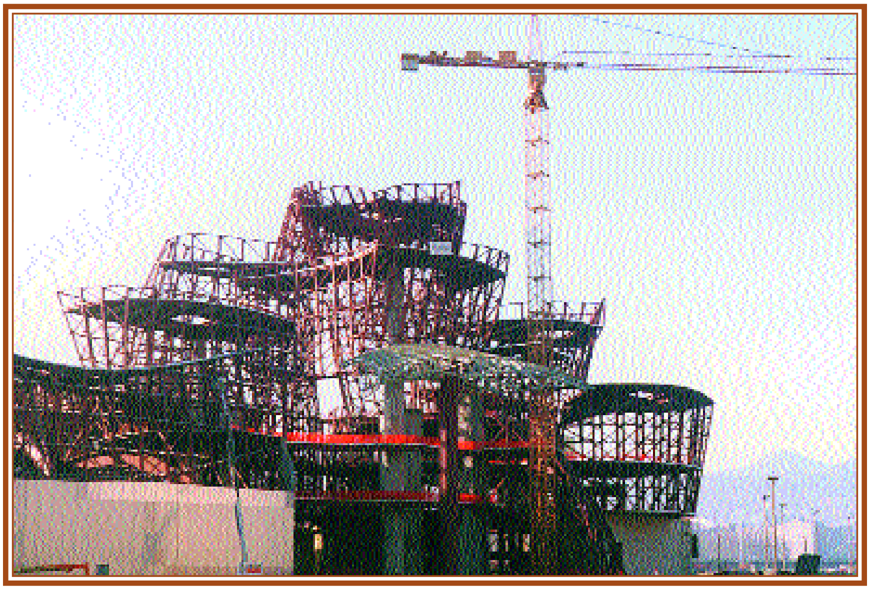
Steel Flower



Steel framing provided both the strength and lightness needed for the Guggenheim Museum's complex geometry

By Hal Iyengar, P.E., S.E., Lawrence Novak, S.E., Robert Sinn, P.E., S.E. and John Zils, P.E., S.E.

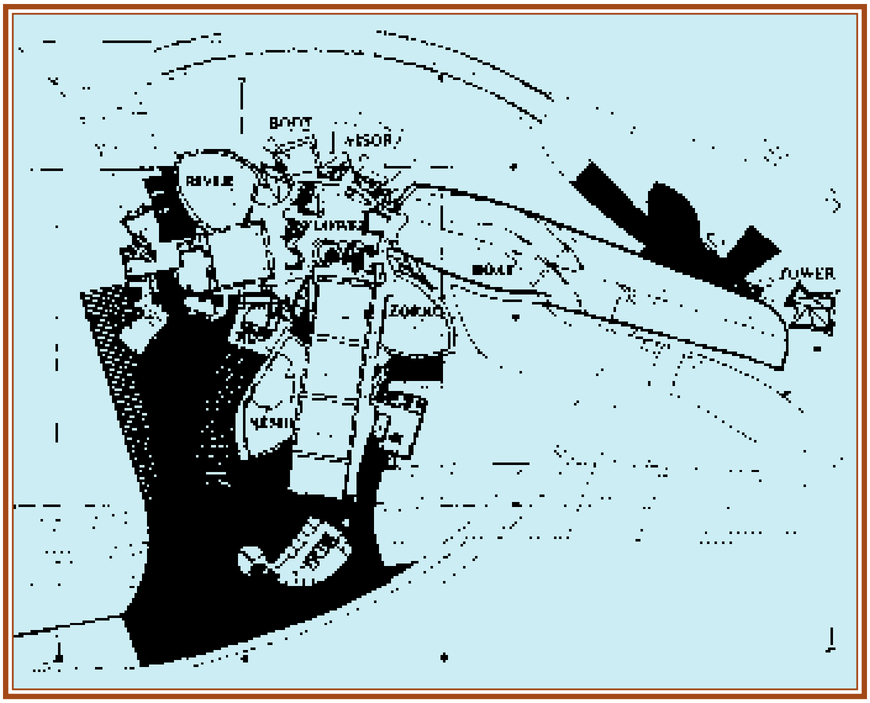
CONSTRUCTED IN THE HEART OF THE INDUSTRIALIZED CITY OF BILBAO in the Basque Country of Spain, the fluid and curving forms of the recently opened Guggenheim Museum have been immediately recognized as one of the most complex, unique and important architectural designs of this century. Variously described as a metallic flower, reminiscent of ships' hulls and prows, a system of metal whorls, architecture as abstract art, and a tumble of freeform masses; the aesthetic design has been universally applauded by both architecture critics and the general public visiting the museum. The innovative use of structural steel in concert with extensive reliance on modern computer capabilities by engineers, architects, detailers, and fabricators played a vital role in realizing the project on time and within budget.

