Stainless Steel Inspires Design Metamorphosis

by Catherine Houska and Kirk Wilson

Stainless steel structural elements have become increasingly important in cutting-edge international design. The range of applications is broad and includes prominent monuments, elegantly detailed glass and stainless curtain walls, striking pedestrian bridges and attractive structures that will be admired for generations. In addition, stainless steel's corrosion resistance and other unique properties make heightened security, safety, durability and longevity possible.

Europe and Japan have made the most extensive use of stainless steel in architectural structural design, but there have been many impressive projects throughout the world. Stainless steel's structural advantages made innovative design breakthroughs possible in the construction of India's new Parliament Library and Bangkok's new International Airport. North America is home to the world's largest structural architectural stainless steel projects and many remarkable smaller designs. Architects can take advantage of the design possibilities by reviewing project examples and learning about stainless steel's unique design characteristics.

Design evolution

Stainless steel has been used for architectural applications since its invention in the early 1900's. There are older structural applications, but the first very large structural application was The Gateway Arch in St. Louis, Missouri, USA (**Figure 1**). It remained the largest in the world (based on weight) until the construction of the National Archives of Canada in Ottawa, Ontario, Canada (**Figure 2**).

Figure 1: The Gateway Arch in St. Louis, Missouri, USA was completed in 1965 and is made of welded 6.3 mm (0.25 inch) Type 304 plate. Photo courtesy of US National Parks Service

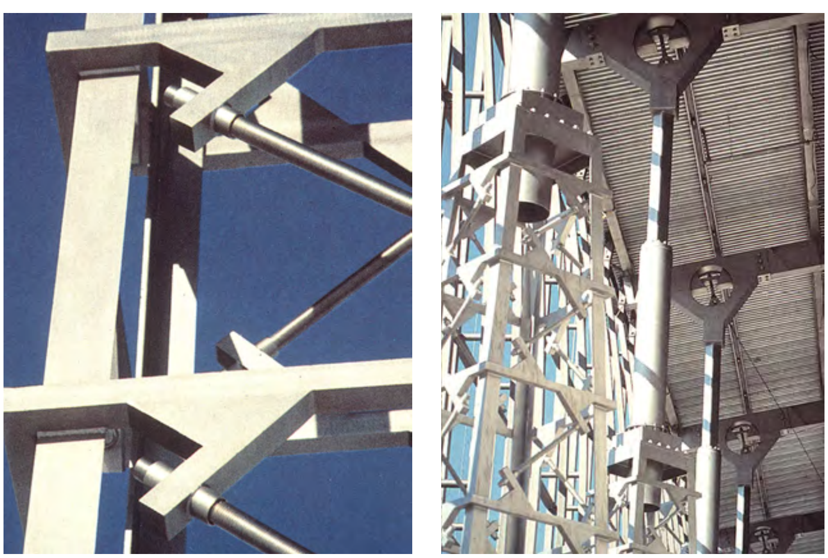


Figure 2 A and B: National Archives of Canada in Ottawa, Ontario, Canada was completed in 1994 and used 2,800 metric tons of types 304 and 316 stainless steel. Photos courtesy of Nickel Institute

In the 1980's, projects like I.M. Pei's Louvre Pyramid (**Figure 3**), with its innovative, low-profile stainless steel and glass design, and J.O. Spreckelsen's La Défense Grande Arch, with its multi-story elevator supports, inspired architects to use similar concepts and helped spur increased interest in stainless steel for structural elements. There have been tremendous innovations since then, which have enabled architects and structural engineers to significantly minimize visible structural supports.

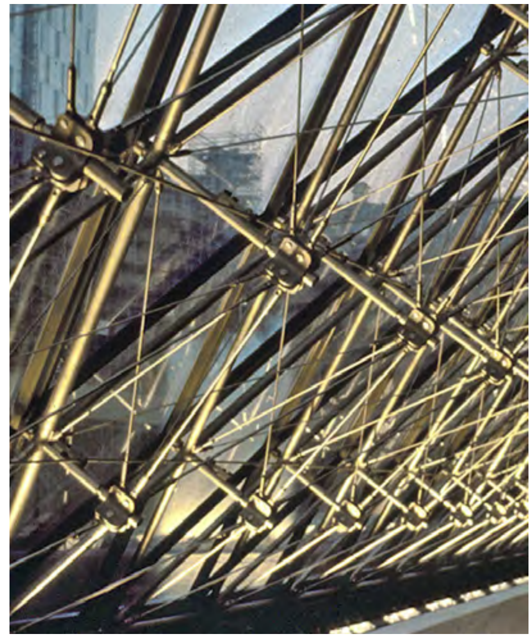


Figure 3 A and B: I. M. Pei's glass and stainless pyramid entrance for the Musée du Louvre used several different stainless steels (type 316, Nitronic 50, and 17-4 PH) to create this trend-setting design. Photos courtesy of TriPyramid

