Unique Discretized Lattice Structure for The Guggenheim Museum Bilbao, Spain

William Baker, Hal Iyengar, Lawrence Novak, Robert Sinn, and John Zils
Skidmore, Owings & Merrill LLP
224 South Michigan Ave., Suite 1000
Chicago, Illinois, USA 60604
tel. 312-554-9090
fax. 312-360-4500
email: william.f.baker@som.com

Introduction

Located in the center 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 daring 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 nearly universally applauded by both architecture critics and the general public visiting the museum. (**Fig. 1**) A unique, versatile shell-like system in structural steel was developed for the free-form museum surfaces which played a vital role in realizing the project on time and within budget.

Figure 1 Completed Museum at Opening, October, 1997

Conceptual Design

In 1991 architect Frank O. Gehry and Associates were 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 conceptual design process from a structural engineering standpoint was unique in that the building was without precedent in terms of geometry, organization and scale. (**Fig. 2**) 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 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. (**Fig. 3**)

Figure 2 Museum Geometry and Scale

Figure 3 Lattice Grid System

Structural System Organization and Development

The initial stage of the project was focused on a search for an appropriate structural system for the complex, doubly curved exterior clad surfaces. (**Fig. 4**) These surfaces and their interior volumes are characterized by tall heights of up to 20 metres without internal structure and 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. (**Fig. 5**)

Figure 4 Curved Surface Modeling

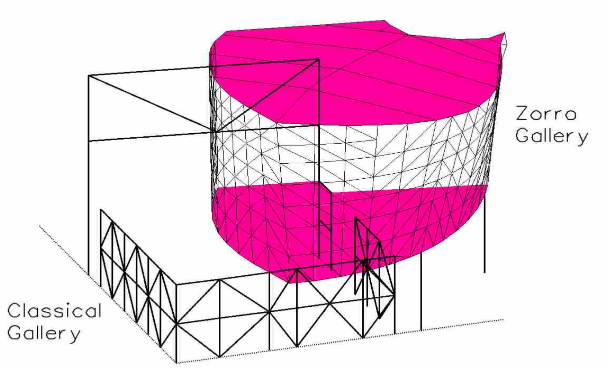

Figure 5 Zorro Gallery - Support Locations

Traditionally, such free-form shapes have been nearly exclusively framed in reinforced concrete as in fact other Gehry designed buildings of lesser scale have been. The scale of this project, however, demanded a lighter, prefabricated 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 surface would not require a separate system. Member proportions and details should be simple, conventional, and repetitive.
2. The structure should be ***disciplined, organized and economical*** without impacting or limiting the architectural design.
3. The structure should be ***fabric-like*** in order to closely follow 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 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 should be able to 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 fabrication shop environment. 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, segmented lattice grid shell 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-prefabricated horizontal "bands" of trusswork which could be vertically "stacked" on-site, without a significant amount of temporary shoring or lateral bracing, in order to complete the full gallery wall structure. (**Fig. 6**) 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. (**Fig. 7**)

