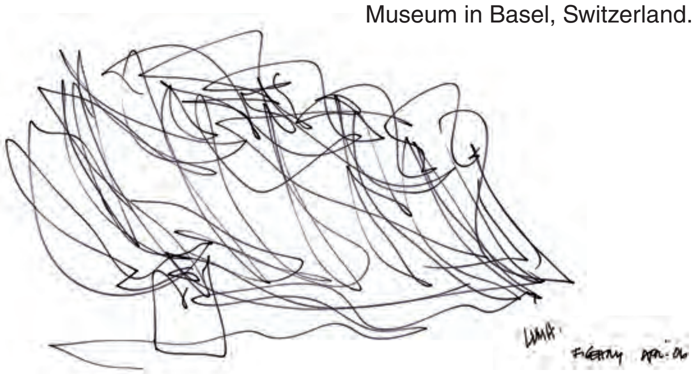
Duplex rigging for glass sails

Canadian-born California architect Frank Gehry's project for Fondation Louis Vuitton exhibits unprecedented aesthetic innovation and technological sophistication. The spectacular glass sails of the roof appear so light and airy, in large part, thanks to the delicate high-strength molybdenum-containing duplex stainless steel support structure.

With the inauguration of the new Fondation Louis Vuitton museum in October 2014, Paris received what many see as its most recent architectural masterpiece. The museum is located in the Bois de Boulogne – one of the capital's two "green lungs" – on the edge of the most exclusive residential area in Paris. The building was conceived in 2001 when French tycoon Bernard Arnaud, the owner of luxury brands in perfumes, champagnes and haute-couture, met the famous American architect Frank Gehry, winner of the prestigious Pritzker Prize. Gehry's works include the renowned Guggenheim Museum in Bilbao, Spain, the Walt Disney Concert Hall in downtown Los Angeles, and the Vitra Design Museum in Basel, Switzerland.



Frank Gehry's spontaneous preliminary sketch for the museum. © Gehry Partners, LLP and Frank O. Gehry.

From a spontaneous sketch to a digital model

If one specific characteristic defines Frank Gehry's style, it is undoubtedly his disdain for the straight line! Most of his works show an affinity for fluid forms, curves and counter-curves enhanced with glass walls, or twisted metal sheets placed on undulating facades. Arnaud, in awe of the architect's Bilbao Guggenheim Museum, was eager to present the City of Light with a prestigious showcase for his own contemporary collection, along with commissioned works, guest artists and temporary exhibitions. Gehry's initial sketch for Arnaud used an almost unbroken line, imagining a vessel with billowing transparent sails. He acknowledges the influence of 19th-century iconic parisian glass pavilions ❯

"To reflect our constantly changing world, we wanted to create a building that would evolve according to the time and the light in order to give the impression of something ephemeral and continually changing." Frank Gehry. © Fondation Louis Vuitton/Todd Eberle and conservatories on his design. Once the quick rough sketch was drawn, what remained was to translate the concept into a feasible project.

Gehry created several scale models from the initial sketch and produced a comprehensive digital model from the most advanced. The digital model allowed components of the hyper-complex structure to be defined, detailed and their dimensions to be calculated. The result? A spectacular vessel with twelve monumental glass sails projecting into the sky, supported by an incredible entanglement of steel columns, wooden beams, braces, transoms and tension rods. All these elements are interconnected and supported by a hard-shell structure that contains the museum's enclosed spaces. Composed of white blocks, the shell structure is called the "iceberg."

Aviation technology for a glass vessel

In the beginning, the challenges facing the project teams – designing such highly complex volumes and shapes, solving stability problems, fabricating and connecting the building elements, preparing detailed implementation plans, working out lifting and assembly schedules for every element of such a giant puzzle – were believed to be impossible to overcome. But the architect had already solved these problems. For the Bilbao Guggenheim museum, Gehry Technologies created a software package called Digital Project. Based on Dassault Systems' CATIA software for designing complex aerospace parts, they expanded it into an integrated collaborative platform. All project partners were required to use this tool along with a common 3D model in order to allow close collaboration between R&D, prototyping, fabrication and building phases of the project. This tightly controlled approach produced exceptional project performance that avoided discrepancies or delay,

The roof support structure is made of wood, steel and duplex stainless steel components. © Eiffage

from the mounting of coupling parts to the perfect fit of structural elements on site. Partners created and shared more than 190,000 digital files as the project proceeded from 2008 to 2014.

A structure where "everything moves so that nothing moves"

The building comprises three major parts. The primary inner-core structure (the iceberg) contains the museum's attractive public and circulation spaces, gallery spaces and service rooms. The stacked boxes of the iceberg are clad with approximately 19,000 white Ductal® panels made from ultra-high performance fiber-reinforced concrete, whose unique curvatures require them to be individually molded. While circulating throughout the iceberg, visitors have access to several outdoor terraces that offer sumptuous and breathtaking views of Paris. From these terraces they can take in the iconic "Old Lady" (Eiffel Tower) and the La Défense business district with its skyline of slender skyscrapers.

