEERING

As explained previously, North American building code requirements for structural fire protection are currently prescriptive; they are based on "standard" fire tests that do not accurately replicate actual constructed conditions or realistic fire exposures. In many cases, real fires result in higher temperatures but for much shorter duration than assumed by the current codes. As indicated previously, Figure 27 shows the temperature/time curve for the ASTM E119 standard fire test with a constant fuel source as contrasted with time/temperature curves in realistic fire exposures with different fuel loads. In these realistic tests, one can clearly see the higher initial temperatures that soon taper off as the fuel source is consumed and diminishes.

In addition, the standard ASTM fire test presumes that structural floor members are fully loaded at the time of the fire. In reality, fires occur randomly and design requirements should be probability based. Rarely will members be fully loaded to design capacity at the time of the fire.

All model codes recognize the need to encourage engineered solutions to the fire protection of floor-to-roof systems that modify or bypass the prescriptive measure found in the codes. They all allow for engineered solutions as long as they can be soundly substantiated. In fact some of the solutions mentioned above such as flame-shielded spandrel girders, water filled columns and the effect on the fire resistance ratings for steel of steel mass and shape are a result of code acceptance of steel industry research.

Also, fire engineering methods using computer modeling techniques recognized by the building codes are being used successfully under provisions in the codes that allow for alternate methods. Recently the Uniform Building Code added information on full-scale fire tests to establish and document alternate fire protection measures.

Fire engineering usually combines actual building occupancy, contents and actual anticipated floor-to-ceiling construction with fire suppression measures in order to model the predicted performance of the structure under anticipated fire conditions. This is done in order to establish what is necessary to meet the hourly rating required by the code i.e.; 1-hour, 2-hour or 3-hour etc.

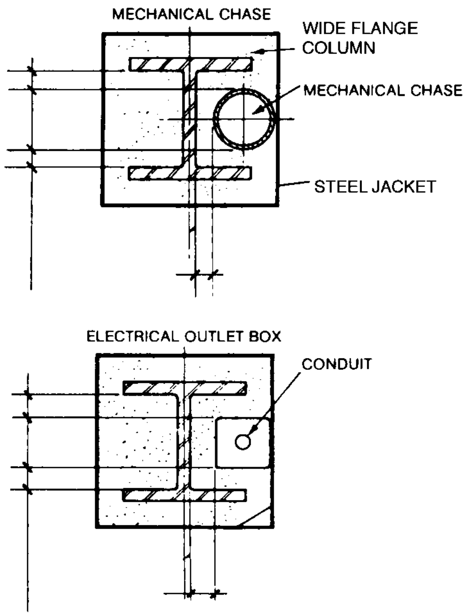

Figure 39. Concrete-based insulating material

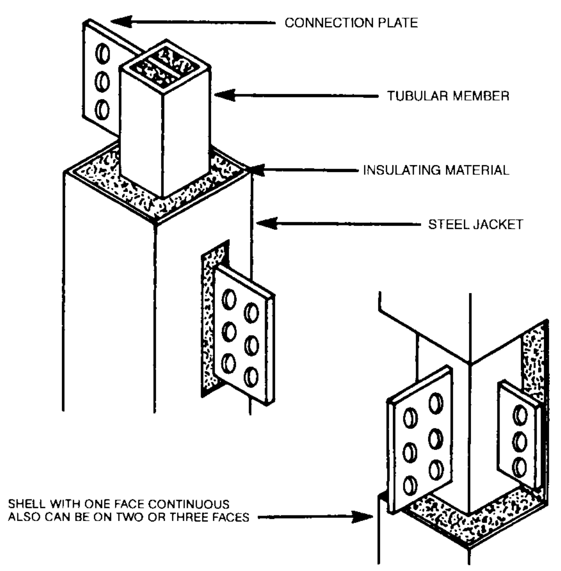

Figure 40. Typical connections in a continuous shell

An engineered solution to the fire protection is often desirable form an aesthetic standpoint such as being able to eliminate fire protection around architecturally exposed columns in the interior of a building. It may be desirable for functional reasons as well. One recent example of fire engineering allowed the elimination of spray-on fire protection on structural steel in a large warehouse storing flammable liquids.

Fire engineering is a specialty normally requiring the additional services of fire protection engineers who understand the performance of steel under elevated temperature conditions. However, for many projects, the incentives in fire protection cost savings are significant and far exceed the additional design costs.

FABRICATION AND ERECTION TOLERANCES

Member Cross-sectional Tolerances

Can out-of-tolerance mill material be adjusted by the fabricator so that it conforms to the appropriate tolerances?

Sometimes. Infrequently, material is discovered after delivery to be beyond mill tolerances. When material received from the rolling mill does not conform to the requirements of ASTM A6/A6M or more restrictive tolerances that are specified in the contract documents, the fabricator can use controlled heating, mechanical straightening, or a combination of both methods, consistent with manufacturer recommendations, to adjust cross-section, flatness, straightness, camber, and/or sweep.

What is the tolerance on depth for built-up girders and trusses?

The appropriate tolerances for the welded cross-section are specified in AWS D1.1-2000 Section 5.23. However, at bolted splices for such members, AWS D1.1-2000 Section 5.23 is silent on this subject. AISC recommends that the permissible deviations for girder depth in AWS D1.1-2000 Section 5.23.9 be applied to depth at bolted splices. Any differences within the prescribed tolerances at such joints should be taken up, if necessary, by shimming.

What is the flatness tolerance for webs of built-up girders?

For members in Statically Loaded Structures, web flatness does not affect the structural integrity of a girder because it primarily resists shear. Accordingly, neither the AISC LRFD Specification nor the AISC *Code of Standard Practice* includes a limitation on the out-of-flatness of girder webs. Such a tolerance is specified for welded plate girders, however, in AWS D1.1-2000 Section 5.23.6.2.

Shrinkage of web-to-flange welds and/or welds that attach stiffeners to the web can create operational difficulties in girder webs, particular those that are less than 5/16-in. thick. Accordingly, the dimensional tolerance for deviation from flatness of a girder web less than 5/16-in. thick, with or without stiffeners, in Statically Loaded Structures should be determined as the larger of 1/2-in. or the value determined in AWS D1.1-2000 Section 5.23.6.2. In Cyclically Loaded Structures, the value in AWS D1.1-2000 Section 5.23.6.3 should be observed. If architectural considerations require a more restrictive flatness tolerance, it should be specified in the contract documents. In all cases, the web thickness specified should be adequate to minimize such distortion.

Member Straightness Tolerances

How are the permissible deviations from straightness described in "Cross-sectional and Straightness Tolerances" accounted for in fabrication and erection?

In most cases, deviations from true straightness and dimension of individual members (within the tolerances specified in ASTM A6/A6M) are compensated for during erection by the relative flexibility of the individual members compared to that of the overall structural steel frame they comprise. In some structures using heavy, rigid cross-sections, however, the stiffness of the member may preclude any adjustment of out-of-straightness that, although within acceptable limits, can prevent tight fit-up of connections. This situation is most likely to occur with multi-story building columns and may cause difficulty in erecting the floor framing members.

Although normal detailing practices may compensate in part for this problem, special shop layout practices are essential for heavy, rigid framing. A straight theoretical working line should be established between member ends as defined by the 2000 AISC *Code of Standard Practice* Section 7.13(c).

What tolerance is applicable for the camber ordinate when beam camber is specified?

As indicated in 2000 AISC *Code of Standard Practice* Section 6.4.4, for members less than 50-ft long, the camber tolerance is minus zero/plus 1/2-in; an additional 1/8 in. per each additional 10 ft of length (or fraction thereof) is allowed for lengths in excess of 50 ft. An exception is also included: members received from the rolling mill with 75 percent of the specified camber require no further cambering. Furthermore it is specified that camber be inspected in the fabricator's shop in an unstressed condition.

