NEW POINT SUPPORTED GLASS SEISMIC SYSTEM

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ABSTRACT

The intent of this paper is to present the seismic performance of a proposed Point Supported Glazing System. This system may be used for cladding facades of buildings in areas of high seismicity and in particular, in the State of California.

The 2001 Edition of the California Building Code (California Building Standards Commission et al., 2002), CBC, is the basis for the design methodology of Building Cladding Systems in California. The seismic provisions of the CBC require that cladding systems be designed to accommodate a maximum inelastic drift of 2 to 2½% of the building height for Seismic Zone 4. Most point supported glazing systems that are commonly used do not accommodate large building drifts. Thus there is a need for an alternate Point Supported Cladding System to address design criteria imposed by the current code.

To verify the CBC performance criteria, Advanced Structures Inc. (ASI) performed a mock-up test on a wall measuring 25 feet wide and 20 feet high. A series of tests imposed a lateral drift in excess of 7 inches, incrementally at the top of the wall frame. All of the glass panels remained fully intact.

The primary goal of the test was to verify that the glass would translate horizontally and distribute drift proportionally over the height of the glazing system without breaking. The test also sought to show that the silicone would withstand the shear demand imposed without rupturing, and without failing any other component of the system.

INTRODUCTION

Presented herewith, is the seismic performance of an alternative Point Supported Glazing System which will accommodate the elastic and inelastic seismic drift criteria outlined in the 2001 Edition of the California Building Code (CBC). The performance of the system was verified by mock-up testing, demonstrating that the proposed Point Supported Glazing System can be used for cladding facades of building structures in areas of high seismicity, such as the State of California (Seismic Zone 4).

The 2001 CBC is the basis for the design methodology used throughout California for the design of structures, including the building cladding systems. The seismic provisions in the CBC require that the cladding system accommodate movements of the structure for the elastic, as well as the inelastic displacement. Most point supported glazing systems that are commonly used do not accommodate large building drifts. Thus there is a need for an alternate Point Supported Cladding System to address design criteria imposed by the current code.

After a brief description of the structure for the alternate cladding system, the seismic load path and method of drift accommodation are explained. To verify the CBC performance criteria, Advanced Structures Inc. (ASI) designed a testing procedure, fabricated the structure and performed a mock-up test on a point supported glass wall measuring 25 feet wide and 20 feet high.

CURRENT CODE PHILOSOPHY AND IMPLEMENTATION

The intent of the code is to prevent

- Non-structural damage in frequent, minor ground shaking
- Structural damage and minimize non-structural damage in occasional moderate ground shaking
- Collapse or catastrophic damage in major ground shaking

Above all, the code aims to preserve life safety under all but the worst cases. The elastic level seismic drift requirements correspond to demand to preserve building functions and finishes due to frequent, minor ground motion. The inelastic seismic drift requirements establish a performance level to avoid collapse and serious injury to the public corresponding to stronger and less frequent events.

The implementation of code philosophy in the design of cladding systems presents some unique issues particularly, the requirement that the cladding system must accommodate movements of the building structure based upon Δ_m. Please note that the code simply states that the cladding system shall “accommodate” the movements, and does not define what is considered acceptable accommodation. Thus it is left to the cladding designer to use an appropriate definition of “accommodation” that is relevant to the performance of the specific building and system.

ASI defined the acceptable criteria that accommodates the building drifts for the mock-up tests, based on sound engineering judgment as,

- Under elastic displacement
  - No damage or disengagement of the frame,
  - No brittle failure of members or glazing system,
  - No breakage of metal or glass panels,
  - Maintain serviceability of the structure and life safety

- Under inelastic displacement
  - Deformation or minor damage of framing members, and/or breakage of glass (defined only as cracking or spalling) may occur,
  - System anchorage may deform, but catastrophic failure cannot occur (i.e. glass panels or fittings falling out or off of the assemblage),
  - Damaged or broken materials may not dislodge from the wall (i.e. pieces of glass in excess of one square feet or glass fitting, falling out or off of the assemblage)

Code Limitations

The code is only an estimate of actual forces and deformations. And in general, the inelastic deformation limit of 0.025*h or 0.020*h (depending on the period of the building superstructure) is considered to be a conservatively large displacement. The mockup frame at the testing facility was deformed by 0.004*h (elastic limit), 0.020*h (inelastic limit) and 0.029*h (overload based on equipment limitations) under separate tests.