The Challenge

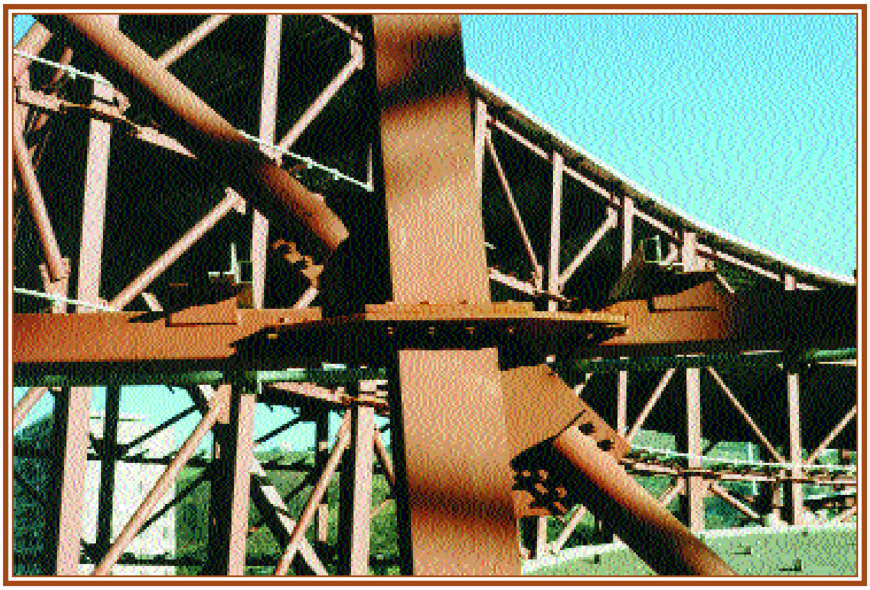
In 1991, architect Frank O. Gehry and Associates, Santa Monica, CA, was successful in winning a limited competition for the museum design organized by Basque Country Regional government agencies and the Solomon R. Guggenheim Foundation. The design brief for the museum called for creating not only one of the great art museums, but one of the greatest buildings in the world. Nearly twice as long and tall as Paris' Georges Pompidou Center, the scale of the $100 million, 250,000 square foot building is such that the entire New York Guggenheim Museum designed by Frank Lloyd Wright can fit within only the central atrium space of the Bilbao museum.

The museum is entered below grade directly into the 50-meter (164') tall central atrium space. From there, galleries of various shapes and sizes radiate out in practically all directions. Some so-called "classical" galleries are rectilinear in geometry and are typically clad in stone. Others are three-dimensionally curved and are generally clad in titanium metal. The largest "boat" gallery, some 140-meters (459') long, 25-meters (82') wide without interior columns, extends below the adjacent Puente de la Salve bridge. The galleries all include generous open volumes on the order of 15-meters (49') to 20-meters (66') tall without internal floors or vertical supports.

