FT monolithic glass panels thicker than ¼ in. often lead to spalling and on rare occasions break off of through-thickness corner fragments without the complete failure of the glass lite. A number of instances of spalling and chipping were observed during these tests, and were recorded and plotted as glass damage. A typical cause of spalling was glass panel bypass in the FG-2000 mockup tests. Only one instance of glass fallout was observed in the planar mock-ups, which occurred during the 5-1/2 in. racking step for one of the FG-3000 mockups. The interior lite of the leftmost glass panel cracked and fell out. During the 6.00 in. racking step, the intact outer pane fell out of the frame and shattered upon contact with the floor. According to the ASCE 7-10 (2010), the maximum allowable drift ratio is 2.5%, while the drift ratio for glass fallout reported here is over 5%. Thus, glass failure is highly unlikely to occur in these wall systems in real building installations under design loads and displacements.

Figure. 9- A Reentrant corner mockup.

TESTING AND PERFORMANCE OF REENTRANT CORNER MOCKUPS

End restraints were placed along the leftmost vertical edge of the planar section of the reentrant mockups in the same manner as planar mockups; however, end restraints were varied at the reentrant corner. In most reentrant corner installations, the only end restraint along the corner would probably be that caused by the interconnections of the planar and reentrant portions of the framing and the head and sill anchors along the reentrant portion of the framing. Thus, at least one mockup of each wall system was tested with no end restraints at either the top or bottom of the reentrant corner framing. In addition, some reentrant corner mockups were tested with end restraints at the reentrant corner. A reentrant corner mockups is shown Figure 9. All of the damage modes described for the planar mockups were also observed and tracked for the reentrant mockups. Not surprisingly, the glass panel and the gasketing in the reentrant portion of the glass framing generally did not experience any distress for the FG-3000 and 3000–TMP mockups, but did in a number of the FG-2000 mockups. For this study, it was of interest to determine the effect of the out-of-plane reentrant panel on the in-plane panels. The glazing pockets along the reentrant panel's top and bottom edges and corner framing detailing allowed the glass panel to rotate out-of-plane without significant resistance so very little force acted on this glass panel. When the reentrant panel was unrestrained, the head anchor and also the upper horizontal mullion of the reentrant panel accumulated damage. During application of large racking displacement amplitudes to the FG-3000 and 3000-TMP reentrant corner mockups, head anchor deformation allowed out-of-plane translation of the upper horizontal mullion. Head anchors are expected to prevent this from happening. A deformed head anchor can be seen in Figure 10.

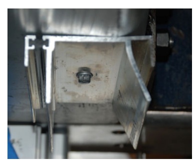
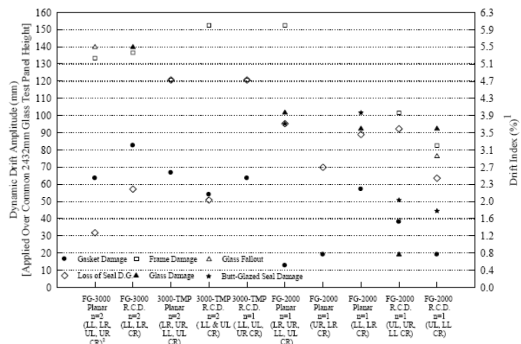


Figure 10. End of test condition of a reentrant corner head anchor.

Test data for each damage mode described herein are presented in Figure 11 for each wall system planar and reentrant corner mockup variation tested. Data plotted in Figure 11 represent the average across all glass panels for the onset of each failure mode. First instance of each damage mode in the mockup would plot somewhat lower, but is not presented herein. Effects of end restraint variations and mockup plan (planar or reentrant corner) on damage modes are readily seen in Figure 11. In general, more restrained boundaries force glass panels to translate and rotate more than an equivalent mockup with less restraint. This additional motion of glass panels relative to the frame leads to an earlier incidence of most damage modes.



[1]Drift index is calculated here by dividing drift limit by the glass panel height and multiplying by 100

[2]Abbreviations: LL-Lower Left; LR- Lower Right; UL-Upper Left; UR-Upper Right; CR-Corner Restraint; R.C.D.-Reentrant Corner Detail; D.G.- Dry Glazed

Figure 11. Summary of test data for all mockups tested.