DESIGN CRITERIA

The design criteria is based on the California Building Code (CBC). The code requires that cladding systems be designed to withstand the maximum elastic drift of the structure without compromising the performance (structural and enclosure characteristics) of the system. The code also requires that under inelastic requirements the cladding system is to be designed to prevent collapse of the system. In addition to the code requirements noted above, ASI has increased the performance of the alternate point supported glazing system to allow increased deflections at or near the inelastic limits to create a system that minimizes the damage to the glass and support system components, even at the inelastic deflection levels. Thus the cladding system will require only minimal repairs after a significant seismic event.

The CBC requires that the calculated story drifts using the Maximum Inelastic Response Displacement (Δ_m) shall not exceed 0.025 times the story height for structures having a fundamental period of less than 0.70 seconds. For structures having a fundamental period of 0.70 seconds or greater, the calculated story drift shall not exceed 0.020 times the story height. The maximum inelastic response displacement, Δ_m shall be computed as follows:

$$\Delta_m = 0.7\ R\ \Delta_s$$

- R = the numerical coefficient representative of the inherent over-strength and global ductility of lateral force-resisting systems
- Δ_s = the Elastic Design Level Response Displacement as determined by analysis

It should be noted that Δ_s and R, are both values that are characteristic of the base building structural system. As the information is critical to the design of the cladding system, it would be beneficial to the design of the system to have the actual calculated values for Δ_s and R from the Building Engineer. However, cladding designers typically do not have this information at the time of design and subsequently design for code maximums.

OVERVIEW OF THE STRUCTURAL SYSTEM

The mock-up structure is comprised of three basic components:

1) the steel backer structure consisting of pin-connected tube steel horizontal and vertical frame,
2) steel spider fittings with slotted holes
3) glass panels with ball and socket glass bolts to connect the glass to the spiders and silicone to seal the glass joints

The spider elements are typically machined or cast in steel. However, the spider elements in the mock-up test were flame cut from steel plate and were bolted to the tube structure. This resulted in rougher holes in lieu of smooth clean hole surfaces. The spider slots were sized to accommodate a drift of 0.020*h over a 10' panel height. Glass bolts were standard ball and socket type, and included bushings in the bottom slot of every spider to ensure that the system would be dead loaded and could easily displace. Glass panels were ½" thick, monolithic and fully tempered. 5-foot glass panels were placed at the top and bottom rows and 10-foot glass panels were placed at the middle row. Vertical and horizontal glass joints were sealed with low modulus silicone sealant.

The spiders with the slotted holes are the crucial element of the system (Figure 1). Their purpose is to allow the glass to accommodate a large drift demanded by horizontal translation. The size of the slot is based on the maximum panel height and the CBC maximum inelastic drift limit of the structure under consideration, either 0.020*h or 0.025*h depending on the period of the building. This allows the system to be used in any building for which the inelastic drift has not been determined by analysis. Without the capability of lateral movement provided by the proposed slots, the building deformation would impose in-plane loads on the glass, and may overstress it or increase the possibility of failure.