Chicago-based Skidmore, Owings & Merrill, LLP was chosen as the structural engineers for the project based upon a previous successful collaboration with Gehry for a project in Barcelona, Spain. The conceptual design process from a structural engineering standpoint was unique in that the building was without precedent in terms of geometry, organization and scale. While most building structures are an extension or derivative of earlier successfully utilized systems, the Bilbao museum structure would have to be developed without the usual benefit of a comparable benchmark project. Furthermore, the architectural themes of fractured and irregular building masses and surfaces were explicitly at odds with the normal structural engineering precepts of stability, organization, and regularity in order to achieve a design which is efficient and cost-effective. The design challenge was therefore to



The Guggenheim's complex geometry was created by a structural steel "fabric" grid that provided support for the building's titanian skin.



create an organized, rational structural system, within the fabric of the architectural design, which could be reasonably designed, detailed, and constructed. In order to achieve this, a unique system in structural steel was conceived.

Structural System

The initial stage of the project was focused on a search for an appropriate structural system for the complex, doubly curved exterior clad surfaces. These surfaces and their interior volumes are characterized by their tall heights up to 20 meters (66') without internal structure and their long, column-free distances spanning between discrete, randomly located support points. Many of the three-dimensional surfaces are themselves interconnected while others are supported or laterally braced by adjacent rectilinear block shaped galleries. Traditionally, such free-form shapes have been nearly exclusively framed in reinforced concrete—as in fact other Gehry building designs of smaller scale have been. The scale of this project, however, demanded a lighter structural system. Based on these parameters, it was thought that the structural system would require the following characteristics:

1. The structure should be equally applicable to a variety of architectural forms so that each element would not require a separate system. Member proportions and details should be simple and conventional.
2. The structure should be disciplined and organized without impacting or limiting the architectural design.
3. The structure should be fabric-like to follow as closely as possible the architectural surfaces in order to simplify the connection of the exterior titanium cladding and interior drywall systems.
4. The structural thickness should be as thin as possible in order to minimize the depth of the void space between the exterior clad surface and the interior drywall and to maximize the usable floor space.
5. The structure should be analytically verifiable, both structurally and architecturally, by currently available computer routines.
6. The structure should be lightweight in order to span efficiently between discrete support points.
7. The structure must be constructed and controlled to tight tolerances in the field in order to fit the geometrically complex exterior and interior cladding systems.

For these objectives, the choice of structural steel as the primary frame material became a natural decision based on its low structural self-weight and the ability to control and verify the structure in a shop environment. The overall concept of the structural system then evolved over a period of a few months through an internal dialogue and through discussions with the architectural team. One of the key concepts in the design philosophy was to closely follow the architectural form. By doing this, the curvature of the shapes proved to be advantageous in resisting lateral loads. The concept of a discrete bearing wall system in structural steel was developed based on an organization of a relatively dense, diagonalized gridwork of members. Finally, the geometry of the exterior surfaces were studied on the basis of horizontal and vertical slicing planes which led to the germination of an idea of organizing the frames in a similarly disciplined, geometrically rigid fashion.