CONCLUSIONS

Primary failure modes observed during racking tests of these storefront wall system mockups are seal loss via gasket movement or sealant damage and frame damage. Glass damage did occur on occasion but was not extensive. Serviceability failures that led to loss of seal would be repairable in an actual installation. The extent of seal loss would depend on the severity of glass/frame movements experienced during an earthquake. Repair of frame damage could be much more costly because in most instances glass panels would need to be removed and the damaged framing components replaced. This would disrupt the use of the building and result in indirect economic losses beyond direct economic losses attributed to repair of the wall system. Although frame damage is not always discernable upon direct visual inspection, storefront and entrance wall system framing in buildings that experience high interstory drift ratios should be examined after an earthquake event. These tests showed that the design of the storefront systems tested is adequate for seismic regions because damage to glass was minimal and could occur only at large drift ratios well beyond the code maximum value of 2.5%.

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Seismic Evaluation of the Four-Sided Structural Sealant Glazing Curtain Wall System for Cathedral Hill Hospital Project

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ABSTRACT

Cathedral Hill Hospital (the California Pacific Medical Center) is a 15-story building to be constructed in Downtown San Francisco. The curtain wall system for this building is primarily of unitized design employing a four-sided structural sealant glazing (SSG) system. To ensure satisfactory seismic performance of the curtain wall system for this project, dynamic racking tests were carried out according to AAMA 501.6 procedure on curtain wall mockups constructed with vertical and horizontal mullions that had section properties similar to the ones that will ultimately be used on the building. Although the curtain wall system designed for this building is unitized, the preliminary tests reported in this paper were carried out on mockups that were constructed as stick-built. The objective of the preliminary tests was to evaluate the performance of structural sealants as well as the glass when the mockup is racked in a worst case scenario. The building and curtain wall design are explained and the results of racking tests presented.

INTRODUCTION

Cathedral Hill Hospital (the California Pacific Medical Center) is a 15-story building that has recently been designed and is to be constructed in Downtown San Francisco. The curtain wall system for this building is primarily of unitized design employing a four-sided structural sealant glazing (SSG) system (ASTM 2009). The four-sided SSG system is referred to as system where the glass panes are attached to the glazing frame on all four sides using structural sealant. The unitized system consists of a shop-glazed framing that has the glass panes attached to the framing in the shop and the panels are then assembled at the job site. In particular, horizontal stack joints are provided that accommodate in-plane sliding between vertically stacked panels which meet at the horizontal stack joint. Although four-sided SSG systems have been used in high seismic regions, such systems have not been used for healthcare facilities in California. This healthcare facility project will be the first of its kind to use this glazing system type.

To ensure satisfactory seismic performance of the curtain wall system for this project, ASCE 7-05 (ASCE 2006) adopted by the International Building Code, IBC (ICC 2006), requires a dynamic racking tests to be carried out on mockups of the curtain wall system according to AAMA 501.6 procedure (AAMA 2009) when three or more sides of the glass panes are not mechanically captured. Performing this test was also a requirement established by Office of Statewide Health Planning and Development (OSHPD) early in the design process so that they could be assured that the four sided curtain wall system would perform satisfactorily on a California hospital. This test procedure is intended to determine the drift associated with glass fallout. ASCE 7-05 (ASCE 2006) requires the drift capacity of the curtain wall, represented by the glass fallout drift, sufficiently exceed the design drift determined based on structural analysis of the building.

Since the aluminum glazing frame sections for this project are custom designed and will be extruded after design documents have preliminary approved by OSHPD, it was decided to carry out preliminary AAMA 501.6 racking tests on mockups constructed using available mullion sections with properties similar to the final sections that will be extruded later. The objective was to show satisfactory performance of a four sided SSG system to help ensure that the conditional design document received approval. The final approval of the design documents will require racking testing associated with the AAMA 501.4 testing protocols, of mockups constructed using the custom extruded sections.

The objective of this paper is to introduce the project and present the main results of the preliminary racking tests. In the following sections, some of the design and detailing aspects of the curtain wall system and the AAMA 501.6 test method are explained. Then, the results of full-scale tests on preliminary mockups of the curtain wall system carried out at Architectural Testing Inc. in York, PA are presented. The mockups were designed to determine the behavior of the glass, framing, connections, and more importantly, the structural silicone under racking displacements. This paper contributes to a better understanding of the behavior of four-sided SSG systems constructed based on stick-built approach for use in high-rise projects in seismic regions.