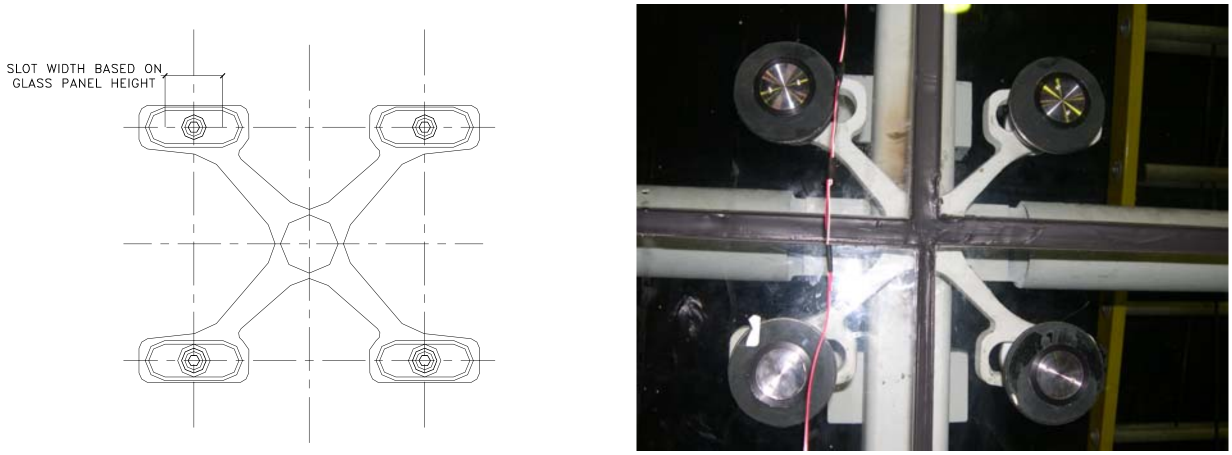

Fig. 1 Slotted Spider Connection Showing Glass Bolts and Bushings in Slots

The intent of this system is to isolate the glass from the primary building structure for in-plane deformations and loads while supporting it vertically and for out of plane loads. Figure 2 illustrates the behavior of the glass panels with slotted spider connections. Building drift is accommodated proportionally through shear deformations at each horizontal glass joint, reducing the stress on the glass. This reduces the probability of breakage and therefore fallout, in an effort to preserve life safety in major seismic events.

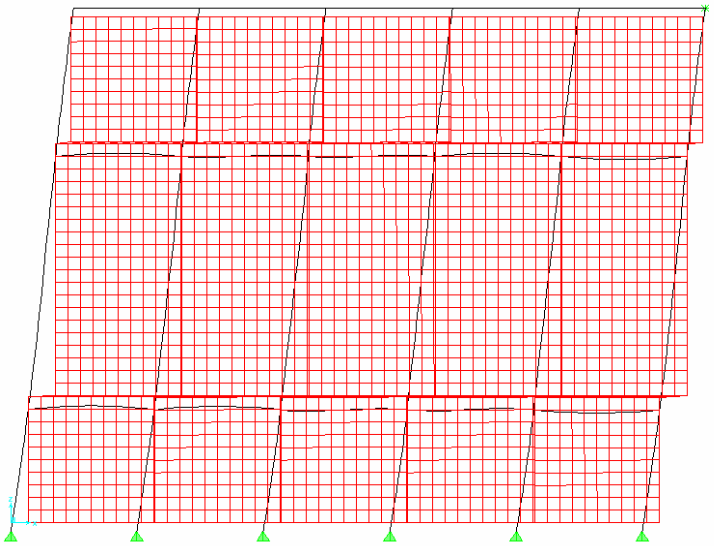

Fig. 2 Elevation Illustrating Shearing Action as a Result of Seismic Drift

Glass bolts connecting the glass to the spiders are also designed to minimize the possibility of failure in the glass. Holes are drilled in the glass to accept the bolt assembly with a malleable bushing against the glass to minimize stress concentrations around the holes. A ball and socket at this connection point prevents transmission of bending stresses in the glass (Figure 3).

Together, the bolts and spiders act like a pin connection for out-of-plane loads, and a roller connection for in-plane loads. Bushings for the bolts are inserted in the bottom slots of each spider to carry the glass dead load (Figure 1). Omitting the bushings in the top slots eliminates vertical support at that location, allowing the glass to expand due to thermal movements without inducing additional stresses in the glass.

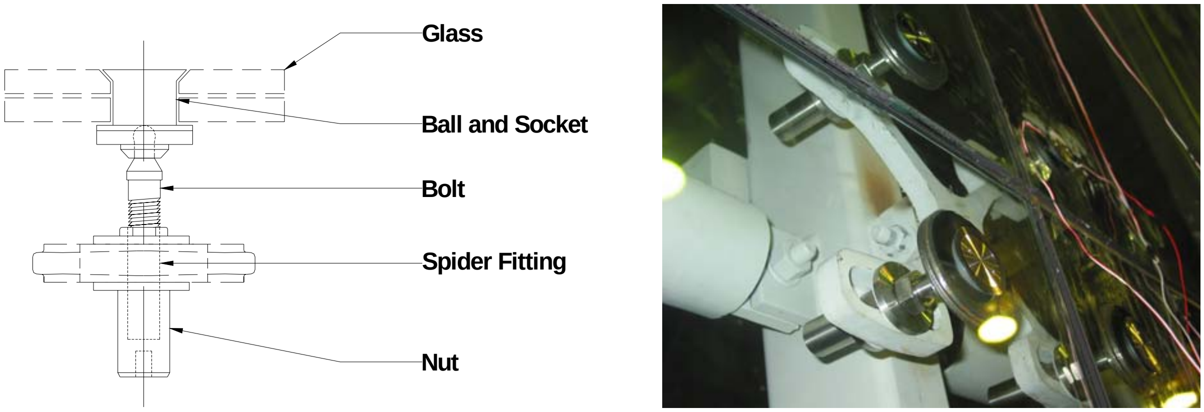

Fig. 3 Glass Bolt Assembly Showing Glass and Spider Elements (Dashed)