These concepts have been applied to a wide range of applications. One example is an elegant glass and Type 304 stainless steel circular stair built for a Chicago penthouse (**Figure 4**). The tremendous design advances are particularly evident when the Louvre Pyramid (1989) is compared with the cube-shaped entrance to Apple's new flagship store (2006) in New York City. Specifically, there has been a tremendous reduction in the visibility of the stainless steel structural components during this period.

Figure 4: This attractive circular stair in a Chicago penthouse uses Types 304 and 316 structural components, glass, and a wood railing. Photo courtesy Brian Gulick

Comparing properties

Stainless steel is in the European, Australian, and Japanese structural design codes and structural shapes are included in widely used international standards and specifications. The stainless steels generally included in the structural design codes are[1]:

- Types 304/304L (UNS S30400/S30403, EN1.4301/1.4307, SUS 304);
- Types 316/316L (UNS S31600/S31603, EN 1.4401/1.4404, SUS 316); and
- 2205 (UNS S32205/S31803, EN 1.4462, SUS 329J3L).

There are some fundamental differences between carbon and stainless steel structural components. Unprotected carbon steels will begin to corrode quickly in most exterior applications, so protective coatings (e.g. paint) are necessary to prevent structural deterioration. This introduces maintenance requirements and precludes the ability to use fine structural detailing as an aesthetic design feature. In contrast, stainless steels are produced for both corrosion resistance and strength. If the stainless steel is properly specified, coatings are unnecessary and jewelry-like structural detailing can be used as a design feature (**Figure 5**).

In structural design, both strength and elongation have to be considered. **Table 1** shows the ASTM standards for carbon and stainless steel shapes, and **Table 2** shows minimum and typical yield and tensile strength levels. The typical strength levels were obtained by reviewing published data for heavier plate from several stainless steel producers. The lowest reported values are shown. The minimum yield strength requirements for carbon steel in industry standards are very close to the typical properties, so there is little reserve strength.

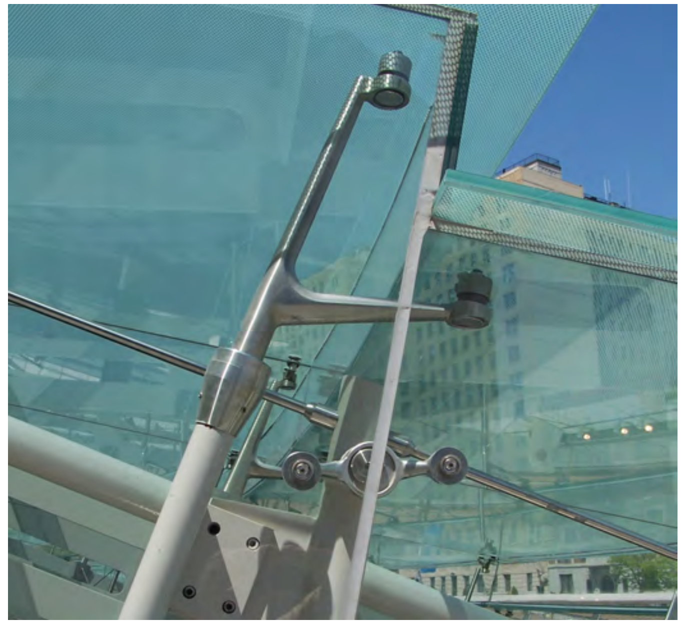


Figure 5: The new entrance for the Brooklyn Museum of Art (New York, USA) used type 316 couplers and 17-4PH castings to create jewelry-like detailing. Photo courtesy of TriPyramid

Table 1: ASTM International Mechanical Property Specifications

Product Form	Carbon Steel	Stainless Steel
Plate, sheet, strip	A 36	A 240
Shapes	A 992	A 276
Mechanical Tubing	A 500	A 554 (304/316), A 789 (2205)