BACKGROUND

The majority of SSG construction is of two-sided type, which commonly consists of attaching the two vertical glass pane edges to mullions using structural sealant while the two horizontal edges are captured within glazing frame pockets using rubber gaskets based on dry-glazed construction system. In four-sided SSG systems, all four sides of a glass pane are attached to the glazing frame using structural sealant (Dow Corning, 2006, 2007). Because of the lack of a mechanical capture for the glass panes in four-sided SSG, reliance is heavily based on the adhesion property of the sealant material to the glass and aluminum substrates. Although sealant manufacturers, curtain wall designers, and glazing installers generally follow well-established standards, guidelines, and procedures for specifications, design, detailing, fabrication, and installation of four-sided SSG systems, nonetheless, some concerns about their seismic performance still exists. For this reason, full-scale mockup testing is necessary to establish satisfaction of the code's seismic provisions. Of course, such concerns in the past have been more about the shear deformation capacity of the structural sealant in stick-built curtain wall systems. Recent experimental studies on racking test evaluation of two-sided and four-sided SSG curtain wall systems (Memari *et al.* 2006, Memari *et al.* 2010) provide some insight to seismic performance of stick-built SSG systems. Most of such concerns have been resolved recently through the use of unitized construction of four-sided SSG systems. Whereas in stick-built construction the glazing frame is usually continuous over multiple stories, and therefore the glazing panel will be forced to rack under story drift and subsequently transfer large strains to structural sealants, the unitized system is structurally discontinuous from story to story. This is accomplished through shop glazing and prefabricating the complete panels and simply attaching adjacent panels to one another through stack joints that easily allow sliding between panels. For this project, typical stack joint details as shown in the renderings of Figure 1 are to be used.

In unitized systems the stack joints effectively create seismic isolation joint that allow one panel to slide with respect to an adjacent panel to accommodate story drift, and therefore, the structural sealants will not be as heavily stressed as in a stick-built construction. For preliminary testing in this project, however, it was decided to investigate a worst scenario, which would mean a unitized system failing to behave as intended and in turn perform as a stick-built system by racking under in-plane story drift. The objective was to understand how the sealants perform under a racked frame condition. By showing that the performance of glass and sealants satisfied the intent of the code provision in a stick-built construction, there will be assurance that the system will perform satisfactorily under an actual unitized construction condition.

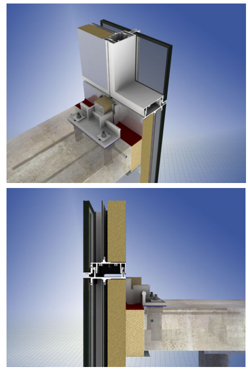
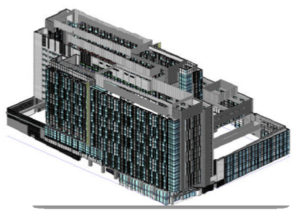


Figure 1. Rendering of stack joints and anchor system.

DESCRIPTION OF THE BUILDING AND THE CURTAIN WALL SYSTEM

The proposed location of California Pacific Medical Center (CPMC) Cathedral Hill Hospital is in the City of San Francisco at the intersection of Van Ness Avenue and Geary Boulevard. Figure 2 shows a perspective drawing of the building and a photograph of its location area. The structural system of the building consists of moment-resisting steel frames with supplemental viscous dampers. The floors will be constructed of concrete fill on metal decks supported on steel beams. The building is comprised of three main components; the “Podium”, the “Tower”, and the Rooftop Equipment and Central Plant. A significant portion of the exterior cladding system of the Tower, Levels 7-15 on the north and Levels 3-15 on the south, is comprised of four-sided SSG unitized curtain wall. Below Level 5 of the Podium on the north, east and west elevations, is a combination of stone cladding, metal panel, punched windows, storefront and unitized curtain wall.



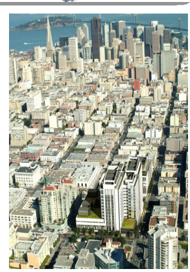


Figure 2. Building drawing and its location.