The point supported glass panels are heat treated (heat strengthened or fully tempered) to resist local stresses at the holes, and can be laminated or monolithic based on the type of application. Low modulus silicones are used to create flexible joints that allow the glass panels to use the full travel provided in the spider slots. Perimeter closures must also be detailed to prevent the glass from contacting adjacent building elements or coming out of the joint under inelastic drift.

The framework supporting the spiders, bolts and glass is considered to be the backer support structure for the Point Supported Glazing System. Because of the slotted holes in the spiders, the deformations of the backer structure do not need to coincide with that of the glazing system. Possible backer structures may include simple tube steel frames or more complex cable systems. The basic requirements of the framework are that it distributes drift over the height of the system and that it maintains structural integrity under the design load conditions.

MOCK-UP AND TESTING

ASI conducted a series of tests on a mock-up support frame assembly and glazing system to demonstrate performance under elastic and inelastic drift conditions. The wall was subjected to lateral translation in incremental magnitudes for three cycles for elastic drift conditions, and one cycle for inelastic drift conditions. Figure 4 below depicts the mock-up frame assembly at the ASI TrussWorks fabrication facility.

Mock-up testing for the point supported glazing system was performed in accordance with the test procedure noted below. The testing regimen included both elastic and inelastic displacements to simulate drift requirements of the code. The following is a description of the test procedure and defined acceptance criteria: Deflection and strain were measured at various locations at incremental displacement steps for test items 1 and 2 below. The overload drift test was conducted for visual observation only.

1. Lateral Drift Test (elastic displacement): The top of the support frame was displaced by 0.004 x Wall Height (1”) parallel to the plane of the glass for at least three full cycles. One cycle is defined as moving to one side then to the opposite side and finally back to the initial position.

   Acceptance Criteria per Specification: “No damage or disengagement of glass, framing members, or silicone shall occur”.

2. Lateral Drift Proof Test (inelastic displacement): The top of the support frame was displaced by 0.025 x Wall Height (5”) parallel to the plane of the glass for at least one full cycle.

   Acceptance Criteria per Code: “Deformation or damage of framing members, and/or breakage of glass may occur defined only as cracking or spalling. System anchorage may deform but catastrophic failure cannot occur (glass panels falling out or off of assembly), nor shall any damage or broken materials fall from the wall (pieces in excess of one square feet or glass fittings, falling off assembly).”

   Additional ASI Acceptance Criteria: no major permanent deformations or damage to the backer support structure and only minor damage to the glass panels and/or fittings.

3. A third overload drift test was conducted to 0.029 x Wall Height (7”) to evaluate the performance of the system beyond its design limits. No acceptance criteria were used for this test.

