Glass bearing walls – a case study

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Abstract

Glass is used as an unbraced, primary load bearing element in a residential project in Santa Fe, New Mexico. The intent was to create a pure wall of glass that would seamlessly integrate with the architecture, and to explore the perceptual and psychological impact of a load bearing glass wall.

The glass bearing wall measures 3.5 m high by 8.6 m in length and transfers the loads from a steel framed roof into a concrete foundation. What is typically referred to as structural glass is a system incorporating fins, tension systems and/or steel frames to support a glass facade. In this project there are no exposed connections or fasteners so the sheer, crystalline nature of the glass can be fully appreciated.

Throughout the evolution of the 20th century modern house the structural system has for the most part remained unchanged from the conventional model of flat floor and roof plates supported by a grid of columns, with non-load bearing facades. Load bearing glass was used in the Santa Fe project to challenge the preconceptions of what constitutes a structural element and make the viewer aware of how we take conventional structure for granted.

The specification, fabrication and installation of this glass bearing wall system required a high degree of collaboration and flexibility, particularly given the remote site and desire to work with local contractors and glass installers.

This presentation describes the process of design and realization from the architect's point of view, with an emphasis on the aesthetic and perceptual aspects of the load bearing glass system. The author proposes that load bearing glass does not have to be an exotic specialty item and can be readily used as a highly expressive part of the architect's vocabulary.

Figure 1
Load bearing glass wall.

Introduction

The project is located on a dramatic site in the Sangre de Christo mountains about 10km north of Santa Fe. The panoramic vistas extend across the desert valley towards mountain ranges about 50 km to the east and north. The site is an exposed mountain hillside at 2200 m altitude with potentially high winds. Access is via a difficult dirt road, posing significant challenges for access of heavy equipment and the delivery of the glass.

The clients are collectors of contemporary art who are particularly interested in the aesthetics and evolution of the modern glass house. Load bearing glass was proposed by the architect as a way to take greatest advantage of the vistas, and to explore the ability of glass to simultaneously serve as an architectural enclosure and a structural element.

The Glass House

The concept of the glass house has been of great interest to architects and engineers throughout the 20th century. Where traditional architecture emphasizes enclosure, shelter and protection against the world outside, the glass house speaks to the importance of light, transparency, the flow of open spaces, and a strong connection between interior and exterior. These qualities were made possible by the development of the slab and column construction system popularized by Le Corbusier in his Domino House of 1914. By eliminating traditional bearing walls he opened the door for the "free plan" and the "free façade", and thus the possibility of significant expanses of glass and a degree of openness that was not previously possible. Iconic structures such as Mies van der Rohe's Barcelona Pavilion and Farnsworth House and Philip Johnson's Glass House are highly refined expressions of this quest for openness. In all of these examples the structural columns were clearly expressed and the glass walls were conceived as infill elements that were secondary to the structural system.

The sculptural clarity of the Barcelona Pavilion of 1929 was an important reference point for much of 20th century design and for this project. The ground plane, the glass and stone walls, and the floating roof plane are masterfully configured to read as pure, independent elements. The design includes eight slender steel columns which allow the glass and stone wall planes to be located as desired in this "free plan". The thinness of the columns and their highly reflective stainless steel surface suggests that they were intended to recede if not disappear. This has the effect of making the wall planes the dominant elements. There is an inherent ambiguity here – is the weight of the roof being borne by the thick stone walls or the slender columns? The issue of structural primacy is left unresolved, perhaps to pose this as a problem to be solved in the future.

Where the Barcelona Pavilion is about the poetic composition of horizontal and vertical planes and the interweaving of form and space, the Farnsworth House of 1947 and Philip Johnson's Glass House of 1949 are more direct expressions of the Domino type. Both have strongly defined roof planes supported by classically composed columns, and both houses are glazed on all four sides. The relation of the roof plane to the columns is very different, with the roof extending out into space at the Farnsworth, but staying bounded by the columns at the Glass House. Houses with large areas of glass quickly became commonplace in the 1920's in Europe and particularly in southern California in the 1950's where the climate was so advantageous, but the ways that glass is conceived and used to this day have not changed significantly since mid century. Despite the recent exponential advances in glass technology, these developments have been slow to find their way into the realm of residential design.

Concept

The Santa Fe residence is organized around a series of parallel concrete walls. These walls serve as an armature around which the house is assembled. Spaces are created by using large expanses of floor-to-ceiling glazing around and between the concrete walls.

Due to the experimental nature of the glass design it was decided to limit the glass bearing system to the most important location in the house, the Living Room which is oriented towards the big views to the west and north. The space measures 7.8 m east–west by 10.2 m north–south. The south wall is 40 cm thick concrete and the east side has steel framing concealed inside a fireplace chimney enclosure. Floor to ceiling glass was planned for the north and west sides of the space in order to create an expansive glass room. It was important to have no visible structure in this corner in order to create an experience of pure space, form and materials.