What is the tolerance on sweep for curved girders?

Permissible variations in sweep for horizontally curved welded plate girders are specified in AWS D1.1-2000 Section 5.23.5. However, because the method of measurement for this sweep dimension is not defined, the tolerance is sometimes misapplied. The permissible variation specified is the deviation of the theoretical mid-ordinate from a chord through the ends of a single fabricated girder section.

If it is required to hold the ordinate of additional points along the beam within a certain tolerance, these requirements should be specified in the contract documents. Note, however, that most girders have sufficient lateral flexibility to easily permit the attachment of diaphragms, cross-frames, lateral bracing, etc., without damaging the structural member or its attachment.

What is the tolerance on twist of welded box members?

As stated in AWS D1.1-2000 Section 5.23.11.4, "…[the tolerance on] twist of box members … shall be individually determined and mutually agreed upon by the contractor and the owner with proper regard for erection requirements." In the absence of a specified tolerance, an attempt is sometimes made to apply the provisions of ASTM A500 or ASTM A6/A6M. However, the provisions of these material specifications should not be applied to fabricated box members.

In an unspliced member, the necessary tolerance on twist is generally a matter of serviceability or aesthetics. In a member that will be spliced, twist must be kept within limits that will allow safe and uncomplicated erection. Shop assembly of the entire member by the fabricator may be necessary to accomplish this. It is recommended that the fabricator and erector mutually agree on the means and methods necessary to achieve installation of an acceptable member in the completed structure (see the first question under "Other General Information"). Connection details for fabricated box members should accommodate twist in the completed member.

In any case, the required twist tolerance should be specified in the contract documents. Note, however, because of high torsional strength and stiffness, correction of twist in a closed box or similar shape is nearly impossible and carries the potential for damage. If the actual twist of a fabricated member exceeds a specified tolerance, whether to attempt correction should be a case-by-case decision made by the SER.

Element Location Tolerances

Is a tolerance on hole or hole pattern location specified in the 2000 AISC Code of Standard Practice?

No. Neither the ±1/16-in. tolerance, where applicable, on overall length of members framed to other steel parts, nor the 1/16-in. clearance on size of standard holes, should be construed as implying that the tolerance ±1/16 in. also applies either to the maximum tolerance on hole location within a pattern of holes or to the position of intermediate connections.

What is the tolerance on location of intermediate and longitudinal stiffeners?

When intermediate stiffeners are spaced at a distance that is approximately equal to the girder depth, weld shrinkage up to 3/8 in. in a 100-ft-long girder is not uncommon. Furthermore, thermal expansion or contraction in a like length of girder due to a temperature differential of 50° Fahrenheit can cause a change in length of approximately 3/8 in. In view of these and other factors, there is a need for a tolerance on the location of longitudinal stiffeners. Because AWS D1.1-2000 Section 5.23 is silent on this subject, AISC recommends the following criteria:

1. Intermediate stiffeners may deviate from their theoretical location ±2 in. as measured from the girder end.
2. Diaphragm and other connection stiffeners may deviate from their theoretical location by no more than twice the thickness of the stiffener.
3. Longitudinal stiffeners may deviate from their theoretical location by a distance equal to 1 percent of the girder depth.
4. If longitudinal stiffeners are interrupted by vertical stiffeners, the ends should not be offset by more than half the thickness of the longitudinal stiffeners.

When forces are to be transferred by contact bearing, is a gap allowed between the contact surfaces?

From the 1999 AISC LRFD Specification Section M4.4, "Lack of contact bearing not exceeding a gap of 1/16-in. (2 mm), regardless of the type of splice used (partial-point-penetration groove welded or bolted), is permitted." If the gap exceeds 1/16 in., but is less than 1/4 in., and an engineering investigation shows that the actual area in contact (within 1/16 in.) is adequate to transfer the load, then the gap is acceptable. Otherwise, per the 1999 AISC LRFD Specification Section M4.4, the gap must be packed with non-tapered steel shims. Similarly, a tolerance of 1/16 in. for bearing stiffeners is allowed in AWS D1.1-2000 Section 5.23.11.1. Such a gap would presumably be closed under load, bringing the stiffener into full contact bearing.

Erection Tolerances

How do individual member deviations impact the alignment and erected position of the overall structural steel frame?

In many cases, individual member deviations that exceed established tolerances will have no adverse effect on the overall structural steel frame. However, in other instances, individual member deviations may accumulate and cause the overall structural steel frame to substantially exceed the overall permissible tolerances for plumbness, level, and line. It is essential that the effect of individual member tolerances on the overall structural steel frame be recognized and accounted for with practical detailing and fabrication techniques that permit compliance with overall tolerances.

Other General Information

How are tolerances determined if they are not addressed in the applicable standards?

The fabrication and erection tolerances in the AISC LRFD Specification for Structural Steel Buildings, the AISC *Code of Standard Practice for Steel Buildings and Bridges*, AWS D1.1, and other existing specifications and codes have evolved over nearly three-quarters of a century. Although these standards generally present a workable format for the fabricator and erector, they tend to address individual members, rather than the role of individual members in the completed structure.

Tolerances for assemblies, such as those on shop-assembled bents, frames, platforms, pairs of girders, etc., are not covered by any code or standard. AWS D1.1 Section 5.23.11.4 states that "... other dimensional tolerances of members not covered by [Section] 5.23 shall be individually determined and mutually agreed upon by the contractor and the owner with proper regard for erection requirements." This practice is recommended in all cases. The agreed upon tolerances should account for the erection tolerances specified in the AISC *Code of Standard Practice*.

If special or more restrictive tolerances are required for the overall structural steel frame, can they be met?

Possibly, but at a higher cost. Special clearances or tolerances may be difficult or impossible to achieve because of considerations such as temperature change, fabrication and construction procedures, and erection stresses. When specified, such requirements must be identified in the contract documents. The additional cost of special or more restrictive tolerance requirements should be justified.

How can the accumulation of mill, fabrication, and erection tolerances be economically addressed?

While individual member tolerances are usually self-compensating and of minor significance in the overall structure, the possibility exists that these tolerances may accumulate and lead to misalignments that are difficult to correct in the field. As an example of the effect individual member tolerances may have on the total structure, consider the tolerances on columns and beams. Individual column and beam members are shown with their respective permissible tolerances in Figure 2. These tolerances come from several sources: permissible camber and sweep are specified in ASTM A6/A6M and AWS D1.1; permissible variation from detailed length for members framed to other steel parts is specified in the AISC *Code of Standard Practice*; mill tolerances on the cross-sec-