Table 2: Comparison of Minimum and Typical Mechanical Properties

Steel	Young's Modulus kN/mm^2 (x1000 ksi)	Yield Stress Min. (Typical) MPa [ksi]	Tensile Stress Min. (Typical) MPa [ksi]	Elongation Min. (Typical) percent
Carbon Steel				
A 36	200 (29)	250 [36] (275 [40])	400 [58] (412 [60])	23
A 992	200 (29)	344 [50]	448 [65]	
A 500 Gr. B	200 (29)	290 [42]	400 [58]	23
Stainless Steel (1, 2)				
304/316	200 (29)	205 [30] (303 [44])	515 [75] (586 [85])	25 (56)
2205	200 (29)	448 [65] (510 [74])	620 [90] (724 [105])	25 (30)

1) The stainless steel yield strength is measured at 0.2 percent strain offset.
2) Published data for heavier plate from several producers were reviewed. These are the lowest typical tensile or yield strength values reported by any of these suppliers.

With stainless steels, different combinations of strength and corrosion resistance may be needed depending on the severity of the location, temperature, pressure, and cyclic loading requirements. The minimums shown in most stainless steel standards are highly conservative, showing the lowest strength levels attainable after full heat treatment. For many structural shapes, designers can obtain strength levels well above the published minimum. The minimum elongation levels that are required in the industry standards are also significantly lower than what is actually achieved in production.

Suppliers should be contacted to determine the yield strength and elongation levels that are readily achievable. Designers can potentially specify a yield strength that is 50 percent higher than the minimum requirements for Types 304 or 316, and over 10 percent higher for 2205. During project specification, the appropriate industry standard should be identified along with the required higher minimum strength levels.

For projects that use smaller structural shapes, even higher strength levels are possible. Cold-forming (shaping the metal while cold) can produce substantially higher strength levels than what is possible for heavy sections. (*See ASTM A 666, Standard Specification for Annealed or Cold-worked Austenitic Stainless Steel Sheet, Strip, Plate, and Flat Bar.*)

Fire Resistance

Stainless steel retains its stiffness better than carbon steel at elevated temperatures. **Figure 6** shows the stiffness retention behavior of stainless and carbon steels. [2] By 800°C (1472°F), carbon steel has a stiffness retention level of about 10 percent, while stainless steel retains approximately 60 percent. This higher level of retained stiffness can make it possible to avoid fire insulation. Although the densities of these metals are similar, there are thermal expansion differences that need to be considered during design (**Table 3**).

Figure 6: Relative stiffness retention at elevated temperature

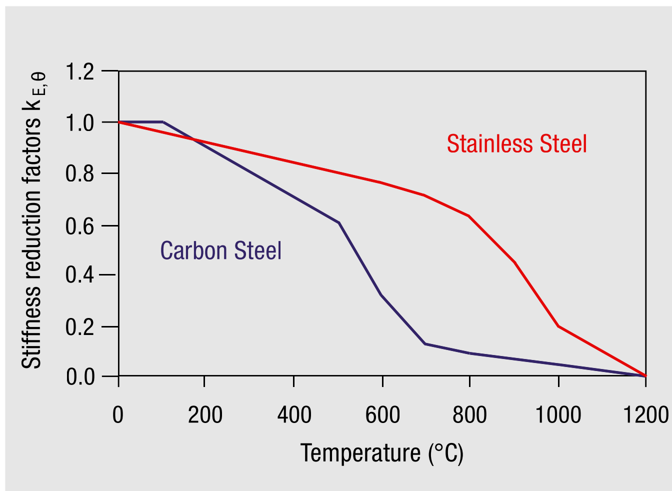


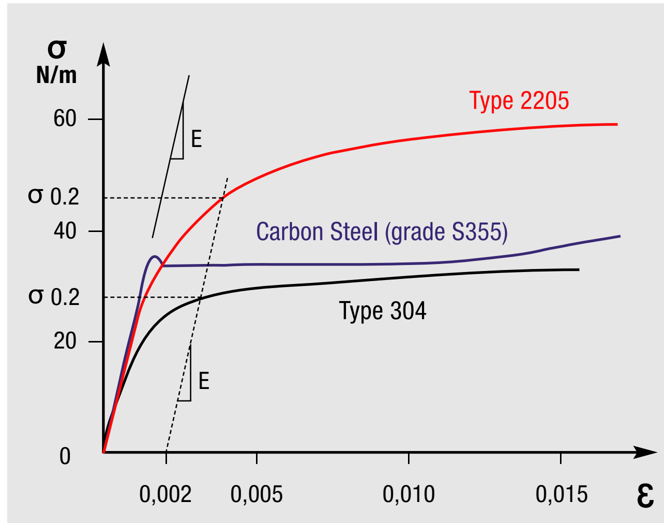
Table 3: Physical Properties

Type	Density		Thermal Expansion 20 to 100°C	(68 to 212°F)
	g/cm^3	oz/in^3	(10^{-6}/°C)	(10^{-6}/°F)
A 36/ A 992/ A 500	7.7	4.5	12	6.6
316	8.0	4.6	16.5	9.2
2205	7.8	4.5	13	7.2