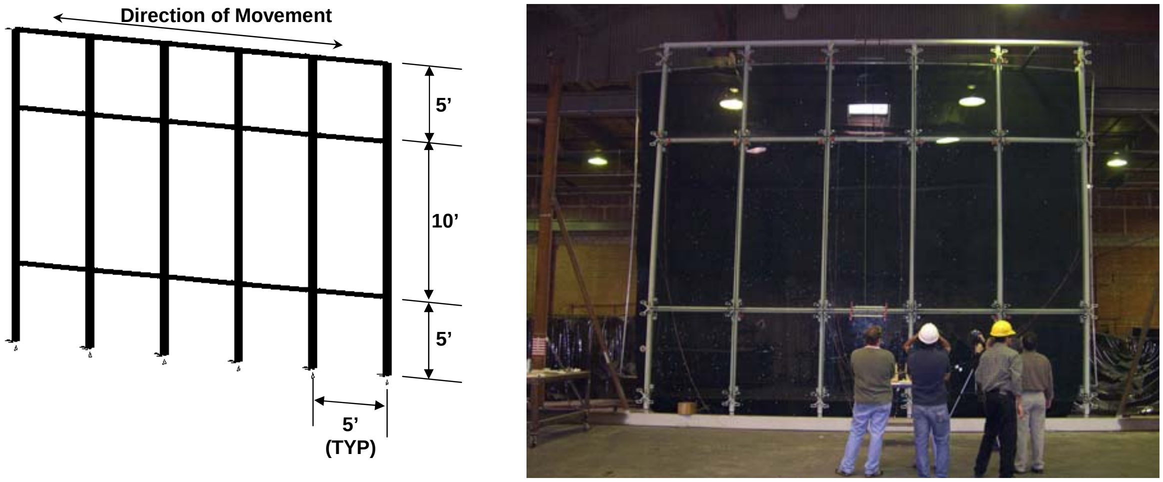

Fig. 4 Schematic of Mock-Up Frame and Actual Frame Assembly at ASI TrussWorks Fabrication Facility in Santa Fe Springs, California

The primary goal of the test was to verify that the glass would translate horizontally and distribute drift proportionally over the height of the wall without breaking the glass panels. The test also sought to show that the silicone sealant would withstand the shear demand imposed without rupturing, and would still deform adequately to prevent imposing large loads on any other component of the system.

Table 1 Test Results

Induced Displacement at Top of Wall	Drift Limit	Maximum Stress (kips per square inch, ksi)		Maximum panel deflection (inches)	
		Location	Magnitude	Location	Magnitude
1”	Elastic 0.004*h	Strain Gage #6	≈0.000	Disp. Gage #1	0.188
4-13/16”	Inelastic 0.020*h	Strain Gage #7	0.480	Disp. Gage #1	0.500
7”	Overload 0.029*h	No data recorded		No data recorded	

In general, the system behaved as exceptionally and met all code criteria and additional criteria imposed by ASI. Glass silicone joints sheared horizontally, accommodating the drift with apparent ease. Only when the frame was racked beyond the design range of the spider slots (overload drift), did the glass show noticeable rotation. No glass or bolt failures were observed. The maximum stress measured in the glass was approximately 1 ksi, which is dramatically lower than the 12 ksi allowable stress limit for fully tempered glass. The only components that did not perform ideally was the bushing translation within the holes, which was due to two main factors: 1) the hole slot in the spider was rough and 2) the bushing was undersized. This would have been prevented had the spiders been machined or cast as previously stated.

CONCLUSIONS FROM TESTING

ASI's point supported glazing system performed as intended in the test, validating its design. Drift was accommodated at horizontal glass joints, and the panels themselves were minimally stressed. Even after exceeding the inelastic drift limit no failures were observed in the glass or other system components.

The bolts and spiders performed well despite having some difficulty due to their binding. They released in short spurts as the frame drifted further. Therefore the binding ultimately did not present a serious problem. A tighter fit-up by increasing the size of the bushing in the spider slot and providing a smoother surface would improve the performance for future applications.

The glass passed the test very comfortably without any cracks or breakage, and the recorded stresses were very low. Since the tested panels were monolithic, the glass bolts were able to bear on the entire inside surface of the holes. In laminated panels, the bolt would typically bear on the hole in only one of the lites. Thus because the measured stresses were relatively low in a single lite, one can conclude that the stresses on a laminated panel will be within limits. The silicone stretched as intended, and no tears were observed. Because a very low modulus silicone was used, this result was expected.

In summary, the engineering principles were confirmed. The glazing system performed without damage well beyond its design limits. Other changes such as different panel heights or drift requirements could also be made with confidence to ensure proper performance. The alternate system utilizing spiders with slotted holes is a viable choice where a drilled glass, point supported glazing system is desired for buildings in areas of high seismicity or where large in plane movement must be accommodated.

PROJECT APPLICATION

The spider component was envisioned as a design for investment castings. It was understood that the flame cut components used in the initial tests would not be an architecturally acceptable solution; therefore the final component was converted in parallel to the tests to a design for stainless steel investment castings. The shape takes full advantage of the casting process allowing a highly complex surface articulation of components, which would be impossible or cost prohibitive to achieve with machined parts.

The findings of the initial test also informed improvements made to the investment castings. A smoother rolling and sliding motion was accomplished with the finer surface finish and higher fabrication tolerances of the spider casting as well as the reduction of friction for sliding parts by minimizing the contact surfaces and the introduction of Teflon washers. These improvements eliminated the binding problems encountered in the first test and were verified in subsequent tests. The new component will be used in its first project application for the San Jose Civic Center Dome, a project designed by the architectural firm of Richard Meier & Partners, currently under construction.