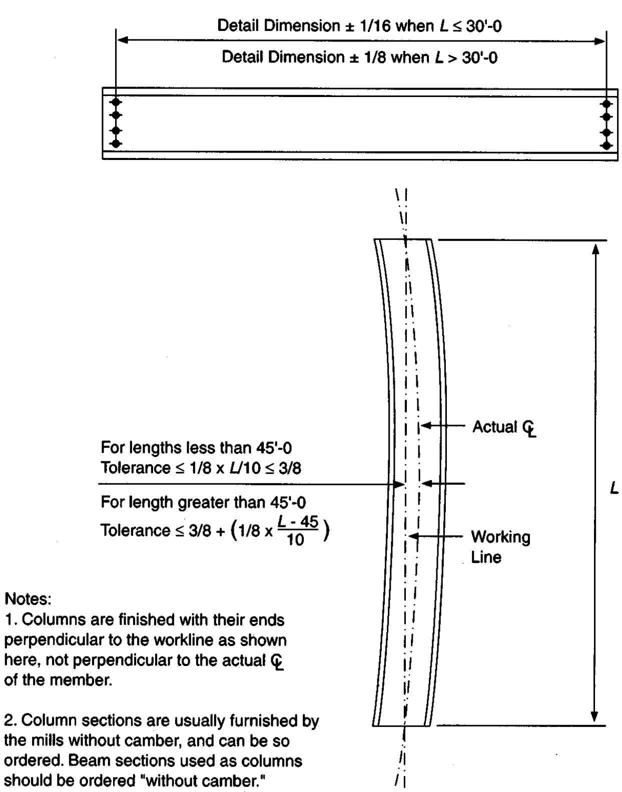

Figure 2. Beam and column fabrication tolerances

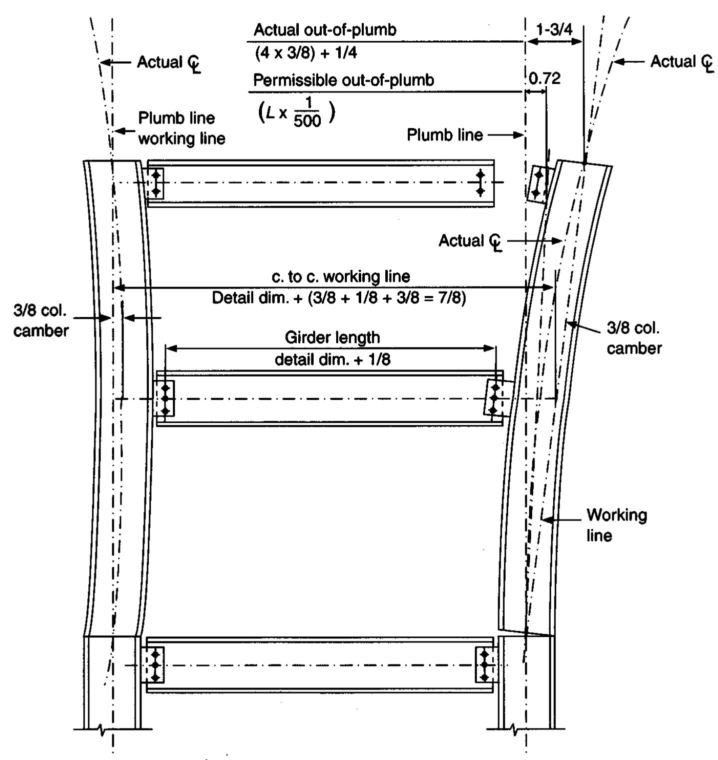

Figure 3. Possible (but unlikely) accumulation of tolerances when details are located from actual centerlines.

tion are illustrated in the 2000 AISC *Code of Standard Practice* Figure C-5.1. The foregoing example involves a possible but highly unlikely scenario.

A case where individual members fabricated within permissible tolerances could make it impossible to erect a heavy two-story column within the plumbness tolerance of ±1:500 is illustrated in Figure 3. Although the condition shown would be unusual and represents the worst case with all member tolerances maximized and accumulated in one direction, it is evident that the accumulation of tolerances requires special consideration. Other possible examples include double-angle and end-plate connections to columns, attached shelf or spandrel angles, large plan dimensions in which many pieces line up, long bracing, expansion joints, and vertical systems such as stairs and multi-story wall panels. Deflections of cantilevered members and tolerance accumulation on complex framing systems involving a long series of connections before the load is in the column (causing accumulation of vertical tolerances) should also be considered.

Details for material supported by the steel framing must provide for the standard tolerances. For example, in buildings with large plans, it is beneficial to develop special details that accommodate the accumulation of fabrication tolerances. Note that building expansion joints cannot be adjusted to proper position without a provision for this adjustment.

The use of oversized holes, short-slotted holes, and long-slotted holes, provided a satisfactory method for achieving erection within tolerances as illustrated in Figures 4 and 5. Other satisfactory methods include the use of finger shims, shop layout to theoretical working lines, and recognition of tolerance accumulation in details for finishes, such as the curtain wall or stonework attachments.

PAINTING AND SURFACE PREPARATION

Painting Requirements

When must structural steel be painted?

As stated in the 1999 AISC LRFD Specification Section M3.1, "Shop paint is not required unless specified by

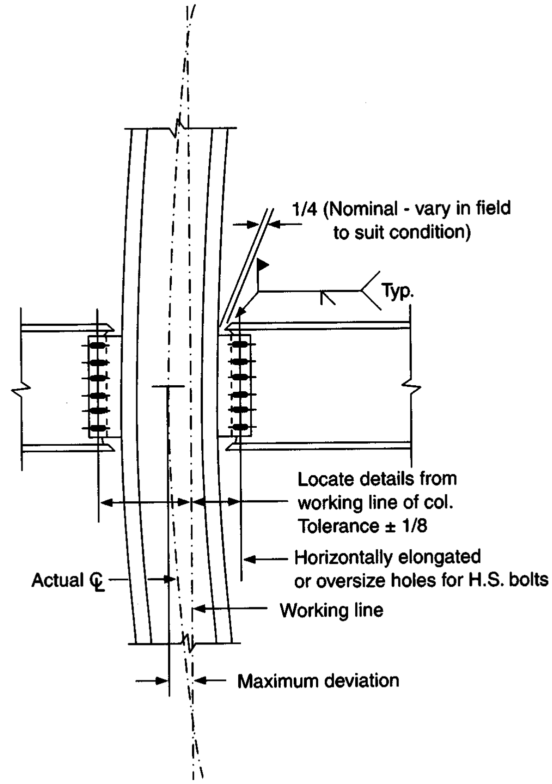

Figure 4. Adjustments for column curvature in beam-to-column connections.

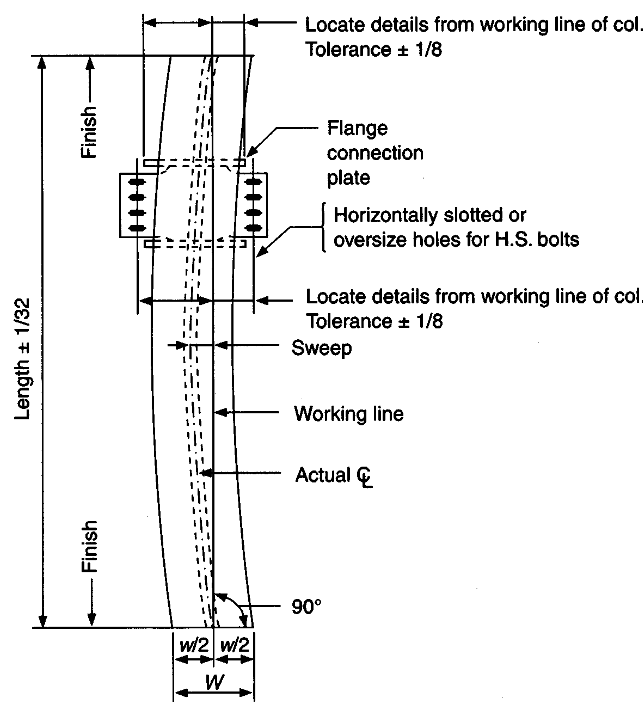

Figure 5. Adjustments for column sweep in beam-to-column connections.

the contract documents." Therefore, fabricated structural steel is left unpainted unless painting requirements are outlined in the contract documents.