Seismic Performance

In seismic zones, designers must consider the high strain levels that could be placed on structural materials. Unlike carbon steels, which reach a ‘stress plateau’ after achieving the yield point, stainless steel’s strength continues to increase providing an additional safety factor (**Figure 7**). In short, the harder you pull on stainless, the stronger it gets.

Figure 7: Comparison of stress-strain behavior of carbon versus stainless steels



Nisshin Steel Research Laboratory

Nisshin Steel’s research laboratory in Osaka, Japan was constructed prior to the nearby 1995 Kobe earthquake [7.2 Richter magnitude]. **Figure 8** shows the building’s exposed and undamaged structural stainless steel beams following the earthquake. Stainless steel has been used in Australia, North America, Europe and Japan for reinforcing existing structures and for new applications in seismic zones.

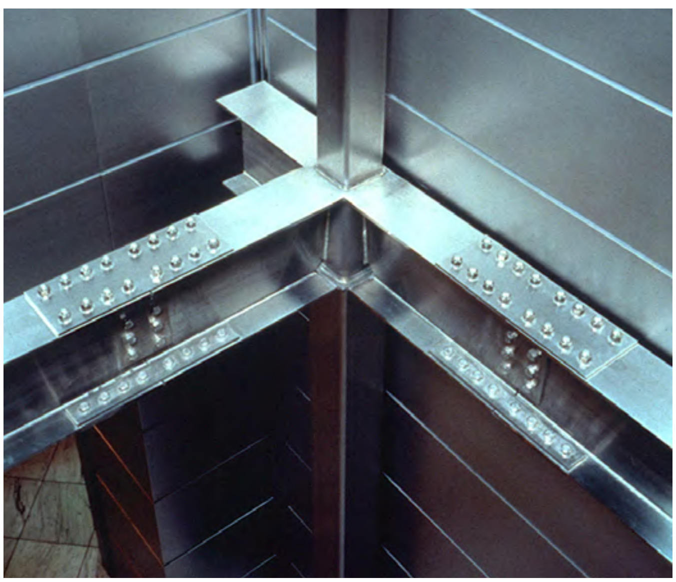


Figure 8: The stainless steel beams in Nisshin Steel’s research laboratory in Osaka, Japan were not damaged by the 1995 earthquake. Photo courtesy Nickel Institute, Catherine Houska photographer

Australian Masonry Failures

Wood, stone, and masonry provide long service lives, but can be quite corrosive to galvanized carbon steel fasteners and structural components, particularly if they are exposed to salts (chlorides). The potential for large-scale catastrophic failure is significant in seismic zones. During Australia’s Newcastle earthquake (1989), there were extensive masonry wall failures. A number of these failures were caused by galvanized steel wall tie corrosion like that shown in **Figure 9**. As a result of this failure analysis, Australia began requiring Type 316 stainless steel wall ties for coastal installations. Even when buildings are not in seismic zones, many countries require stainless steel masonry wall ties when there is deicing or coastal salt exposure.

Figure 9: Australia’s Newcastle earthquake in 1989 caused masonry walls to collapse and the exposed galvanized wall tie corrosion was identified as the cause of these failures. Photo courtesy Noel Herbst

Saint Pio of Pietrelcina Church
The Renzo Piano Building Workshop worked with the structural engineering firm Arup to design the Saint Pio of Pietrelcina Church in Foggia, Italy. It uses a series of independent stone arches and stainless columns and struts to support its wooden roof structure (**Figure 10**). The combination of wood, Type 316L stainless steel, and stone structure is aesthetically appealing, but it is also designed to withstand seismic events. Completed in 2004, the building's stainless steel structural members help to create a feeling of transparency and lightness. The stone mortar was reinforced with stainless steel fibers, creating a stone structure capable of dissipating the energy produced by earthquakes.