Glass Bearing System

Working closely with Dewhurst Macfarlane, several options for a load bearing glass system were studied. The first concept was a load bearing L shaped glass column located in the corner, in plane with non-bearing glass panels that would enclose the space. An alternative configuration was a cruciform column. Options of two or three layers of laminated glass were considered, and the issue of annealed or tempered glass was examined. Annealed glass was preferred because a cracked ply could retain some strength as part of the laminated assembly, whereas a tempered glass ply would have no residual strength. This desirability of an identifiable "crumbling" failure mode has been very well studied and presented in the development of the ATP Pavilion. [1]

We discussed whether this columnar element should be made to disappear into the non-bearing glass, or whether it would be psychologically reassuring to make it visible, perhaps by means

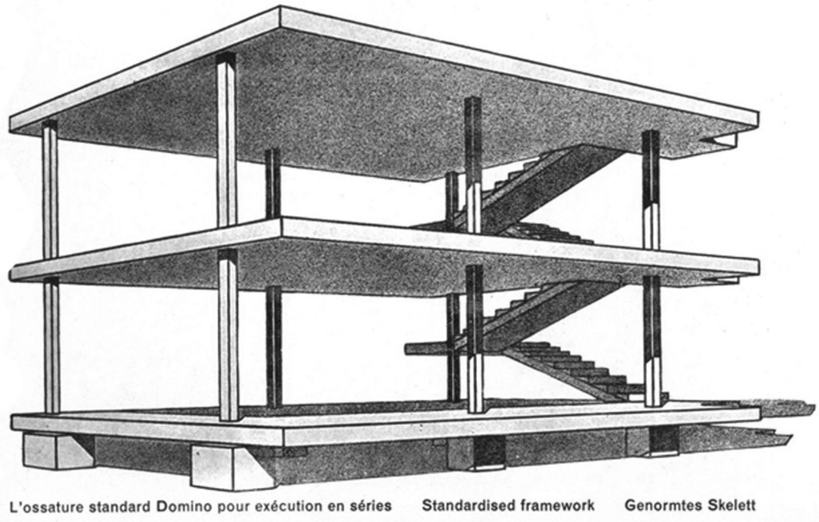

Figure 2

Maison Domino, Le Corbusier, 1914

Figure 3

Barcelona Pavilion, Mies van der Rohe, 1929

Figure 4

Farnsworth House, Mies van der Rohe, 1947

Figure 5

Glass House, Philip Johnson, 1949

of a dichroic coating. The clients were interested in issues of space and perception in contemporary art and architecture so it was agreed to make the load bearing column blend into the glass walls.

From the earliest discussions it was agreed that a thorough mockup and testing program would be a necessary part of the process. It was important to appraise the client early on that it would be necessary to build full size mockups and do extensive testing, and that the process of designing load bearing glass would be very different from traditional structural engineering. The local glass installers were brought into the process at this stage to ensure that they were willing and able to meet all the project requirements. While the budget for the project was generous, there was an ongoing effort to develop details that would be relatively easy to fabricate and cost effective.

Further research into the corner column concept revealed complex connection issues that would make fabrication and installation difficult. A cam/bezel connection was proposed in order to evenly distribute the load into each ply of a multi-ply bearing element. The concentrated load on a corner column and the absence of any redundancy would have required a very high safety factor.

Bearing Wall Development

It was decided to make the longer west wall into a multi-panel bearing wall. The 8.6 m length (less then the overall room size of 10.2 m due to a door) allowed the load to be distributed over a large bearing area. The multiple panels provided redundancy in case of failure. A continuous steel beam was located above the bearing wall in order to simplify the roof framing and provide an easy place to make the connection details at the head. There is a cantilevered roof overhang on the exterior side of this exposure which reduces the torsion on this beam. The glass would work in compression so the controlling characteristics would be its flexibility and slenderness.

The goal was to create a pure plane of glass so we needed to conceal all connection hardware at the top and bottom of the bearing wall by burying it in the ceiling and floor. In the spirit of the Barcelona Pavilion, the glass wall wanted to be a completely independent, sculptural element, without visible connections, bracing or stiffeners.

Further study determined that the dead load of the roof was sufficient that there would be no requirement to resist uplift, thereby eliminating the need for any type of connection that would resist tensile forces. Making the connections to take purely compressive loads allowed the connection details to be greatly simplified. Throughout this process Dewhurst Macfarlane worked closely with the local structural engineers to coordinate the glass wall with the design of the roof, for example to ensure that the roof diaphragm was stiff enough that lateral loads would not be introduced into the glass bearing wall.