In building structures, steel need not be primed or painted if it will be enclosed by building finish, coated with a contact-type fireproofing, or in contact with concrete. When enclosed, the steel is trapped in a controlled environment and the products required for corrosion are quickly exhausted. As indicated in the 1999 AISC LRFD Specification Commentary Section M3, "The surface condition of steel framing disclosed by the demolition of long-standing buildings has been found to be unchanged from the time of its erection, except at isolated spots where leakage may have occurred. Even in the presence of leakage, the shop [primer] coat is of minor influence (Bigos, Smith, Ball, and Foehl, 1954)." A similar situation exists when steel is fireproofed or in contact with concrete; in fact, paint is best omitted when steel is to be fireproofed because primer decreases its adhesion.

In exterior exposed applications, steel must be protected from corrosion by painting or other means. Likewise, steel must be protected from corrosion in special applications such as the corrosive environment of a paper processing plant or a structure with oceanfront exposure.

When a paint system is required, how should it be selected?

When paint is required, SSPC emphasizes the importance of the development of a total paint system. Among the primary considerations for this design decision by the owner, architect, or engineer are:

1. The end use of the member.
2. A realistic estimate of time and severity of exposure of each coat of paint.
3. An economic evaluation of the initial cost as compared to future maintenance cost.
4. A practical determination of the division between shop and field work and responsibilities.

What should be included in contract documents when steel is to be painted?

The following information should be specified when steel is to be painted:

1. The type and manufacturer of the specified paint (one alternative is the fabricator's standard shop primer)
2. The required level of surface preparation (expressed as an SSPC designation, i.e., SP2)
3. The desired dry film thickness

All technical data and directions for application of the specified paint, including required curing time, will be obtained by the fabricator from the paint manufacturer and need not be repeated in the contract documents, other than by reference.

What paint system is implied by the general requirement of a "shop coat" or "paint"?

When contract documents call for a "shop coat" or "paint" without specific identification of a paint system, this is interpreted as the fabricator's standard primer applied to a minimum thickness of 1 mil on steel that has been prepared in accordance with SSPC-SP2, with no conditional performance implied.

Paint Film Thickness

How is paint film thickness determined?

The most commonly used paint-film-thickness measuring devices are wet-film thickness gauges and magnetic instruments for dry-film thickness measurement. When properly used during paint application, a wet film gauge is a direct-reading instrument that furnishes an immediate indication of thickness at a time when inadequacies can be corrected, usually without the need for a full subsequent coat. The residual dry-film thickness can be determined from the wet-film thickness because the percent volume of solids in most paints is known. Alternatively, the correlation can be determined from actual dry-film thickness measurements taken at several areas. The readings of magnetic instruments for measurement of dry film thickness are often misinterpreted because they depend upon a number of variables such as initial calibration, type of cleaning, blast pattern profile, amount of mill scale remaining, and relative hardness of the paint film. However, when properly used, both wet-film and dry-film measurements provide an indication of the thickness of the paint over the peaks of the surface profile.

The primary measuring device for most types of paint should be the wet-film thickness gauge used during actual painting, with proper correlation to the percent volume of solids in the paint being applied. When magnetic instruments are used as a check on the dry film, SSPC-PA2 should be used for the dry-film thickness measurement.

What frequency of paint film thickness inspection is appropriate?

A sampling plan is defined in SSPC-A2 on the basis of the square footage of the structure being painted, which is useful for field painting applications. For sampling in shop painting applications, AISC recommends that 2 members be tested in every 25 tons or each shop layout of pieces to be painted. Any deficiencies in paint thickness or other specification requirements must be called to the attention of the fabricator by the owner/inspector at the time of completion of painting.

Is a thicker paint film thickness than required acceptable?

Yes. Because the specified paint thickness is usually a minimum requirement, greater thickness is permitted if it does not cause excessive mud cracking, runs, sags, or other defects of appearance or function.

Surface Preparation Requirements

What surface preparation should be specified for steel that is to remain unpainted?

Steel that is to remain unpainted need only be cleaned of heavy deposits of oil and grease by appropriate means after fabrication. If other considerations dictate more stringent cleaning requirements, an SSPC-SP2 or other appropriate grade of cleaning should be specified in the contract documents.

What level of surface preparation is specified for painted surfaces in the AISC Code of Standard Practice?

As indicated in the 2000 AISC *Code of Standard Practice* Section 6.5.2, in the absence of other requirements in the contract documents, the fabricator hand cleans the steel of loose rust, loose mill scale, dirt, and other foreign matter, prior to painting, by means of wire brushing or by other methods elected by the fabricator, to meet the requirements of SSPC-SP2 (hand tool cleaning).

Is it permissible for a fabricator to perform surface preparation beyond that called for in the contract documents?

Yes, unless prohibited in the contract documents.

What degree of cleaning is implied when surfaces are indicated to be "blast cleaned"?

When blast-cleaned surfaces are specified in contract documents without identification of the desired degree of cleaning, SSPC-SP6 (commercial blast cleaning) is assumed.

Where are surface cleaning requirements defined?

The acceptance criteria for the degree of preparation are specified in SSPC-VIS-1, The Pictorial Surface Preparation Standards for Painting Steel Surfaces, for all SSPC surface preparation levels (SP1 through SP10).

How is the blast profile inspected?

When blast profile limits are specified, a Keane-Tator profile comparator, or equivalent, is acceptable for spot checking representative production blasting. Note that the specified profile range must be evaluated relative to the profile of the steel prior to blasting. Therefore, the total profile range will usually be greater than the range specified.

When inspection of surface preparation is required, when should such inspection be made?

When inspection is required in the contract documents, it should be made as soon as practical after the surface has been prepared. Inspection should be scheduled to avoid delays in the fabrication shop. Additionally, because the adequacy of surface preparation cannot be readily verified after painting, it should be inspected prior to application of the primer coat.

What edge preparation is required for painting?

Generally none, however, because a wet paint film is drawn by surface tension to a lesser thickness over sharp edges, some paint system specifications for severe exposures call for special edge treatments, such as grinding a light chamfer on sharp edges, striping corners or edges with shop paint to increase film thickness, or grinding corners to a minimum 1/16 in. radius. It should be noted that the term radius has precise meaning and an attempt is sometimes needlessly made to check corners with a radius template and require repairs at corners that do not conform closely to the specified radius. Because there is no significant difference in paint film thickness or life between a beveled corner and a corner that is ground to a small radius such treatment of edges is discouraged unless specified in the bid documents or in the paint manufacturer's directions. When required, edge treatment requirements should be limited to "breaking" the corner (eliminate the sharp 90 degree edge) with no reference to a specific dimension.

SSPC Surface Preparation Levels

What is the appropriate acceptance criteria for surface preparation in accordance with either SSPC-SP2 or SSPC-SP3?

While the 2000 AISC *Code of Standard Practice* Section 6.5.2 calls for the removal of loose rust, loose mill scale, etc., the lack of specific definition (especially as to what constitutes "loose" mill scale) leaves the acceptance criteria subject to varying interpretation for both SSPC-SP2 (hand tool cleaning) and SSPC-SP3 (power tool cleaning). A mutually acceptable standard should be agreed upon by the owner so that the architect or engineer may knowledgeably design the paint system and the fabricator may realistically furnish the degree of surface preparation required.

When SSPC-SP6 surface preparation is specified, what acceptance criteria should be applied?

As stated in SSPC-SP6 (commercial blast cleaning) Section 2.2, "staining shall be limited to no more than 33 percent of each square inch of surface area and may consist of light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale or stains of previously applied paint. Slight residues of rust and paint may also be left in the bottoms of pits if the original surface is pitted." Because specifying this requirement for each square inch is impractically restrictive, AISC recommends that this requirement be applied instead to the total surface area.