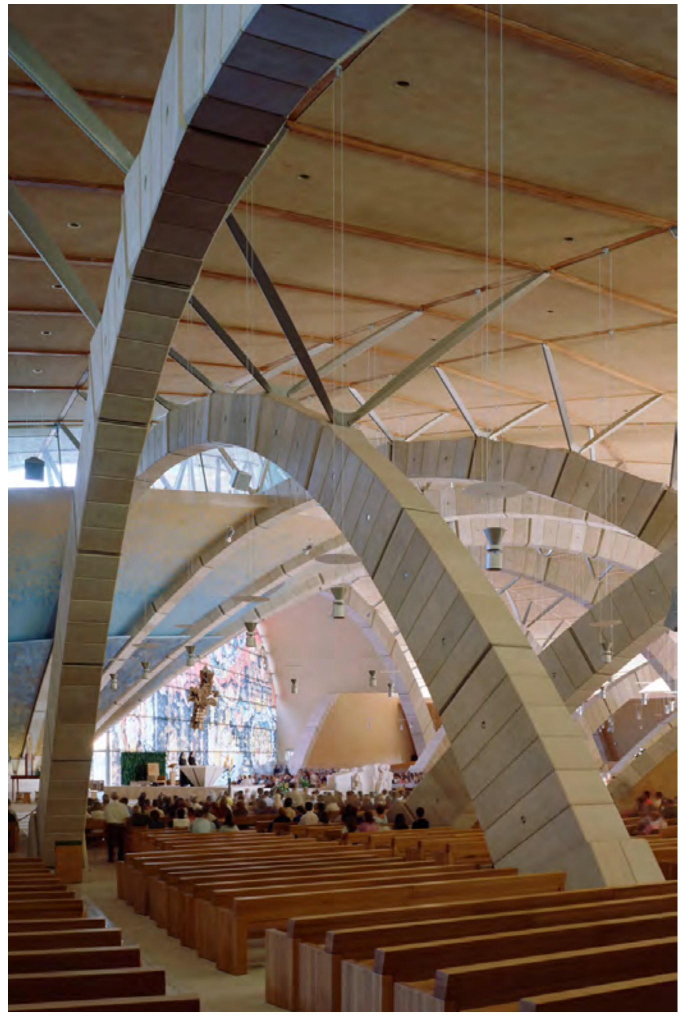


Figure 10 A and B: Saint Pio of Pietrelcina Church in Foggia, Italy, used Type 316 to withstand seismic loads while creating an open airy design. Photo courtesy Centro Inox

Fabrication

If a design includes welding, a structural stainless steel welding code should be referenced in the project specifications to ensure a structurally sound product and define requirements such as welder qualification and inspection. One example is American Welding Society (AWS) D1.6, *Structural Welding Code – Stainless Steel*. Carbon steel structural welding codes are not appropriate and should not be used. Mechanically fastened designs should reference appropriate industry stainless steel fastener standards, and galling must be considered if future fastener removal may be required.

Corrosion Resistance

Stainless steel's high level of corrosion resistance provides a significant aesthetic and structural design advantage. Crisp structural details can be used as prominent design elements instead of masking them under layers of paint. The ability to eliminate maintenance recoating makes stainless steel a low-maintenance material with a long, cost-effective service life.

There are numerous articles and industry association brochures that can be very helpful in stainless steel selection.[3] Type 304 is appropriate for most interior and mild outdoor applications. Type 316 is usually selected for applications with low to moderate coastal or deicing salt exposure and/or moderate industrial or higher urban pollution levels. High-strength duplex 2205 offers a significant increase in corrosion resistance over Type 316 and should be considered for more corrosive locations or where maintenance cleaning is difficult or costly.

Smoother surface finishes retain fewer corrosive deposits, which improves corrosion performance and minimizes the possibility of unattractive staining. Regular maintenance cleaning to remove corrosive deposits will help to prevent surface staining on any stainless steel. In salt-laden environments, it is important to seal Types 304 and 316 mechanical joints using welding or good quality construction sealants to prevent crevice corrosion.

Project Examples

The Grande Arch Lifts at La Défense

Completed in 1982, J. O. Spreckelsen and architect François Deslaugiers' Grande Arch (**Figure 11**) design takes maximum advantage of the unique characteristics of high-strength duplex stainless steel to create supports for the structure's elevator towers. The design is essentially a series of slender, superimposed, boat masts that create a web-like appearance. Stainless steel was selected for the project because of its structural characteristics (high yield and fatigue strength), minimal maintenance, and long-term performance. Both mirror-like and brushed finishes were used to highlight different elements of the design.