The curtain wall unitized panel for this building is typically an 8’-4” wide by 14’-0” or 17’-0” tall unit in the Tower as shown in Figure 3, or 17’ tall at the Podium (floors 1-7) floors. There are three 8’-4” panels and one 4’-0” wide panel at each typical 29’-0” bay. Figure 3 illustrates the four basic compositional modules within the 8’-4” wide units. These are basically the same configuration, but are mirrored or flipped units, which serve to create visual complexity within the skin of the building. All exterior glazing of the hospital is 1” thick insulating glass units (IGU) which are fully supported on all four sides by glazing frame members attached to glass through structural silicone. The factory coated finish on all extruded aluminum components of the curtain wall system will be a two-part Kynar polyvinylidene fluoride (PVDF). PVDF is a specialty resin plastic material in the fluoropolymer family and is used generally in applications requiring the highest strength, and resistance to solvents, acids, bases and heat, and it is the premier finish for curtain wall and window aluminum extrusions. There is a horizontal movement 'stack' joint 7 3/4” above the top of slab as shown in Figure 1 at each floor accommodating lateral movement and vertical deflection at each floor. As shown in Figure 1, there is a vertical ‘stack’ movement joint at each side of the typical unit.

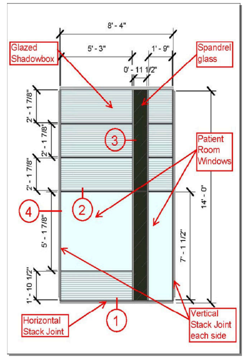


Figure 3. Typical unitized curtain wall panel.

The unitized curtain wall system is connected to the building by a pair of vertical hook plates (two per panel) attached to the nesting vertical stack mullions just below the horizontal stack joint. These vertical plates are ‘hooked’ on to an extruded aluminum bearing plate with serrated edges which in turn is bolted to the cast-in Halfen channel anchors at the slab edge as shown in Figure 1. Additionally, the vertical hook plates will be mechanically fastened to this bearing plate once final alignment has occurred. The hook anchor plate incorporates height adjusting screws which provide vertical alignment of the unit during installation. Slotted holes in the aluminum bearing plate allow for in-and-out alignment.

DISCUSSION OF GLAZING SYSTEM DESIGN FOR WIND AND SEISMIC LOADS

The Cathedral Hill Hospital project involves the use of a custom designed unitized curtain wall system. While structurally very similar to other unitized curtain wall systems, the aesthetic requirements for this project mandated that a custom aluminum extruded mullions be created. In addition to being a unitized curtain wall system this is also a four-sided SSG (Figure 4) system. No sides of the glass are mechanically captured to the mullions. The bottom (sill) horizontal mullion is mechanically engaged into the head mullion of the unit below (Figure 4). The mechanical connection of the vertical stack mullions to the slab through the hook plates restrains top of each the unit from movement in the three translational component directions. The mechanical engagement of the sill to the head of the unit below restrains only the out-of-plane movement. Figure 4 shows typical details of the horizontal and vertical stack joints.

For wind loading (perpendicular to a given building elevation), the glass lites span in two-way action to their perimeter edges. Each of the four sides is adhered to the mullions with SSG sealant, which transfers all of this loading in either tension or compression. In tension under out-of-plane wind loading the SSG sealant has an allowable capacity of 20psi. Out-of-plane seismic loading is frequently much lower than wind loading and consequently not a governing load case. Because in-plane restraint is not provided at the bottom of each unit the primary mode of behavior for a unit due to in-plane seismic loading is to "sway." This requires that each unit resist this loading either by frame action with each horizontal and vertical mullion connection resisting shear, tension, and moment; or the glass lites must act as shear resisting elements with all stresses being transferred through the SSG sealant connecting the glass to the mullions. While some moment can be transferred between the horizontal to vertical glazing frame member connections, this connection is primarily designed for direct shear and tension. The walls of aluminum mullions are typically thin (less than 0.125") and therefore fairly flexible when subjected to moments resisted solely by screw fasteners between the members. The glass lites, however, present a relatively stiff element into the unit construction. This stiffness is tempered by the flexibility of the SSG sealant, the clearance between the edge of the glass, and the protruding fins of the mullions (Figure 4). For seismic design of four-sided SSG systems, it is essential to evaluate the maximum stresses experienced by the SSG sealant and make sure the sealant bead size is sufficient to keep stresses below the sealant allowable.