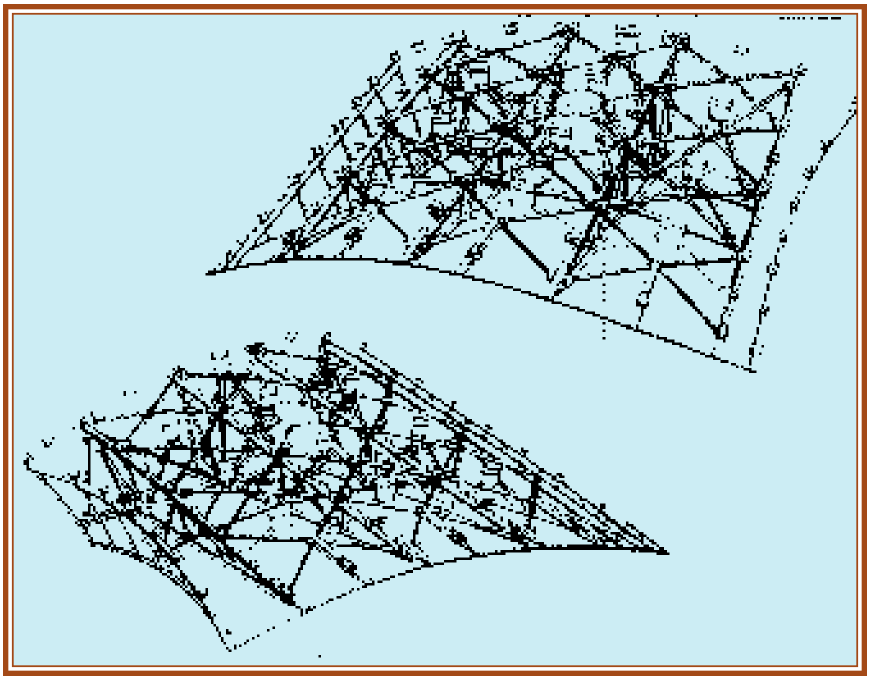
The structural system finally developed for the complex titanium-clad forms may best be described as a three-dimensional diagonalized fabric grid in structural steel. The system has the ability to span long column-free distances due to the overall depth of the structure and low self-weight of the frame structure itself; while at the same time having significant stiffness against lateral loads due to the ever-present curvature of the various geometries. This frame organization provides similar material economies and thin structural thicknesses historically associated with reinforced concrete shell structures. The structural system concept was completed with the introduction of the idea of shop-fabricated horizontal “bands” of trusswork which could be easily vertically “stacked” on-site, without a significant amount of temporary shoring or lateral bracing, in order to complete the full gallery wall structure. The joints would be made by providing horizontal bearing plates at each node allowing both vertical and horizontal angle changes between members to occur while being consistent with the truss stacking erection concept. The structural engineering concept for the complex three-dimensionally curved surfaces was finally set; but the process of designing the structure for the museum had, however, only begun.