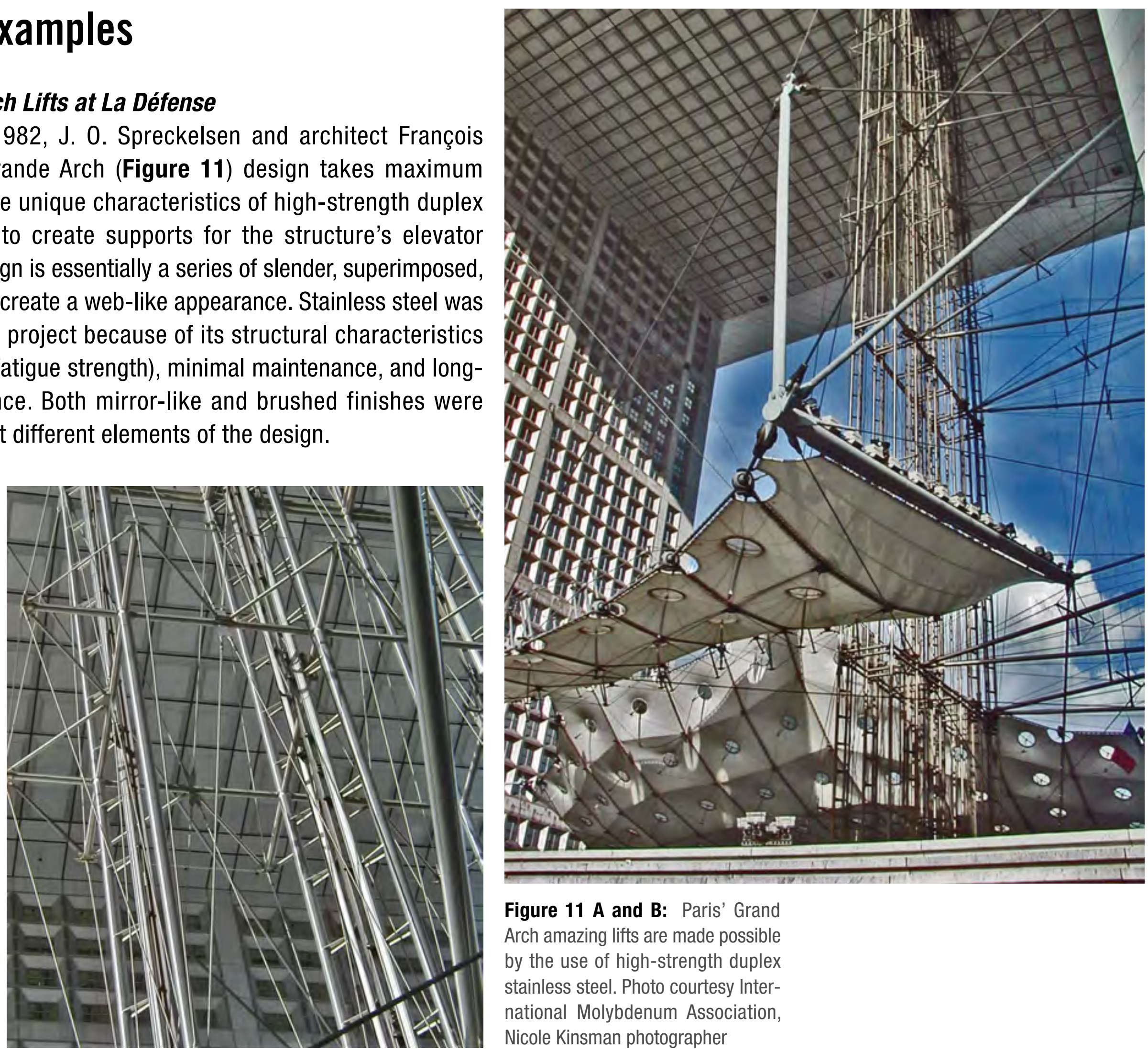


Figure 11 A and B: Paris' Grand Arch amazing lifts are made possible by the use of high-strength duplex stainless steel. Photo courtesy International Molybdenum Association, Nicole Kinsman photographer

7 World Trade Center

7 World Trade Center (7WTC) was the last building to fall in the aftermath of the terrorist attacks on New York City's twin towers on September 11, 2001 and the first to be rebuilt (**Figure 12**). Building replacement occurred quickly to restore the electrical transformer substation housed in the original building and provided needed class 'A' office space. Completed in 2006. The new 52-story office tower was designed by Skidmore, Owings & Merrill LLP (SOM) to emphasize life-safety by surpassing building code standards.