When SSPC-SP10 surface preparation is specified, what acceptance criteria should be applied?

As stated in SSPC-SP10 (near-white blast cleaning) Section 2.2, "staining shall be limited to no more than 5 percent of each square inch of surface area and may consist of light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale or stains of previously applied paint." Because specifying this requirement for each square inch is impractically restrictive, AISC recommends that this requirement be applied instead to the total surface area.

Field Touch-up and Repair

How should contract documents address the problem of job-site mill-scale flaking?

When SSPC-SP2 (hand tool cleaning) or SSPC-SP3 (power tool cleaning) surface preparation is specified and a short-exposure-life prime coat is subsequently applied, tight mill scale generally remains on the surface prior to shop painting. Likewise, tight mill scale may remain with SSPC-SP7 (brush-off blast cleaning) surface preparation. Depending upon the time of exposure, job-site conditions, and type of prime coast, some of this tight mill scale may loosen, resulting in mill-scale flaking. When required, provision should be made in the contract documents for an appropriate field touch-up and repair program. Traditionally, this work has been delegated to the painting contractor.

Is the fabricator/erector responsible to clean steel after it has been erected?

No. Shop-painted steel that is stored in the field pending erection should be kept free of the ground and so positioned as to minimize water-holding pockets, dust, mud, and other contamination of the paint film. However, because site conditions are frequently muddy, sandy, dusty, or a combination of all three, it may be impossible to store and handle the steel in such a way as to completely avoid accumulation of mud, dirt, or sand on the surface of the steel. When required, provision should be made in the contract documents for an appropriate cleaning program.

Is the fabricator/erector responsible for field touch-up to the repair of blemishes and abrasions that result during handling and storage after painting?

No. During storage, loading, transport, unloading, and erection, blemishes and abrasions caused by slings, chains, blocking, tie-downs, etc. occur in varying degrees and should be expected. Responsibility for field touch-up should be assigned in the contract documents. Traditionally, this work has been delegated to the painting contractor.

Other General Information

When welded surfaces are to be painted, what considerations are required?

Some by-products of welding may be detrimental to paint performance and should be removed or neutralized prior to painting. Slag, chemical residue, and spatter compounds other than weld metal that are determined to be incompatible with the coating system should be removed or neutralized. Compatible residue, spatter compounds, and spattered weld metal that cannot be removed by hand scraping need not be removed provided that it is not detrimental to the performance of the structure or paint system.

FIRE PROTECTION

Fire Protection Systems

What surface preparation should be specified for steel that is to be fireproofed?

Steel that is designated to receive a field-applied contact-type fireproof coating should be shop cleaned of dirt, oil, grease, and loose mill scale by appropriate means. Rust, dirt, and other materials that might impair bond that accumulates between the time of fabrication and the time of application of the fireproof coating is not the responsibility of the fabricator/erector; such responsibility should be assigned in the contract documents.

Fire Exposure

What procedures should be followed when assessing steel that has been exposed to a fire?

Dill (1960) concludes that, while exposure to fire will almost certainly cause warping and twisting of members, it does not inevitably follow that the strength of the steel is reduced. It is almost certain that any steel that has been heated hot enough to undergo damaging grain coarsening or that has been cooled rapidly enough to harden it will be so badly distorted that it would have no consideration for re-use anyway. This leads to the general statement that steel that has been through a fire but that can be made dimensionally re-usable by straightening with the methods that are available may be continued in use with full expectation of performance in accordance with its specified mechanical properties. Essentially then, the question is one of economics: if the steel can be straightened for less money than fabricating and installing a new piece, then that should be done.

Two possible exceptions to the above include quenched and tempered structural steels and high-strength fasteners. The mechanical properties of such heat-treated items may be affected by prolonged fire exposure and should be tested to determine the effects of the fire, if any.

Another reference is Council on Tall Buildings and Urban Habitat (1980).

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COMMON QUESTIONS ANSWERED

This section of the Appendix contains a listing of frequently asked questions (FAQs), along with answers. The reader is encouraged to visit www.aisc.org/faq.html for a more comprehensive and regularly updated listing of FAQs. Additionally, the reader is encouraged to visit the quality certification portion of www.aisc.org for questions on quality certification.

DEFINITIONS

The following terms and abbreviations appear throughout the text of this section. In general, defined terms are capitalized in the text.

AESS Architecturally exposed structural steel, as defined in the AISC *Code of Standard Practice* Section 10

AISC American Institute of Steel Construction

ANSI American National Standards Institute

ASCE American Society of Civil Engineers

ASME American Society of Mechanical Engineers

ASTM American Society of Testing and Materials

AWS American Welding Society

CMTR Certified mill test report

HSS Hollow structural section

Mill The steel material manufacturer

RCSC Research Council on Structural Connections

SER Structural Engineer of Record

SSPC Steel Structures Painting Council

Statically Loaded Structures. Structures subject to loading that characteristically is slowly applied and removed, as would be typical in building, sign, and tower structures; dead, live, wind and similar loads are generally considered to be static

Cyclically Loaded Structures. Structures subject to loading that is applied and/or removed at a rate that cannot be considered to be static and requires consideration of fatigue, as would be typical in bridge structures and crane runways

MILL PRODUCTION AND TOLERANCES

Cross-sectional and Straightness Tolerances

Where are the (mill) dimensional tolerances for structural shapes and plates given?

Permissible variations for structural shapes and plates as received from the mill are established in ASTM A6/A6M-01 Section 12. These historically developed standard tolerances define the acceptable limits of variation from theoretical dimension for the cross-sectional area, flatness, straightness, camber, and sweep for rolled sections.

It should be noted that cross-sectional tolerances are expressed as a percentage of weight or area, not as tolerances on dimensions such as the flange and web thicknesses.

Generally, standard fabrication practice accommodates these structurally acceptable variations. In special cases such as high-rise construction, the accumulation of mill tolerances may require consideration in design by the SER. If more restrictive tolerances are required, they must be specified in the contract documents.

Surface Condition

Where are the permissible variations in surface condition for structural shapes defined?

ASTM A6/A6M-01 Section 9 defines the permissible variations in the surface condition for structural shapes and plates in the as-rolled condition. It should be recognized that surface imperfections, such as seams and scabs, within these specified limits may be present on material received at the fabrication shop; particularly on heavy-weight cross-sections because of higher finishing temperatures and production difficulties. Certain steel chemistries, such as that for ASTM A588, will also exhibit a higher incidence of surface imperfections.

Special surface-condition requirements must be specified in the contract documents. Material purchased to meet the requirements of ASTM A6/A6M is usually subject to acceptance or rejection based upon visual inspection both at the rolling mill and at the time of receipt by the fabricator, although more extensive inspection methods may be used. This inspection is important because mills normally limit their contractual liability to replacement or credit. Because occasional surface imperfections may be discovered after the fabricator's acceptance of mill material, particularly after blast cleaning, any requirements for remedial work should also be specified in the contract documents.

What corrective procedures are available to the mill when variations in surface condition do not meet specified tolerances?

ASTM A6/A6M-01 Section 9 specifies limited conditioning that the mill may perform when as-rolled material does not meet specified tolerances. Note that it further states that "conditioning of imperfections beyond the [specified] limits ... may be performed by [the fabricator] at the discretion of [the fabricator]".

Unless required in the contract documents, code-compliant surface imperfections generally need not be repaired or removed if they are not detrimental to the strength of the member. When required, they may be repaired by grinding or welding. The responsibility for any required repairs should be assigned in the contract documents so that it is clearly understood by all parties involved, including the owner's representative (e.g., general contractor), fabricator, erector, and painter.