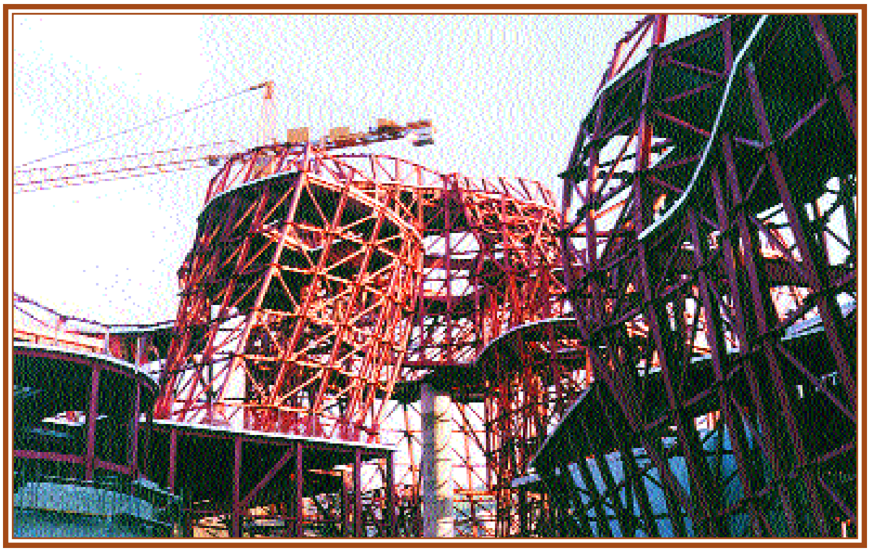
Design Process

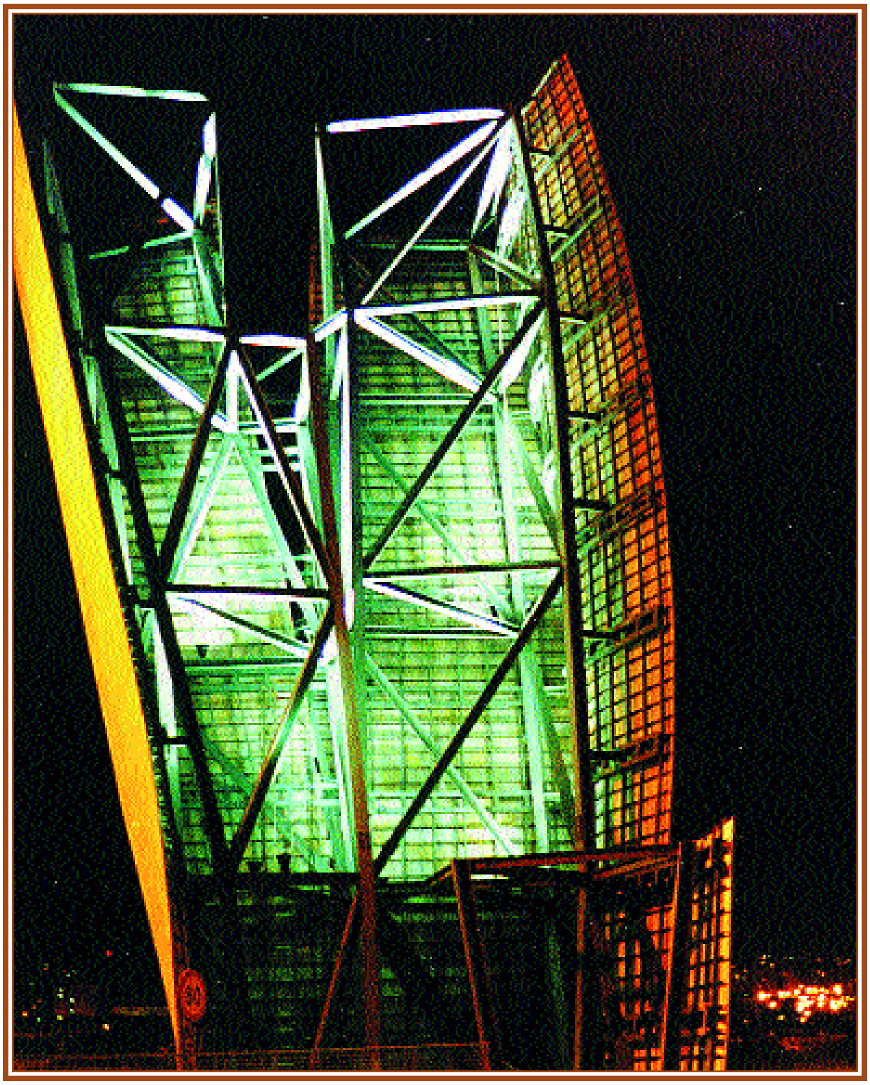
Initial architectural designs were created with physical models of cardboard, paper, wood, etc. Substantially complete physical modeling was then transferred electronically to computer medium through a digitizing and probing process of the exterior surfaces. This digitizing process resulted in a consistent three-dimensional wire net of control points that could be verified with respect to the physical models. At this point, the geometric data was manipulated in the computer using CATIA software which was originally developed for use in designing French "Mirage" fighter planes. CATIA was used to smooth and rationalize the various curved surfaces as well as to create offset surfaces locating the potential structural envelopes. With the offset surfaces defining potential locations for structural members available in CATIA, the architectural and structural teams together developed a discrete segmented "wireframe" of nodal points and lines eventually defining the structural centerlines. The segmented structural wireframe was created by passing horizontal and vertical slicing planes at regular intervals through the offset surfaces in CATIA; the intersections becoming the locus of structural nodal points.