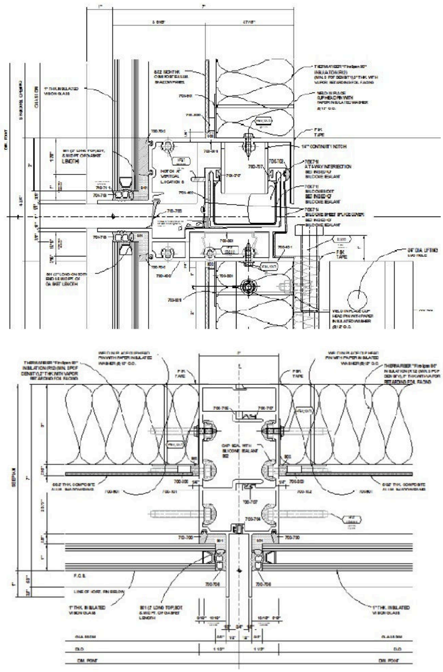


Figure 4. Typical horizontal and vertical stack joints.

For this project, the sealant bead was originally sized to accommodate the maximum wind load on the largest lite of glass at just below the 20psi allowable. For seismic loading the allowable stress, based on a 5:1 safety factor established by OSHPD, is 30psi. Based on finite element analysis of elastic models of the wall system (not discussed in this paper), the sealant bead under in-plane seismic loading typically experiences stresses less than 20 psi with few exceptions where the stresses reach approximately 24psi.

DISCUSSION OF THE AAMA TEST PROTOCOL AND TEST RESULTS

The AAMA 501.6 testing protocol requires that the mockup consist of what is determined to be the "critical lites of glass." More specifically, the protocol requires test mockups to include those lites of glass in the curtain wall system with the largest glass area, the thinnest glass, the most vulnerable glass type and glazing system type, the smallest glass-to-frame clearances, the smallest height-to-width ratio, and the largest drift index. Figure 5 shows the mockup that was constructed for preliminary testing. As Figure 5 shows, the mockup is of stick-built type in order for this initial testing to cause the mockup to be racked and to determine the code required minimum delta fallout displacement ($\Delta_{fallout}$). According to ASCE 7-05 (ASCE 2006), $\Delta_{fallout}$ shall be larger than the product of $1.25*I_p*D_p$, where I_p is the important factor and D_p is the design relative story displacement (drift). For this project, and more specifically this mockup, the product of $1.25*I_p*D_p$ was determined to be 3.75 in. This was the displacement that the mockup needed to reach under racking load without glass fallout in order to pass the test.

With the mockup configuration testing method selected ("rack" not "sway") it was imperative that the glass, SSG bead size and type, and mullion paint (Kynar) be determined to exactly match what will be installed on the building. Sealant type, bead geometry, surfaces to be adhered to, and glass edge clearance all had to match what would be used on the project (Figure 4) in order for the results of the testing to be considered valid for determining the performance of the final design. The resulting details for a horizontal and vertical section through the mullions for the preliminary mockup are shown in Figure 6.

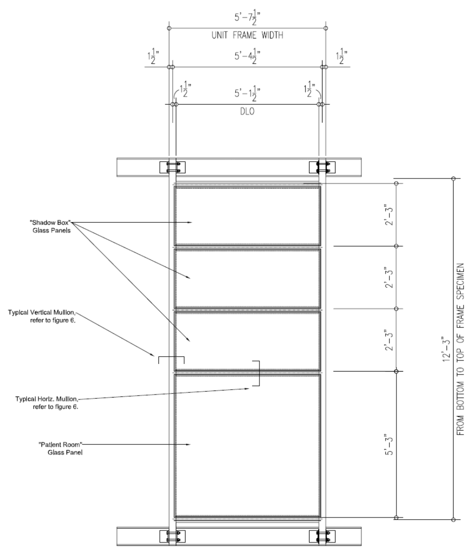
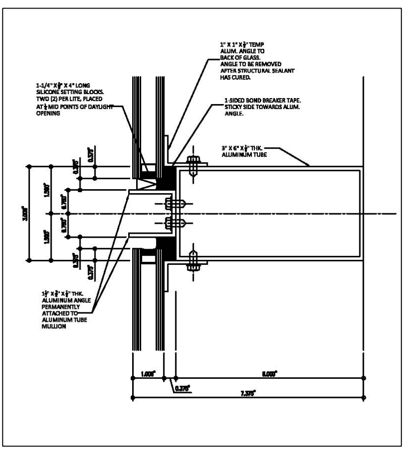


Figure 5. Mockup designed for preliminary testing.