How should edge discontinuities in mill material be treated?

Non-injurious edge discontinuities in Statically Loaded Structures need not be removed or repaired, unless otherwise specified in the contract documents. Injurious defects, such as a longitudinal discontinuity that will be subjected to through-thickness loading, should be repaired by welding and/or grinding. The requirements for treatment of such edge discontinuities must be clearly specified in the contract documents and the repair procedure should be approved by the SER.

In Cyclically Loaded Structures, the provisions of AWS D1.1:2000 Section 5.15.1.2 for edges that are to be welded are appropriate for non-welded edges, except that:

1. With the approval of the purchaser, discontinuities need not be explored to a depth greater than 1 in. When the depth of a discontinuity exceeds 1 in., the discontinuity should be gouged out to a depth of 1 in. beyond its intersection with the surface and repaired by the deposition of weld metal as indicated in AWS D1.1:2000 Section 5.15.1.1.
2. For discontinuities over 1-in. long, with depth exceeding 1/8 in. but not greater than 1 in., the discontinuity must be removed and repaired, but no single repair should exceed 20 percent of the length of the edge repaired.

Ordering Steel

What information is required to be reported in a Certified Mill Test Report (CMTR)?

The information required to be reported in a CMTR is as given in ASTM A6/A6M-01 Section 14. This includes but is not limited to the steel grade and nominal sizes supplied and tension test results. This document may be in written form or, per ASTM A6/A6M-01 Section 14.8, transmitted electronically.

What must the specifier indicate when material is subject to a domestic purchasing requirement?

When a domestic purchasing requirement is in effect for a given project, the specifier must indicate in the contract documents and purchase order that material must be melted and manufactured in the United States of America.

When a project is subject to a metric design requirement, what shapes are available?

ASTM A6M, the metric equivalent of ASTM A6, covers the metric series of structural shapes that is in use in the United States. Because it is a soft metric conversion, the metric series is physically identical to the inch-pound-unit shape series. The dimensions are given in millimeters (mm) with mass expressed in kilograms (kg); note that the mass must be multiplied by the acceleration of gravity 9.81 m/s^2 to obtain kilonewtons (kN).

Note that a soft conversion is made by directly converting the U.S. customary unit value to a metric equivalent, for example, 1 in. equals 25.4 mm; conversely, a hard conversion is made by selecting new values in round metric increments, such as replacing 1 in. with 25 mm.

To what ASTM Specifications are hollow structural sections (HSS) ordered?

ASTM A500 grade B (although ASTM A500 grade C is increasingly very common) and A847 are appropriate when specifying square, rectangular, and round HSS. These specifications cover cold-formed production of both welded and seamless HSS; ASTM A847 offers atmospheric corrosion resistance properties similar to that of ASTM A588 for W-shapes. Pipe-size rounds (P, PX, and PXX) are also available in ASTM A53 grade B material.

Other General Information

Color combinations are commonly used to indicate various steel grades. Where are these color combinations established?

Colors that identify the various grades of structural steel are currently established in ASTM A6/A6M-01 Section 18.6; for example, green and yellow for ASTM A572 grade 50 steel, blue and yellow for ASTM A588 steel and green and black for ASTM A992 steel. Note that it is anticipated that color coding will no longer be required in future versions of ASTM A6/A6M.

Where are chemistry requirements for structural steel specified?

Chemistry limitations and requirements are specified in the ASTM specifications for structural steels, such as ASTM A36, A572, A588, etc. Steel producers are required to report steel chemistry for each heat of steel produced on a CMTR (see the first question in the Ordering Steel section).

Structurally, is there a difference between a 1/2 x 4 bar and a 1/2 x 4 plate?

Structurally, none; furthermore, plate is becoming a universally applied term today. However, the historical classification system for such structural material would suggest the following physical difference: all four sides of a 1/2 x 4 bar would be rolled edges, i.e., the mill rolled it to that thickness and width. A 1/2 x 4 plate will have been cut from a 1/2-in. plate of greater width either by shearing or flame cutting.

What are the common length limits on structural steel members as ordered from the mill?

Common mill lengths range from 30 ft to 65 ft in 5-ft increments. However, because individual mill practices and standards vary, it is best to consult with individual mills directly. When steel is purchased from a warehouse, the selection of available lengths may be further limited. Additionally, the method of shipment may also limit the available length.

GENERAL FABRICATION

Material Identification and Traceability

What is required for the identification of material?

Identification means the ability to determine that the specified material grade and size is being used. An identification system is required in the 1999 AISC LRFD Specification Section M5.5: " The fabricator shall be able to demonstrate by a written procedure and by actual practice a method of material application and identification, visible at least through the "fit-up" operation, of the main structural elements of a shipping piece. The identification method shall be capable of verifying proper material application as it relates to:

1. Material specification designation
2. Heat number, if required
3. [CMTR] for special requirements [if required]."

What is the difference between traceability and identification of material?

Traceability means the ability to identify a specific piece of steel in a structure, throughout the life of the structure, and its specific CMTR. As such, traceability requirements are significantly more expensive than the identification requirements in the previous question. The owner should clearly understand the differences, limitations, and relative costs involved.

Traceability is not a requirement in the AISC LRFD Specification and, when required, must be clearly specified in the contract documents prior to the ordering of material. The following elements of traceability should be selected only as needed:

1. *Lot traceability vs. piece-mark traceability vs. piece traceability:* Lot traceability means that the materials used in a given project can be traced to the set of CMTR's for that project. Piece-mark traceability means that the heat number can be correlated for each piece mark, of which there can be many individual

pieces. Piece traceability means that the heat number can be correlated for each piece, which effectively demand separate piece marks for each piece.

Each of these three successive levels of traceability adds significant costs. Piece traceability, the most expensive option, is necessary only in critical applications, such as the construction of a nuclear power facility. Piece-mark traceability is often specified for main members in bridges. Lot identification is most common in other applications where traceability is required.

2. *Main-material traceability vs. all-material traceability:* Main-material traceability means that beams, columns, braces, and other main structural members are traced as specified above. All-material traceability means that connection and detail materials are also traced as specified above.

   All-material traceability, the more expensive option, is necessary only in critical applications, such as the construction of a nuclear power facility. In other cases, main-material traceability is sufficient, when traceability is a requirement.

3. *Consumables traceability* means that lot numbers for consumables such as bolts, welding electrodes, and paint can be traced. This is necessary only in critical applications, such as the construction of a nuclear power facility.

4. *Required record* retention defines the level of detail required in documenting traceability (who, what, when, where, how, etc.).

5. *Fool-proof record retention vs. fraud-proof record retention:* Fool-proof record retention means internal verification of records. Fraud-proof record retention means external certification of records. Fraud-proof record retention is necessary only in critical applications, such as the construction of a nuclear power facility. In other cases, foolproof record retention is sufficient, when traceability is a requirement.

How does a fabricator maintain traceability, when it is required?

Each heat of steel produced by the mill is tested for chemical content and mechanical properties and the results are recorded on a CMTR, which is provided to and maintained in the records of the fabricator. Each piece that is rolled from this heat is then labeled with an identification mark that relates to the corresponding CMTR. The fabricator applies an identification mark to each piece. Because this piece mark remains with the piece throughout the fabrication and erection process, the material is traceable back to the CMTR for that individual piece.

Many connecting elements and similar fittings are too small to accommodate the marks to identify the piece from which they were cut. Additionally, such items are commonly made from stock materials with marks that may have inadvertently been abraded or lost during years of storage. In such cases, the fabricator provides written certification that the stock material meets the contract requirements.