In creating the structural wireframe models for the complex metal-clad surfaces in conjunction with the architectural team, a series of guidelines were set in order to organize the steel framework. These "rules" were imposed on the structural development for the purposes of creating a disciplined and regular primary structure within the constraints of the architectural design:

1. All members would be straight segments between nodal points.
2. The grid spacing would be approximately 3 meters by 3 meters (10'x10'). This was found to be dense enough to generally conform to the curved surfaces while at the same time allowing for reasonably dimensioned horizontal "band" trusses to be prefabricated and transported to the site.
3. The structural nodal workpoints would be a constant 600mm (2') dimension from the exterior clad surface.
4. Horizontal members would be at constant elevation except at sloping roof lines.
5. Inclined column members would be created by passing







In recognition of the museum's prominence in the city, the owner's wanted a tower (above) to be included with the project.

Shown opposite is the building's frame at the main entrance to the museum.

vertical slicing planes normal to the ground surface through the offset surfaces in CATIA. The orientation of the column web would lie perpendicular to the exterior surface as determined by averaging the normal vectors along the run of the column. The web orientation of the column would remain at a constant angle for the full vertical run of the column (no warping).

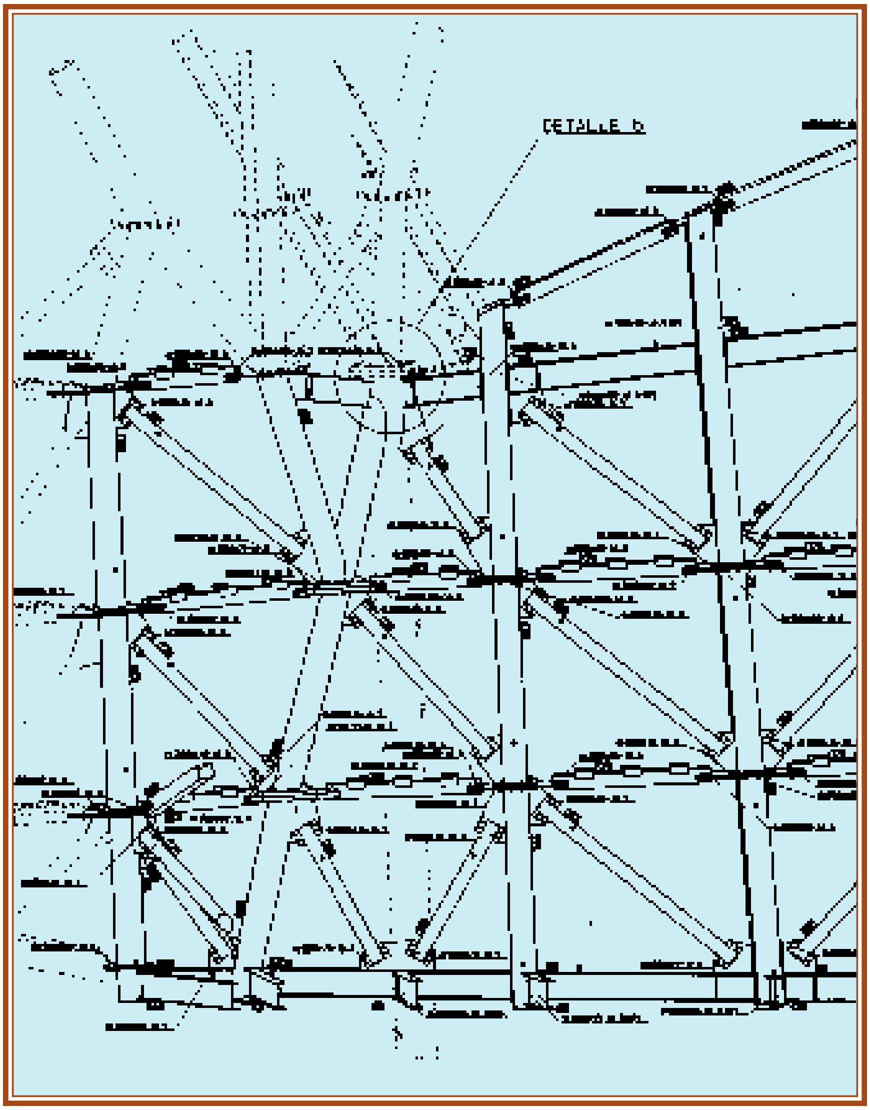
6. Diagonal members to be oriented in a tensile (Pratt) arrangement based upon gravity load considerations.
7. Wherever possible, minimum sizes are to be used as follows (unless found analytically to be insufficient structurally) to create economies in the structural steel mill order and to simplify the architectural/structural engineering coordination process:
   - Vertically inclined columns: standard, rolled, European standard HD 310mm x 310 x 97 kg/m (approximately the cross-section of an HP12 x 63) and HD 260mm x 260 x 73 kg/m (slightly larger than the cross-section of an HP 10 x 57) (50 ksi yield).
   - Corner vertical members: 250mm (10") diameter x 10mm (.39") wall thickness seamless pipe section (42 ksi yield).
   - Horizontal members: 160mm (6.3") x 160 x 6mm (.24") wall thickness square tube (42 ksi yield).
   - Diagonal members: 155mm (6.1") diameter x 6mm wall (.24") thickness seamless pipe section (42ksi yield).