This included increasing the structural performance standards of the perimeter wall, while creating an open, transparent lobby. These seemingly different requirements were met by using high-strength duplex stainless steel and Type 316. The storefront glazing and doors are set below a girder and within a grid of mullion posts. Both the girder and posts are made from built-up 2205 plate. Built-up, type 316 plate beams cantilevered from the girder support the glass canopy, and the type 316 cable net wall above it is supported at the ceiling and sidewalls.

"High-strength duplex grade 2205 alloy stainless steel was necessary to accommodate the tremendous loads imposed on these stainless steel framing elements by the tensioned stainless steel cables, maintain desired minimal visual sightlines, and meet the enhanced structural performance standards", said SOM's Christopher Olsen, AIA. The 2205 has a fine directional brushed surface finish. The visibility of welded joints was minimized and some built-up assemblies were mechanically joined with concealed fasteners.

Figure 12: 7 World Trade Center (7WTC) uses high strength duplex 2205 to create an open, transparent lobby while enhancing life-safety. Photo courtesy International Molybdenum Association, Catherine Houska photographer

Figure 13: Helical Bridge uses Type 316 and glass to create a movable pedestrian bridge. Photo courtesy Christopher von der Howen

Helical Bridge

Sculptor Marcus Taylor designed Helical Bridge (**Figure 13**) with structural engineers Happold Mace. It is one of several stainless steel pedestrian bridges completed in London, England in 2004. This compelling stainless steel and glass pedestrian bridge is located over a small canal. The covered bridge is 7 m (23 ft) long, and 3.5 m (11.5 ft) in diameter. Type 316 hollow sections were bent into a spiral shape to give the tube-shaped bridge its form. They provide anchorage for the glass panels and offer visual interest. A retracting mechanism is concealed from view. It is actually a 'drawbridge' that appears to corkscrew into the bank as it is retracted to permit boats to pass. Type 316 was selected due to the bridge's exposure to brackish water.

Woodland Bridge

Gray Organschi Architecture worked with Edward Stanley Engineers LLC to design a sustainable woodland pedestrian bridge that would visually blend into the environment (**Figure 14**). Its elegant, wooden, serpentine deck has Type 304 structural supports to reduce visual impact. The thin tube columns supporting the structure are grouted into the bedrock of the ravine, eliminating bulky supporting footings, and blending with the surrounding tree trunks. Stainless steel's corrosion resistance made this supporting detail possible. The wooden deck of the bridge is glued-laminate (glulam) and has stainless steel railings and fittings. Structural corrosion failure is a common problem when carbon steel is in contact with damp wood, but this is not an issue with stainless steel. There is no need for regular maintenance and long service life is ensured.

Figure 14: This Type 304 and wood bridge was designed to be environmentally sensitive, provide long service life, and blending into the landscape. Photo courtesy Edward Stanley, Edward Stanley Engineers, LLC.

Apple Cube

Completed in 2006, the 'Apple Cube' is the entrance to the firm's flagship store in New York City, USA. It appears to be essentially all glass (**Figure 15**). This very complex, minimal design makes extensive use of small, high-strength duplex 2205 structural members, which visually blend with the glass to further decrease their visibility. Highly polished squares of Type 316 on the exterior are used to create the spots of light in the matrix.

A spectacular curving stainless steel and glass staircase and elevator bring customers into the below-grade level store (**Figure 16**). The stair handrails and most of the other interior hardware are Type 304. The handrail tabs and connection components and the straps that join the cylindrical glass pieces to the outer stair balustrade and the inner elevator drum are duplex 2205 for added strength. The architect for this project was Bohlin Cywinski Jackson and Eckersley O'Callagham was the structural engineer.