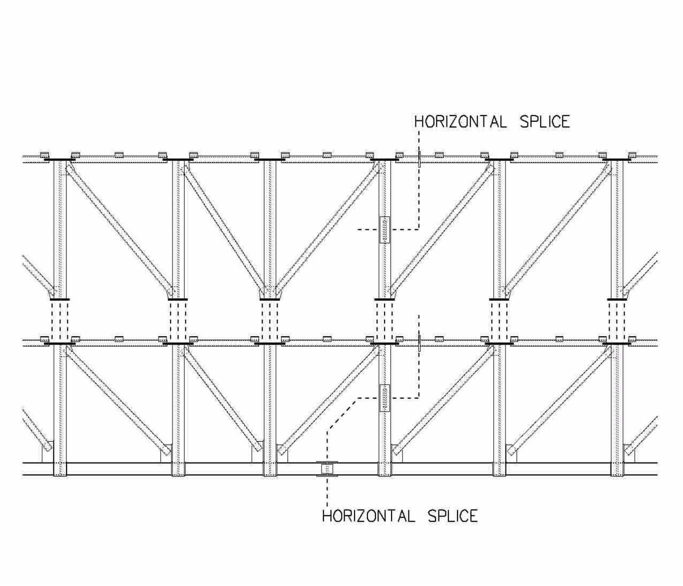

Figure 6 Fabrication/Erection Stacking Concept

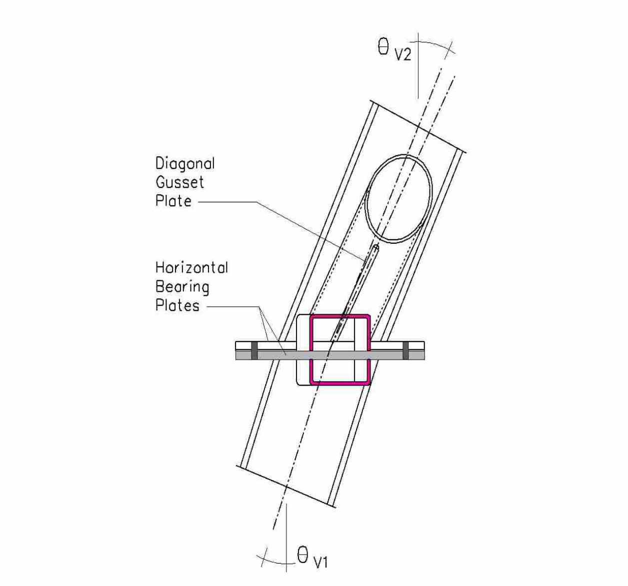

Figure 7 Section - Typical Nodal Joint

The 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. (**Fig. 8**) 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. 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. (**Fig. 9**)

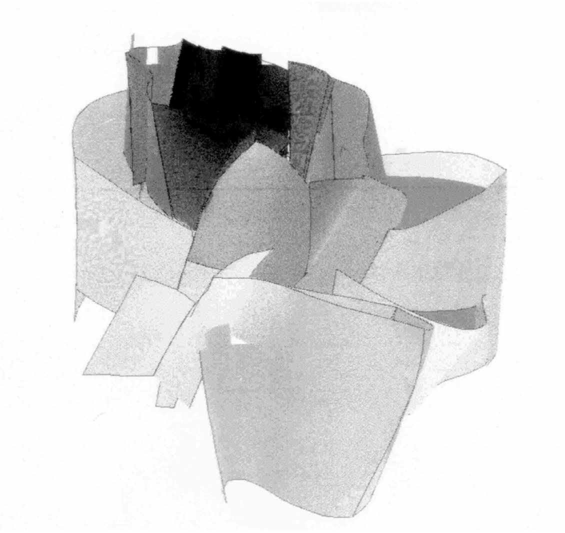

Figure 8 CATIA Surface Analysis

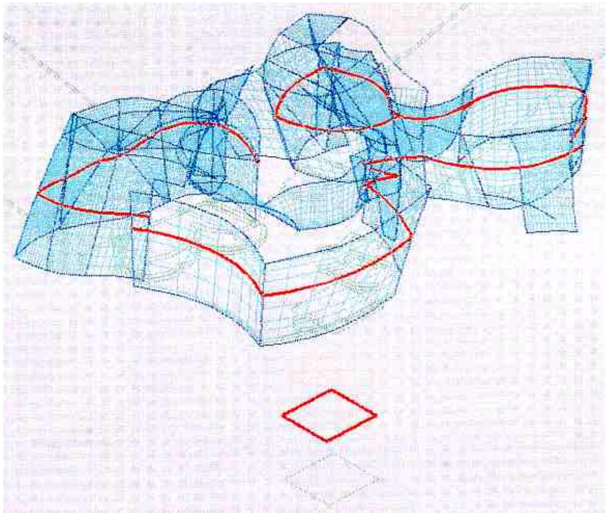

Figure 9 Structural Wireframe Evolution

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 metres by 3 metres. 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 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 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. Rather than custom-designing each individual frame member, a limited palette of steel member sizes were to be used (except those otherwise found analytically to be insufficient structurally) to create economies in the structural steel mill order and to control and simplify the architectural/structural engineering coordination process:

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.