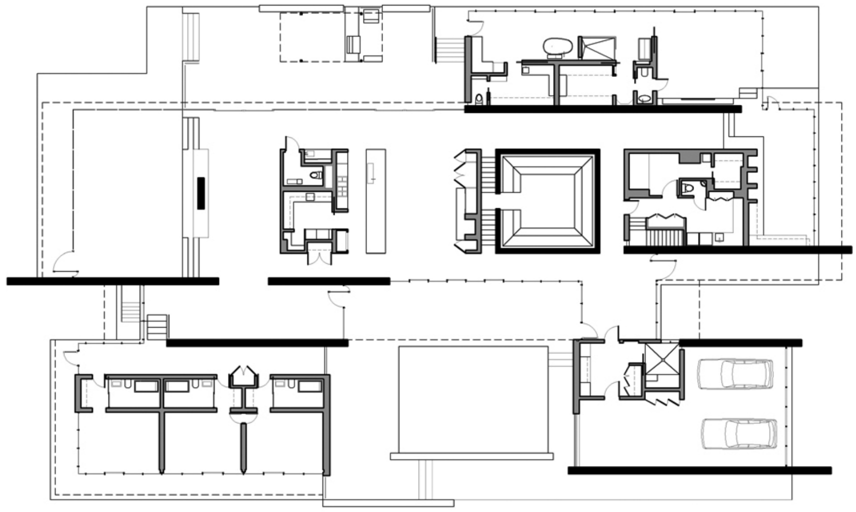

Figure 6
Overall Plan.

Options for the number of panels were studied. Lamination could be easily done up to 2 m in width, so a minimum of five panels would be required. The final selection was to use seven panels each approximately 1.2 m wide. This was based on ease of fabrication and visual appearance. The joints between panels were approximately 1 cm wide and were filled with clear silicone.

The decision was made to use three ply glass panels with a 3/4" inch fully tempered ply in the center, 1/4" fully tempered plies on each side, and 0.06" PVB interlayers. The use of seven panels created a high degree of redundancy, and the center 3/4" ply had enough compressive strength to meet the safety factor requirement of 3. Because the outer 1/4" plies were not needed for load bearing they were designed to be 1/4" shorter than the center ply, thereby ensuring that all the load was transmitted through the center ply. The 1/4" was determined to be adequate to compensate for up to 1/8" of slippage during the lamination process. This greatly simplified the fabrication of the panels and the connection details. Due to the reliance on only the center ply, heat soaking was specified for these pieces of glass. Most glass manufacturers were not eager to provide heat soaked glass so this narrowed the choice to two vendors. A maximum deflection of L/100, or 3.5 cm over a 3.5 m height, was considered the maximum that the client would find acceptable, and a deflection of between L/120 to L/150 was the target range.

The option of creating an insulated load bearing glass was studied. This would have been accomplished by making one of the two glass faces longer and load bearing, and using the other to create the insulating cavity. However, the spacer bars and adhesives would have created black stripes that would have significantly changed the appearance of the glass wall. If a system of clear spacer bars and sealants was available it would have been seriously considered. Creating load bearing insulated glass would have added a significant degree of complexity to the project and compromised the aesthetics. In the future it would be very attractive to find techniques to create insulated glass without the visual drawbacks of the spacer bars and sealants.

Head and Sill Connection

A deep U-shaped shoe that ran the full width of the glass panels was developed for the head and sill connections. The shoes were designed to fit snugly against the glass panels with neoprene spacers on each side. Purchasing a shoe of the correct dimensions was not possible so a shoe of precisely the right width was fabricated by using two steel angles that were machined and fixed together. Each shoe has two threaded rods, located at the quarter points, to transmit the load into the roof steel or foundation and allow precise leveling of the shoes to ensure very even load distribution across the end surfaces of the 3/4" ply.

To ensure the even distribution of the roof load a stack of spring washers were used at each of the head connections. A system of nuts on the threaded rods allowed the height of the stack of spring washers to be carefully equalized. The exact height of this stack could then be checked several months after installation to ensure that the panels were still being uniformly loaded. Additionally, in the event of abnormal loading of the roof or the loss of a panel the spring washers would assist in redistributing the load.