Figure 15: The 'Apple Cube' is the entrance to the firm's flagship store in New York City and achieves its light airy structure by supporting the glass with high strength duplex 2205 and Type 316 stainless steel. Photo courtesy TriPyramid Structures, Inc, Midge Eliassen photographer

Figure 16: The staircase below the apple cube uses high-strength duplex 2205 to secure the glass stair treads and Type 304 for railings and other details. Photo courtesy TriPyramid Structures, Inc, Midge Eliassen photographer

Schubert Club Band Shell

The attractive and deceivingly simple lines of the Schubert Club band shell in St. Paul, Minnesota USA, make it an elegant destination for open-air concerts. Completed in 2002, the band shell is on Raspberry Island in the middle of the Mississippi River (**Figure 17**). James Carpenter Design Associates and structural engineers Skidmore, Owings & Merrill LLP (SOM) and Schlaich Bergermann realized that a corrosion- and wind-resistant structural design was necessary. The resulting band shell is a double curved 7.6-m (25-ft) wide stainless steel and glass lattice that spans 15.2 m (50 ft) between two concrete piers. The island is subject to flooding and a nearby highway bridge exposes the band shell to deicing salts. Additionally, public park maintenance is minimal. For that reason, designers chose Type 316 for the structural framing.

Figure 17 A and B: Schubert Club band shell used Type 316 and glass to create a design that is resistant to high winds, deicing salt from a nearby highway bridge, and seasonal flooding. Photos courtesy James Carpenter Design Associates and Shane McCormick

Kimmel Center

Rafael Viñoly Architects created Kimmel Center in Philadelphia, USA. It is a unidirectional cable net structure (**Figure 18**). The innovative design was completed in 2001 and reduced the visible support structure by half relative to the more typical two-way cable net wall. The sophisticated design keeps constant tension on each cable, reducing the amount of steel required to support each arch. The semi-circular wall has a 25.9-m (85-ft) radius that works like a jib on a sailboat. As the wind blows, the 'sail' fills and the center of the wall moves until the force on it is equal to the wind pressure. The center of the wall can move as much as 0.76 m (2.5 ft). This is ten times the deflection of a rigid wall. The hardware is Type 316 stainless steel.

Figure 18 A and B: Kimmel Center is a unidirectional cable net structure. Type 316 stainless steel helped to make this design possible. Photos courtesy E. Dennis and Raphael Vinoly Architects

The U.S. Air Force Memorial

The late Jim Freed of Pei Cobb Freed won the U.S. Air Force Memorial's design competition with an amazing bomb-burst flight formation-inspired design and then worked with the structural engineering firm Arup to make it a reality. Completed in 2006, the sculpture (**Figure 19**) is located on the hillside where the Wright brothers first demonstrated airplanes to the US Army.

The sculpture is a highly visible addition to the Washington, DC, skyline. Three spires ranging in height from 64 m (210 ft) to 82 m (270 feet) curve upward and outward supported entirely at their bases. The spires are composed of welded, 19-mm (0.75-in.) thick Type 316 plate with a custom, multi-step finish that meets daytime low reflectivity requirements while illuminating beautifully at night. Their elegant, curved shape make them one of the world's most challenging stainless steel structural designs to date. A damping system is used to counterbalance the vibration that might occur otherwise with exposure to normal wind levels.

Figure 19 A and B: The U.S. Air Force Memorial features three curved spires of welded, 19-mm (0.75-in) thick, Type 316 plate measuring up to 82 m (270 f) tall. Photo courtesy Patrick McCafferty

Conclusion

Continued innovations in stainless steel structural design will allow designers and engineers to create even more compelling structures that capitalize on the use of bare metal to express details as sculptural design elements. This unique aesthetic advantage is the result of selecting appropriate stainless steels to provide long service life and low maintenance requirements. The resulting designs are not only spectacular, but also wonderful examples of sustainable architecture.

Notes

1 See "Design Manual for Structural Stainless Steel-Third Edition", EuroInox, Building Series, Vol. 11, 199 pages.
2 See L. Gardner and K. T. Ng's "Temperature development in structural stainless steel sections exposed to fire," *Fire Safety Journal*. Also see G. Waller and D.J. Cochrane's "Stainless Steel for Durability, Fire-resistance and Safety", *Nickel Institute Technical Series.*
3 "Which Stainless Steel Should Be Specified for Exterior Applications?," Catherine Houska, International Molybdenum Association (IMOA); "Stainless Steels in Architecture, Building and Construction: Guidelines for Corrosion Prevention," Catherine Houska, Nickel Institute "Stainless Steel Selection for Exterior Applications," Catherine Houska, *The Construction Specifier* (January 2003) and "Architectural Metal Corrosion: The Deicing Salt Threat," Catherine Houska; *The Construction Specifier*. (December 2006); and www.stainlessarchitecture.org and www.imoa.info.

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