While the primary structural frame is segmented and composed entirely of straight pieces between work points, the secondary framing system directly supporting the titanium cladding is curved. Secondary horizontal “ladder” frames composed of two small, continuously curved horizontal pipes and intermittent transverse channels are attached in the field to the primary system horizontal tubes at a limited number of angle “ears” shop welded to the tubes prior to erection of the primary system. (**Fig. 10**) These ladder frames support both the external metal clad surface as well as the internal drywall system. Vertical, curved unistrut members are

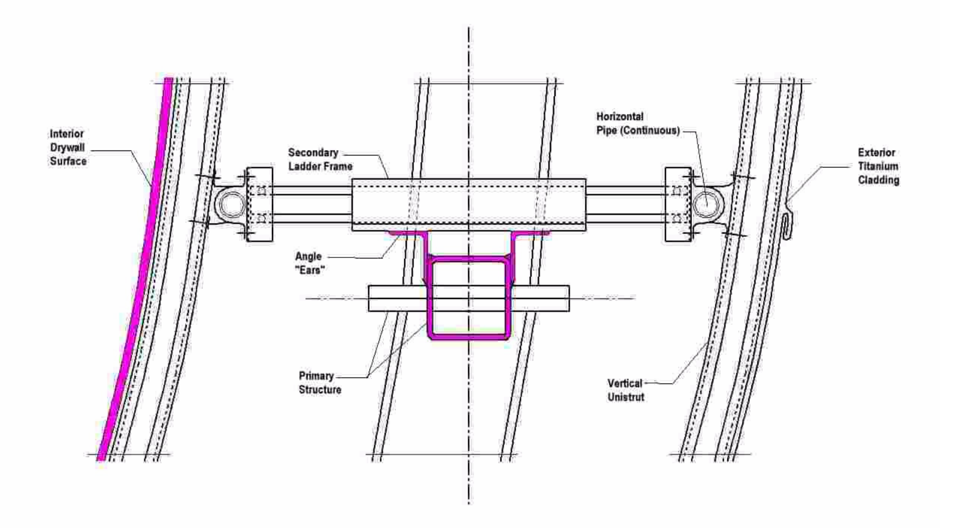

Figure 10 Secondary Cladding System Attachment to Primary Frame

Figure 11 Secondary Structure Installation

attached to horizontal pipes of the secondary system and directly support insulation, a galvanized back-pan, waterproofing, and finally the titanium sheets. Dimensional adjustment in all directions is provided for at the secondary horizontal to vertical connection point. The titanium cladding used on the project is less than 1mm thick. (**Fig. 11**)

Structural Engineering Documentation

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 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.

Structural Steel Detailing, Fabrication and 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 which 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. (**Fig. 12**) This resulted in very little site adjustment or reaming of bolt holes in the field and relatively speedy erection of the steel frames. 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. (**Fig. 13**)

Figure 12 Horizontal Band Truss Shop Fabrication

Figure 13 Boat Gallery - Under Construction

Conclusion

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 critical factor in the successful completion of the project. 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. The versatility of steel may now be extended to new applications in geometrically free-form architecture.

Credits

Owner: Consorcio Del Proyecto Guggenheim Bilbao, Bilbao, Spain
Structural Engineer: Skidmore, Owings & Merrill LLP, Chicago, Illinois, USA
Architect: Frank O. Gehry and Associates, Santa Monica, California, USA
Architect/Engineer of Record: IDOM, Bilbao, Spain
Structural Steel Detailer, Fabricator, and Erector: URSSA, S. Coop. Ltd., Vitoria-Gasteiz, Spain