Standard connection geometries and load-carrying capacities were developed based on this limited number of sizes which could be easily verified by the architectural team in terms of interference with both the exterior clad and interior drywall surfaces. The limited number of cross sections for the frame members allowed for an efficient engineering verification process for all of the various imposed loads and load combinations. Upon analysis, it was found that perhaps 95% of all of the members in the complex three-dimensional frames were sufficient based on the minimum number of shapes with the remainder custom sized based on their individual structural requirements.

Structural Engineering Documents

Consistent with the unique nature of the project, the structural engineering design drawings were organized with a view toward the eventual use of the computer for data manipulation by all members of the design and construction teams. In fact, the drawings were prepared primarily as a check against the computer-based information with any discrepancies between the two resolved by the various teams. The definition of the geometry for the metal clad structures was based on a project (x,y,z) coordinate system. Each nodal work point coordinate was specified on the drawings as referenced by inclined column mark versus elevation. A schedule of planar angles were prepared to define the orientation of each column web in the project system. Further depiction of the frame geometry on the record drawings was provided by a series of three-dimensional isometric views including continuations along all interfaces between the various forms. Each surface was also presented in pure, unfolded elevation upon which the member sizes were keyed to adjoining schedules for the verticals, horizontals, and diagonals. Standard framing plans were provided for all gallery floors, roofs and parapets.

It was understood by all of the parties involved in the project that the computer files would be as important, if not more so, than the paper drawings created. Very rigorous attention was paid to the dimensional accuracy of the computer-based information as this would be the data actually used in the creation of subcontractor shop drawings. To this end, the construction drawing computer files (in AutoCad .dxf format) for the project were submitted to the contractors as part of the project documentation. For the complex metal clad structures, specially created three-dimensional color-coded "wireframe" files were submitted to the structural steel fabricator as well. These computer files included the workline geometry of the frame in project coordinates as



Pictured above is a horizontal truss prior to erection.

well as the member sizes indicated by various colors keyed to a master list of section sizes. These computer-based wireframes were checked by the steel detailer against the paper drawings and formed the basis for the creation of the steelwork shop drawings.

Steel Detailing, Fabrication & Erection

The steel fabricators for the project used a very powerful detailing program developed in Belgium, BOCAD, to create three-dimensional graphic files of the steel assemblies from the structural wireframes developed by SOM. While each nodal joint is unique in terms of the geometry of the interconnecting members, there were only a handful of different joint types that could be organized in a subroutine and then included in the BOCAD database. BOCAD was then able to completely draw, three-dimensionally, the entire frame including connection plates, bolts, member bevels, etc. From this fully three-dimensional data, individual piece drawings and sub-assemblies were culled in order to create detailed and dimensioned shop drawings. This fully automated process of shop drawing preparation was responsible for creating piece and assembly drawings virtually error-free.