Manufacturers of consumables such as bolts, welding electrodes and paint provide documentation as to the content and specification compliance of their products. This documentation is provided to and maintained in the records of the fabricator. The packaging in which the products are shipped is referenced to this documentation.

In some cases, the fabricator may purchase materials through a warehouse. When this is the case, the warehouse must transmit the necessary documentation from the manufacturer to the fabricator.

Cutting and Finishing Steel

What methods are available for cutting steel and what is the corresponding range of utility for each?

The following methods are commonly used to cut steel:

1. Friction sawing, which is performed with a high-speed rotary blade, is commonly used by steel producers and is limited only by machine size. This cutting method, however, is no longer commonly used in fabrication shops.
2. Cold sawing, whether by rotary saw, hack saw, or band saw, is limited only by machine size.
3. Oxygen-acetylene (and related fuel) flame cutting, which can be mechanically or hand-guided, is commonly used for general cutting and edge preparation operations, such as coping, beveling, notching, etc.; its utility is virtually unlimited.
4. Plasma cutting, which is mechanically guided, is generally useful for cutting plate of up to 3/4-in. thickness.
5. Laser cutting, which is mechanically guided, is generally useful for cutting plate; thickness limitations vary.
6. Shearing, which is performed with mechanical presses, is generally useful for cutting plates and angles and is limited only by machine size and capacity.

Additional minor material removal and finishing may also be accomplished by one of the methods listed in the next question.

What methods are commonly used to provide finished surfaces, when required?

Some of the cutting methods in the previous question result in surfaces that are finished without further treatment. When this is not the case, the following methods are commonly used to provide finished surfaces:

1. Milling, which is commonly used to bring members to their required length and end finish.
2. Face machining, which can be used to finish large areas to exact dimensions.
3. Planing.
4. Grinding, which is commonly used for edge preparation, including treatment of flame-cut edges, removal of burrs, etc. when required.

Can the end of a column, as received from the rolling mill, be considered to be a finished surface?

Yes, provided the mill cut is at right angles to the column axis and meets the surface roughness requirements in ASME B46.1.

Is it commonly necessary to mill bearing surfaces after sawing?

No. As stated in the 1999 AISC LRFD Specification Section M2.6, "compression joints which depend on contact bearing ... shall have the bearing surfaces of individually fabricated pieces prepared by milling, sawing, or other suitable means." The 2000 AISC *Code of Standard Practice* Section 6.2.2 Commentary states that "Most cutting processes, including friction sawing and cold sawing, and milling processes meet a surface roughness limitation of 500 per [ASME B46.1]." Cold-sawing equipment produces cuts that are more than satisfactory.

What constitutes acceptable thermal cutting practice?

Structural steel preferably should be thermally cut by mechanically guided means. However, mechanically guided cutting may not be feasible in some cases, such as the cutting of copes, blocks, holes for other than bolt holes, and similar cuts. Accordingly, hand-guided thermal cutting should be allowed as an alternative. Regardless, thermally cut surfaces must meet the appropriate roughness limitations as summarized in the next question.

What are the appropriate roughness limitations for thermally cut edges?

Inadvertent notches or gouges of varying magnitude may occur in thermally cut edges, depending upon the cleanliness of the material surface, the adjustment and manipulation of the cutting head, and various other factors. When thermally cut edges are prepared for the deposition of weld metal, the 1999 AISC LRFD Specification Section M2.2 and AWS D1.1-2000 Section 5.15.1.1 provide acceptance criteria that consider the effect of discontinuities that are generally parallel to the applied stress on the soundness of welded joints. Additionally, correction methods for defects of various magnitudes are stipulated therein. When thermally cut edges are to remain unwelded, the following surface condition guidelines are recommended:

1. If subjected to a calculated tensile stress parallel to the edge, edges should, in general, have a surface roughness value not greater than 1,000 as defined in ASME B46.1.
2. Mechanically guided thermally cut edges not subjected to a calculated tensile stress should have a surface roughness value not greater than 2,000 as defined in ASME B46.1.
3. Hand-guided thermally cut edges not subjected to a calculated tensile stress should have a roughness not greater than 1/16 in.
4. All thermally cut edges should be free of notches (defined as a V-shaped indentation or hollow) and reasonably free of gouges (defined as a groove or cavity having a curved shape). Occasional gouges not more than 3/16-in. deep are permitted.

Gouges greater than 3/16-in. deep and all notches should be repaired as indicated in the next question.

When surface roughness for thermally cut edged does not meet the limitations in the previous question, how is the surface repaired?

Roughness exceeding the criteria in the previous question and notches not more than 3/16-in. deep should be removed by machining or grinding and fairing-in at a slope not to exceed 1:2½. The repair of notches or gouges greater than 3/16-in. deep by welding should be permitted. The following criteria are recommended:

1. The discontinuity should be suitably prepared for good welding.
2. Low-hydrogen electrodes not exceeding 5/32-in. diameter should be used.
3. Other applicable welding requirements of AWS D1.1 should be observed.
4. The repair should be made flush with the adjacent surface with good workmanship.
5. The repair should be inspected to assure soundness.

To what profile must re-entrant corners, such as corners of beam copes, be shaped?

Re-entrant corners should provide a smooth transition between adjacent surfaces, but generally need not be cut exactly to a circular profile. The recommendation in the 3rd Edition AISC LRFD Manual (Part 9) is that an approximate minimum radius of 1/2 in. is acceptable. However, the primary emphasis should be that square-cut corners and corners with significantly smaller radii do not provide the smooth transition that is required. From the 1999 AISC LRFD Specification Section J1.6, it is acceptable to provide radius transitions by drilling (or hole sawing) with common-diameter drill sizes (not less than 3/4 in.) as suggested in the 1999 LRFD Specification Commentary Figure C-J1.2.

When the corner of a cope has been square-cut, a common solution is to flame-cut additional material at the corner to provide a smooth transition as illustrated in Figure 1. Note that the sides of the cope need not meet the radius transition tangentially. Any notches that occur at re-entrant corners should be repaired as indicated in the previous section, "Cutting and Finishing Steel".

Use of Heat in Fabrication

Is it permissible to use controlled heat to straighten, curve, or camber structural steel shapes?

Yes. AWS D1.1-2000 Section 5.26.2 permits heat-straightening of members that are distorted by welding and stipulates rules for this procedure. These rules are equally applicable for all heat straightening or curving. Furthermore, the 1999 AISC LRFD Specification Section M2.1 and a discussion in the 3rd Edition AISC LRFD Manual (Part 2), provide a sound basis for the use of controlled heat to straighten, curve, camber, and form structural steel. The proper control of heat application generally involves the use of rosebud tips on torches to disperse the applied flame and temperature indicating crayons or similar devices to monitor the induced temperature.

Is it permissible to accelerate cooling of structural steel after the application of controlled heat?

Yes, provided heated steel for Cyclically Loaded Structures is first allowed to cool ambiently to 600° Fahrenheit. Because the maximum temperature permitted by the 1999 AISC LRFD Specification Section M2.1 for heating operations is below any critical metallurgical temperature for the material being heated, the use of compressed air, water mist, or a combination thereof should be permitted to accelerate the final cooling of the heated. For members to be used in cyclically loaded structures (i.e., where fatigue and toughness are design issues) it is recommended that such accelerated cooling not begin until the temperature has dropped below 600° Fahrenheit. This limitation is more historical than technical in nature. As a fair balance between the desires of the fabricator and the concerns of the owner, it provides an added safeguard to prevent the abuse of excessive cooling and undesirable residual stresses should accepted procedures not be strictly monitored.

Bolt Holes

What are the acceptable methods for making bolt holes?