The secondary structure, fixed on the building and rising in all directions, supports the amazing glass sails that billow in the Paris sky. It comprises steel columns and wooden beam "tripods" that support a monumental network of long-span laminated larch wood beams and carbon steel trusses. From 3 to 35 m long and variously angled, these elements gently swirl underneath

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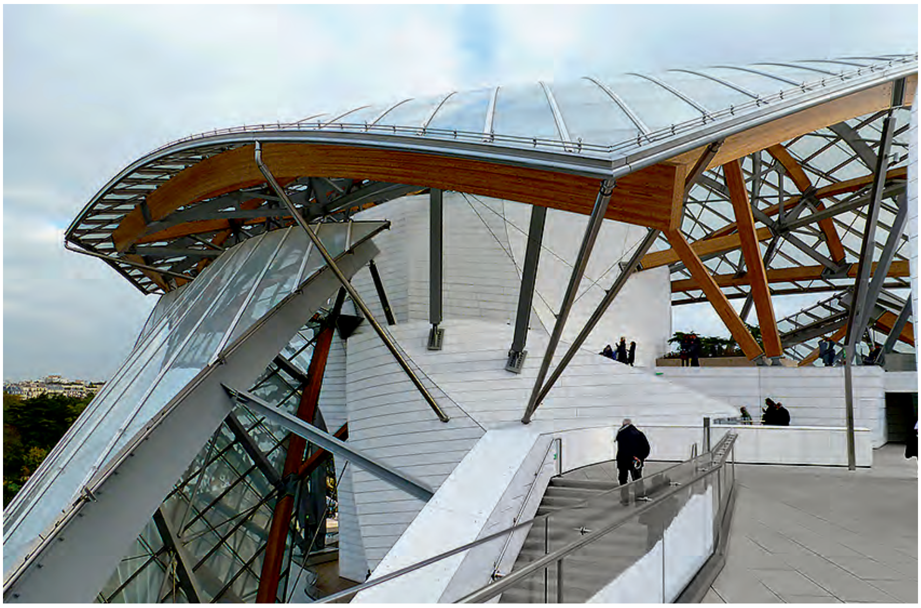
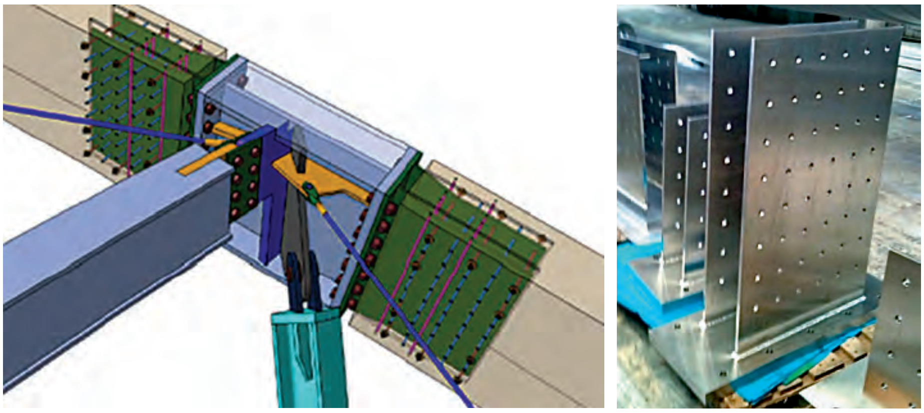


Fixed to the building inner-core, the "iceberg," wood and steel "tripods" support the isostatic suspension frame of the glass sails. © Effitext

The glass panels are supported by a light duplex stainless steel grid. Duplex stainless steel, a flexible building material, can be shaped to the needs of the designer without requiring any protective paint.

the sails. The wooden beams are fitted with 540 duplex stainless steel inserts to ensure firm connections. Connecting all these elements requires 430 unique, geometrically complex nodes made from 100-mm thick carbon steel/duplex stainless steel hybrid plates. The nodes link the wooden and metal elements, ensure the structure's stability, and permit the normal movement of every element in the massive, complex assembly, "making it possible that everything moves so that nothing moves!" as one engineer observed.

The freestanding tertiary structure includes the twelve curved-glass sails wrapped around and above the iceberg and the impressive duplex stainless steel grid that supports them. Three sails act as umbrellas for the building while the other nine sweep around it, creating the appearance of a "ghost ship" sailing above the treetops of the Bois de Boulogne. The sails weigh between 200 and 350 tonnes each and span up to 30 m. Their individual surface areas range from 500 m^2 to 3,500 m^2, and total 13,500 m^2. The sails contain a total of 3,584 curved-glass panels with different thicknesses. The individual 1.5 m x 3 m panels were hot-formed to unique curvatures that depend upon their locations on the sails. This innovative technique, originally developed by the automotive industry, avoided the need for expensive custom molds for each panel.