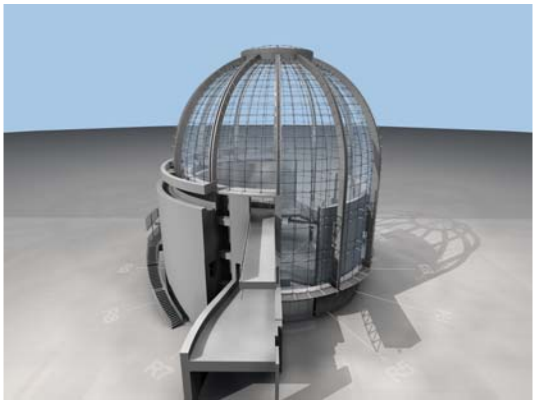

Fig. 5 Rendering of the San Jose Civic Center Dome

The backer structure of the glazing system for the San Jose Civic Center Dome utilizes a horizontal cable truss system tensioned between a vertical steel rib structure with additional vertical cables supporting the dead loads. The spider is pinned to the spreader bars of the cable truss. The dead load support cables are clamped to the front of the spiders.

The mock-up tests have proven that the system works satisfactorily with spiders fixed to vertical framing members, but the San Jose project introduces a clear advantage by using a horizontal backer structure. During the lateral translation in a simulated seismic event, the spiders mounted on the vertical framing follow the inclination of the framing member eventually inducing a rotation into the spider, which will be transferred through the glass bolts into the glass panels. An application with a horizontal backing structure eliminates this rotation, since all components travel parallel with the joint lines, reducing stresses on the glass supports even further.

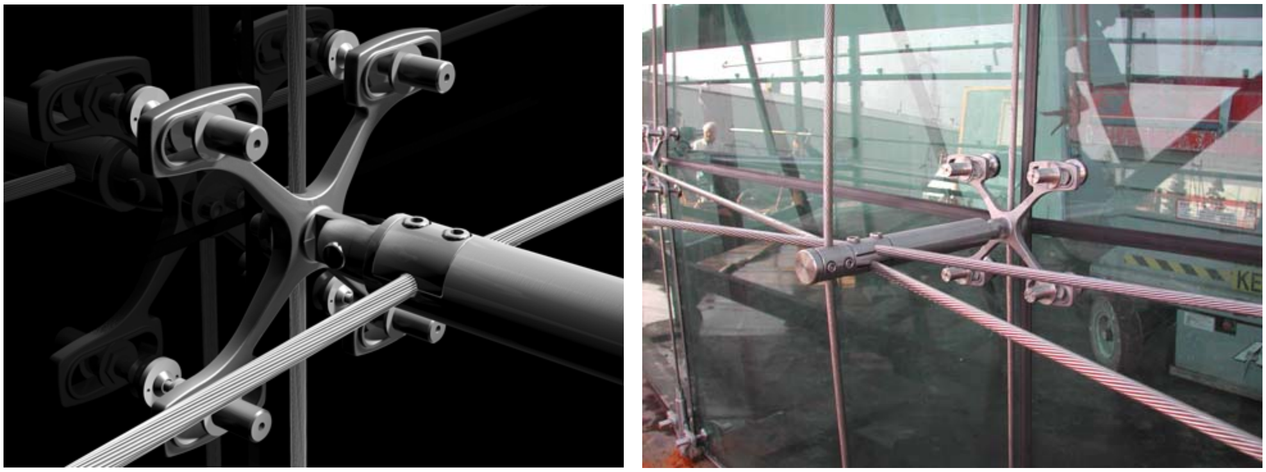

Fig. 6 Computer Rendering of the Final Spider Design and Finished Components in the San Jose Mock-Up

A large scale mock up test, representing a portion of the project, was conducted for the San Jose Dome with all of the finalized components of the system. This mock up addressed all the issues raised in the conclusion of the initial tests, effectively eliminating all binding and allowing smooth travel of the bushings along the slots. During the lateral drift proof tests, the wall was displaced by 7.2” (0.02*h) each way for a total of three cycles, returning to its original position after each cycle without any damage to components and weather seals.

Fig. 7 San Jose Civic Mock-Up and Maximum Inelastic Joint Deformation After Testing

REFERENCE

California Building Standards Commission and the International Conference of Building Officials (2002). *2001 California Building Code, California Code of Regulations, Title 24, Part 2 (Volume 1)*