The horizontal truss "band" sub-assemblies were trial fitted in the fabrication shop to adjacent horizontal frames as well as bands immediately above and below. This resulted in very little site adjustment or reaming of bolt holes in the field and relatively speedy erection of the steel frames. The horizontal bearing plate at each node also forms the connection point for the horizontal and diagonal members of the frame. The original design for the node specified shop welding of the horizontal and diagonal members to the node plate but was later modified by the steel fabricator, URSSA S. Coop, Ltd., to shop bolted connections to allow for more tolerance in the fit-up process. Partially complete frames were found to have significant inherent stiffness, which allowed for straight-forward erection with little temporary bracing or shoring required to keep the members aligned and within reasonable tolerances. The steel fabricators as well as the cladding system sub-contractor utilized expected deflection plots of the deformed structure plus a significant amount of spot surveying of the completed frame to verify that the erected structure was indeed within tolerance and behaving as analyzed by SOM. All of the steelwork for the project was sandblasted to receive a shop-applied primer due to the exposed and highly visible public nature of the work on the museum.

Exposed Steel Sculptures

While the majority of the steelwork for the museum is concealed within the metallic titanium and stone clad surfaces of the exterior, or only partially expressed on the interior with surrounding drywall enclosures; the structures for various external complementary sculptural forms featured the use of exposed painted structural steel as a component in the overall architectural concept. These structures are unique in system and geometry and also serve to demonstrate the powerful capabilities of the detailing routines employed by the steel fabricator for the project. The exposed nature of these structures required tailored systems to be employed for each, quite different than those used for the curved surfaces of the museum itself. These elements received a multi-coat paint system of shop applied primer over sandblasted substrate, shop finish coat, and a final coat applied in the field after erection.

The 26m (85') tall canopy or "Visor" overlooking the adjacent Nervion River is approximately 25 meters (82') by 20 meters (66') in plan and is supported on a single slender, cantilevered vertical 2.0 meter (6.5') diameter steel pipe pylon with a 40mm (1.6") wall thickness. The Visor structure involves four cantilevered trusses tapering from four meters deep at the pylon to a minimum at the tip. The design for the visor called for patterned and asymmetrical wind loads of up to 200 kg/m2 (about 40 psf).

Without internal floors, the 50-meter (164') tall figural "Tower" is nevertheless not without function. This element forms a visual marker extending the limits of the project and embracing the existing Puente de la Salve bridge. The 200-meter (656') long adjacent "boat" gallery extends below the bridge and eventually is terminated at the tower base. The exposed steel frame of the tower is partially clad in stone with the internal structure visible to varying degrees depending upon the point of observation. From a single base, the structure widens as it extends vertically and actually bifurcates into two separate forms near mid-height. All members are open wide-flange shapes with shop-welded nodes at times requiring the joining of as many as 12 members at a single point, all at non-orthogonal angles.

The museum was opened to the public in October, 1997. The universal and repetitive nature of the unique system developed for the

Guggenheim Museum Bilbao resulted in a unit steel price for the 3,900 tons of structural steel comparable to a standard steel framed building project and was a factor in the project opening on-time and within budget. Advances in the use of computers for steel detailing and fabrication now allow for the realization of extremely complex projects which perhaps ten years ago would have been deemed impossible. It can now be said that the versatility of steel has been extended to new applications in geometrically free-form architecture.

Hal Iyengar is a Retired Partner, Lawrence Novak is an Associate, Robert Sinn, Associate Partner, and John Zils, Associate Partner with Skidmore, Owings & Merrill LLP, in Chicago.

Project Team

Owner:	Consorcio Del Proyecto Guggenheim Bilbao, Bilbao, Spain
Struct. Eng.:	Skidmore, Owings & Merrill LLP, Chicago
Architect:	Frank O. Gehry and Associates, Santa Monica, CA
Architect/EOR:	IDOM, Bilbao, Spain
Fabricator:	URSSA, S. Coop. Ltd., Vitoria-Gasteiz, Spain (also includes detailing & erection)