Duplex stainless steel inserts connect wooden beams and steel columns. © Eiffage

Duplex, the metal of choice to rig the glass sails

Satisfying the complex array of constraints imposed by this unusual work of art and its suspension frame was no small task. The materials solution was somewhat unconventional – 2205 duplex stainless steel containing 2.5%–3.5% Mo instead of the more commonly specified Type 316L stainless steel that would have had sufficient corrosion resistance to withstand the atmospheric conditions in Paris. The duplex grade is much more corrosion resistant and is primarily intended for more corrosive environments, for example in chemical processing or offshore oil drilling. However, it was selected here because its minimum yield strength is more than twice as high as that of Type 316L. The yield strength advantage translates to a 30 percent reduction in the structure's weight. With cantilevered trusses and beams spanning up to 30 m there was no choice: duplex stainless steel had to be used to make it work. The higher strength and corrosion resistance are actually leading to a general shift among architects from Type 316L to 2205, especially for prestigious structures and for more corrosive locations. Maintenance costs and aesthetics were also important factors in the material choice. Although parts and elements that can be easily accessed for cleaning are made of painted carbon steel, the light suspended grids that are difficult to reach are duplex stainless steel.

The glass sails required approximately 25,000 different parts. The nodes, which articulate the main suspension frame and the duplex grid, are an assembly of 120 mm-thick duplex plates to which 9,000 duplex stainless steel mounting "ears" are welded. Gutters of 220 mm ›

Stainless steel pipes for reliable and sustainable rainwater management

Gutters on the roofing, acting as downspouts, collect rainwater from the 13,500 m^2 glass surfaces and discharge it into the pool at the foot of the building. Before being used to clean external surfaces, the water is filtered and purified to remove contaminants or micro-organisms that could be deposited on the glass. All glass sails will be manually cleaned twice a year from suspended cradles, using mechanized brushes. Rainwater will also feed the museum non-drinkable water network.

Protection of art works was an important criterion for the choice of the indoor piping materials. In rooms where leaks could damage exhibits, pipes are made of welded Type 316L stainless steel and sound-insulated with glass-wool sleeves. This approach was chosen over traditional PVC piping with solvent-cemented connections that were deemed less reliable. For some indoor water piping, stainless steel and aluminum pipes are connected with flanges.

Straight or curved, duplex gutters are fitted with fixing "ears" and mounting plates. © Gérard Tordjman diameter, 20 mm thick duplex stainless steel, help to stiffen the support grid, recover rainwater on the periphery of the roofing, and drain it to downpipes on the front or inside the iceberg (see box on p. 7). They are welded to duplex stainless steel mounting plates, that are fitted with "ears" and other hanging and fixing devices. The support grids include duplex tubular transoms (90 and 80 mm diameter, 8 mm thick) that are up to 12 m long and connect to duplex stainless steel mullions that support the glass panes. Added to these elements are braces, tension rods and thousands of bolts, all of them in duplex stainless steel as well. Finally, duplex stainless steel is used for the rails for suspended cleaning cradles and hundreds of securing fasteners (tie-down rings, pigtail hooks) spread on the tripods and the steel grids.

With its glass sails and the water features throughout, the new museum resembles a ship sailing above the Bois the Boulogne. © Fondation Louis Vuitton/Todd Eberle

Eiffage, the main contractor for the large sails, worked closely with the supplier of the fabricated duplex stainless steel parts ThyssenKrupp Materials France (TKMF). Fabrication of the various components demanded attention to detail and precision. In order to avoid deformation due to heating and to comply with the tight flatness tolerances, TKMF acquired specialized high-pressure water-jet equipment to cut the components. The cutting process is so slow that it required two years of continuous day and night shifts on the new machine to prepare all pieces. Because of the great variation in dimensions and curvature, the roofing components had to be milled on five-axis machines. The variety of these parts was so great that engineers considered two identical parts to constitute a series! At the end, all duplex stainless steel was finished with a 220-grit directional polish to add to the overall brightness of the building, meeting Gehry's aesthetic requirements. To avoid risk of corrosion that could damage grid components, engineers verified the microstructure of all parts metallographically. Very few on-site welds were needed since 99 percent of the secondary- and tertiary-structure joints are bolted. They aligned perfectly during construction thanks to the close coordination among all involved parties.

In this era where buildings are no longer simple square boxes, and architects are constantly pushing the limits of what is physically feasible, stainless steel doesn't just make these audacious shapes possible but makes them beautiful. (Thierry Piérard)

An impressive architectural success by the numbers

- 15,000 tonnes of steel are present in the whole of the building structures, which is twice the amount in the Eiffel Tower!
- 2,000 tonnes of carbon steel are used in the suspended frame of the secondary structure.
- 1,500 tonnes of high-strength duplex stainless steel support the majestic glass sails.
- 3,430 glass panes, individually hot-formed in different thicknesses to various curvatures, cover the 13,500 m^2 of surface area contained in the 12 sails.
- 430 unique, geometrically complex nodes link all wooden and metal elements.
- 540 duplex inserts connect wooden beams and carbon steel columns.
- 10 km of duplex stainless steel curved mullions have been manufactured and welded.
- 5 km of stainless steel transoms adjust with millimeter accuracy.
- 2 km of stainless steel gutters contribute to the stiffening of the support grid.