Acceptable methods for making bolt holes include:

1. Punching
2. Sub-punching and reaming
3. Drilling
4. Hole sawing
5. Flame piercing and reaming
6. Flame cutting, subject to surface quality requirements as discussed in the next question.

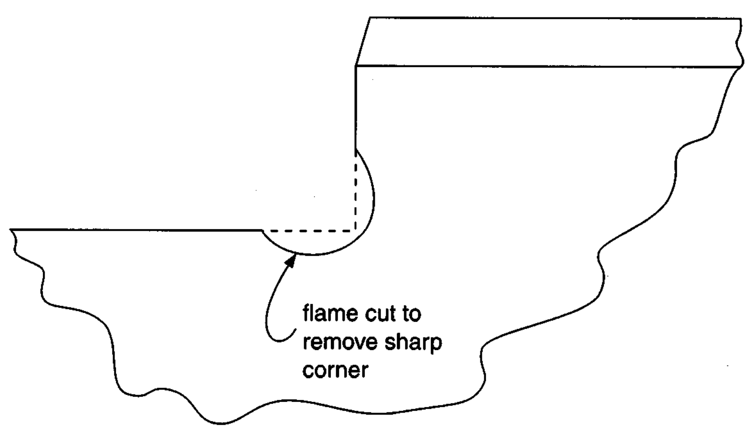

Figure 1. Correction of square-cut copes.

What variation in profile is generally acceptable for bolt holes?

The slightly conical hole that naturally results from punching operations is acceptable, as noted in Table 3.1 of the 2000 RCSC Specification. The width of slotted holes that are produced by flame-cutting, or a combination of punching or drilling and flame-cutting should generally be not more than 1/32-in. greater than the nominal width except that gouges not more than 1/16-in. deep are permitted. In Statically Loaded Structures, the flame-cut surface need not be ground smooth; for Cyclically Loaded Structures, the flame-cut surface must be ground smooth.

Must burrs be removed in bolted connections?

From the 2000 RCSC Specification Section 3.4, "Burrs that extend 1/16 in. or less above the surface are permitted to remain on the faying surfaces of snug-tightened joints…[and pretensioned joints]. Burrs that extend over 1/16 in. above the surface shall be removed from all joints. Burrs that would prevent solid seating of the connected plies prior to the pretensioning of slip-critical joints … shall be removed." From RCSC Bolt Bulletin No. 5, "… burrs are not detrimental to the performance of bearing connections. [In slip-critical connections] if burrs are so small that they are flattened during the snugging, it is not necessary that they be removed." It is further stated therein that larger burrs can remain if extra care is taken in the bolt installation process to achieve the proper bolt tension.

Correction of Fabrication Errors

Must fabrication errors always be repaired?

No. Because the human element is involved in all phases of structural steel fabrication, material inadvertently may be cut to the wrong length, holes may be misplaced, parts may be located incorrectly, or notches or gouges may occur. However, many such errors or deviations need not be altered or repaired and are acceptable without change or penalty to the structure or its end use. Furthermore, some repair work may be more detrimental, as would that which creates higher residual stresses. In general, the SER should evaluate the deviation and whether it would be detrimental to the end use of the product.

In some cases, repair will be required and can usually be made so that the member will meet all performance criteria. Corrective measures to meet the requirements of shop drawings and specifications may generally be made by the fabricator during the normal course of fabrication, using qualified personnel and procedures that meet AISC and AWS specifications. Such action is considered to be a part of the fabricator's quality control program and should not require either notification of, or approval from, the owner or SER. However, in cases where major work is involved (cutting or removal of welded members from a welded assembly, modification of design, deviation from critical dimensions, etc.), the SER must be consulted and a plan of corrective action agreed upon.

What repair is appropriate for material that is cut too short?

When material is short of the minimum required length, welded splices or deposited weld metal, when applied with appropriate welding procedures and specified material, should be permitted with the approval of the SER.

What repair is appropriate for mislocated bolt holes?

Generally, mislocated fastener holes are not detrimental to the strength of a member if the remaining effective net section is adequate for the loads. As such, they may be left open, filled with bolts, or plug welded in accordance with AWS D1.1-2000 Section 5.26.5 with the approval of the SER. Ultrasonic inspection is not generally required for plug-welded fastener holes. Alternatively, if a bolt hole is mislocated by a small amount, say less than a bolt diameter, it is often possible to adjust the connection material to accommodate the error.

What repair is required when a minor member mislocation occurs?

When detail parts are placed in error, minor mislocations should be investigated to determine if relocation is necessary. When relocation is necessary, such as when dimensions are critical, the error is major, or the incorrectly placed part is visually unacceptable under an AESS requirement, the incorrectly placed part should be removed. For a welded detail, flame cutting, gouging, chipping, grinding, or machining may be required. Care should be taken to avoid damage to the main material of the associated member. The surface of the main material should be ground smooth and repaired, if necessary.

What is "moderate reaming" as indicated in the 2000 AISC Code of Standard Practice Section 7.14?

During the course of erection, it occasionally becomes necessary to ream holes so fasteners can be installed without damage to the threads, resulting in a hole that is larger than normal or elongated. The hole types recognized by the AISC and RCSC Specifications are standard, oversized, short-slotted, and long-slotted, with nominal dimensions as given in the 1999 AISC LRFD Specification Table J3.3. From the 2000 AISC *Code of Standard Practice* Section 7.14 Commentary, "the term "moderate" refers to the amount of reaming, grinding, welding or cutting that must be done on the project as a whole, not the amount that is required at an individual location. It is not intended to address limitations on the amount of material that is removed by reaming at an individual bolt hole, for example, which is limited by the bolt-hole size and tolerance requirements in the AISC and RCSC Specifications." Note that reamed holes must meet the provisions for minimum spacing and minimum edge distance in the 1999 AISC LRFD Specification Sections J3.3 and J3.4, respectively.

When more major misalignments occur, it is indicated in the 2000 AISC *Code of Standard Practice* Section 7.14 that they are "... promptly reported to the [owner] and the fabricator by the erector, to enable the responsible entity to either correct the error or approve the most efficient and economical method of correction to be used by others."

Other General Information

What precautions are required when cold bending material with sheared or flame-cut edges?

When cold bending plates or performing other operations involving cold bending and a sheared or flame-cut edge, care must be taken to preclude the initiation of cracks at the edge. Minimum inside radii for cold bending plates of various steel grades are indicated in AISC 3rd Edition LRFD Manual Table 10-12 (Part 10). It is indicated in the corresponding text therein that the tabular values may have to be increased when bend lines are parallel to the direction of final rolling or longer than 36 in. Additionally, the Manual states that "Flame-cut edges of hardenable steels should be machined or softened by heat treatment. Nicks should be ground out and sharp corners should be rounded."

What are the common length limits on fabricated structural steel members?

The maximum length of a fabricated assembly is primarily limited by shipping and erectability concerns, such as overall length and total weight. However, because individual practices and capabilities vary, it is best to consult with the fabricator directly.

The common solution to a member length concern is a splice, which may be necessary and/or desirable for fabrication, shipping, and/or erectability considerations. When approved by the SER, fabricator-initiated splices in members are acceptable.

Common steel items, such as metal deck and open-web steel joists, are not considered to be structural steel in the 2000 AISC Code of Standard Practice. Why?

Even though items such as metal deck and open-web steel joists may be provided by the structural steel fabricator, they are not considered to be structural steel because they are neither manufactured nor fabricated by the structural steel fabricator. As such they are listed in Section 2.2 as "other steel or metal items". Items that are normally part of the fabricator's work are listed as structural steel items in Section 2.1.