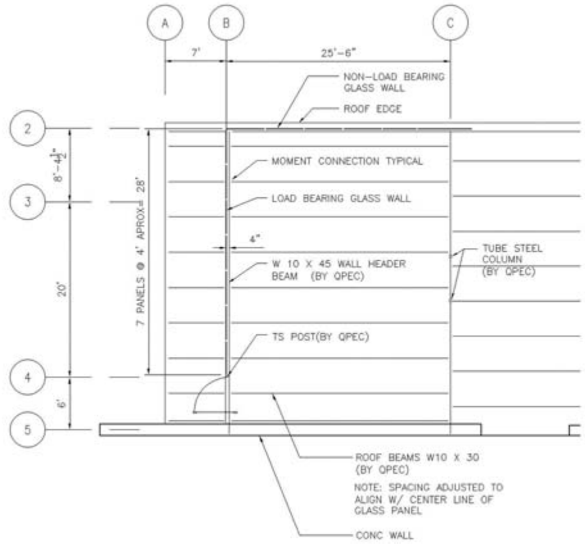

Figure 7
Plan of Structure.

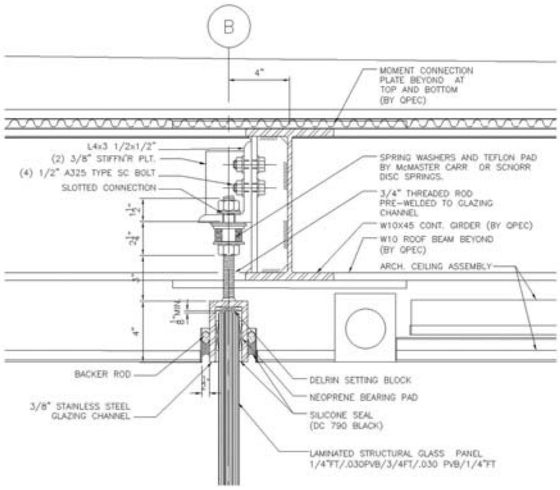

Figure 8
Head Detail.

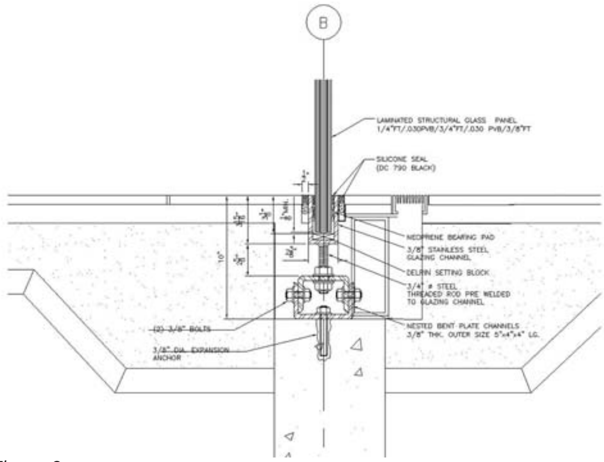

Figure 9
Sill Detail.

Figure 10
Shoe Detail.

Testing & Installation

A full sized glass panel and a series of smaller test panels were fabricated for testing. The full panel was subjected to a series of increasing axial loads while a variety of lateral loads were applied so simulate various wind loads. The smaller samples were tested to failure. As previously indicated to the client, the design and execution of the testing procedure was time consuming and had a significant cost. This reinforced the importance of thoroughly preparing the client for the time and effort required to develop even a relatively simple system such as this one.

A number of construction sequence issues were reviewed with the contractor before the installation was started. The glass was planned to arrive as late as feasible to reduce the possibility of damage by other construction. The roof steel was to

Figure 11
Roof Framing.

Figure 12
Top Shoe Detail.

Figure 13
Panel Installation.

Figure 14
Completed Installation.

Figure 15

Interior looking out.

Figure 16

Exterior.

be erected at or slightly below its final elevation and held in place with shoring. The shoes would be installed onto the glass panels in the field just prior to craning the panels into place. When the glass panels were installed they would then be very gradually tightened up against the roof connections to slowly and evenly transfer the load onto the glass. The 2.6 m roof cantilever could not be installed until after the glass was in place so particular attention was paid to the protection of the installed glass. The preparation was thorough and complete and the glass installation was completed in less than a day.

Summary

The architectural space formed by the load bearing glass wall is visually remarkable and psychologically very intriguing. The large area of roof which cantilevers out past the glass wall is very dramatic in the way it both frames the landscape and pulls the viewer out towards it. The hovering roof plane provides an unusual sense of shelter because there is clearly no visible means of support. Once the viewer is made aware that the pure glass wall is holding up the roof the perception changes again to one of surprise and curiosity.

Glass bearing walls represent an important step in the quest for truly transparent structure that allows a seamless flow between interior and exterior. The use of glass bearing walls is an exciting opportunity to blur the distinction between engineering and aesthetics and thereby expand the vocabulary of architecture.

[1] Designing and Planning the World's Biggest Experimental Glass Structure, F. Bos et al, GPD 2005

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