According to AAMA 501.6 protocol, three replicates of a given mockup shall be tested on a dynamic racking test apparatus in order to determine the drift corresponding to glass fallout. For this project, the test apparatus was located at the ATI test facility in York, PA and is shown in Figure 7 with a typical mockup mounted. Based on the AAMA 501.6 loading protocol, crescendo racking test consisting of a concatenated series of "ramp up" intervals and "constant magnitude" intervals each consisting of four sinusoidal cycles shall be applied to the specimen. The in-plane racking displacement steps between constant amplitude intervals shall be 0.25 in. The test shall be carried out at a frequency of 0.8 Hz for displacement amplitudes of 3.00 in. or less and at a frequency of 0.4 Hz for larger amplitudes. Glass fallout drift ($\Delta_{fallout}$) is defined as the drift corresponding to a piece of glass at least 1.0 $in.^2$ in area breaking away and falling out of the mockup. For this project, the test was stopped after each step to inspect the specimen, and therefore, the concatenated displacement-time history used is shown in Figure 8. An important objective in these tests was to also determine the drift capacity of the structural silicone at glass fallout limit state. For this reason, as has been mentioned, the mockups were designed and attached to the test facility as stick-built systems. The mockups tested had dimensions of 5 ft – 7 1/2 in. wide by 13 ft – 11 in. high. Figure 9 shows one mockup on the test facility. The glass panels used in the mockups were 1 in. thick IGU for both vision and spandrel lite with ceramic frit. The glass type used was ¼ in. thick heat-strengthened.

According to ATI test report (ATI 2010), the results show that no glass fallout occurred in any of the three mockups at the target drift of 3.75 in. The overall $\Delta_{fallout}$ for the mockup was reported to be 4.25 in. drift based on bottom vision lite fallout, which is 13% larger than the design drift of 3.75 in. Minor sealant tear is reported on the exterior side at 3.00 in. drift and on the interior side at 3.75 in. drift. Figure 9 also shows typical sealant tears at such drift levels. Therefore, as the test results indicate, at drifts close to the design drift, some sealant tearing occurred but not sufficient for any glass to become disengaged. The sealant tearing progressed at drifts beyond the design drift.



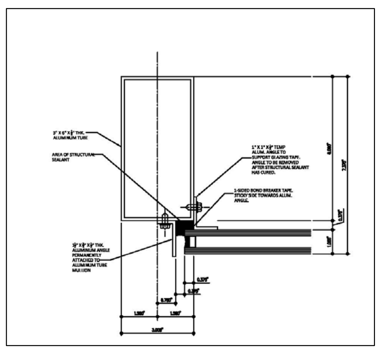


Figure 6. Horizontal and vertical section details for the preliminary mockup.

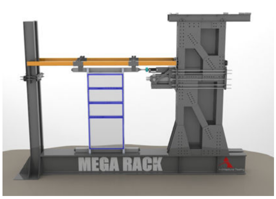


Figure 7. ATI test facility.

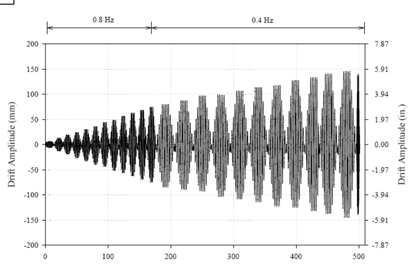


Figure 8. Displacement-time history used.

Figure 9. Typical mockup and sealant damage.

CONCLUSIONS

The main conclusion from the test program is that even under the highly unlikely condition that the unitized system's stack joints do not function as designed and cause the curtain wall to rack as a stick-built system, the curtain wall system satisfies ASCE 7-05 seismic provision of $\Delta_{fallout} \geq 1.25\ I_p\ D_p$. Of course, since the final design will be of unitized construction, the glass fallout is certainly not expected to occur under the design drift. The test results show that some sealant tear at drifts close to the design drift of 3.75 in. for a stick-built construction are expected. However, for a unitized system wherein the stack joints allow the adjacent panels to slide past one another in a sway mode, structural sealant damage is not expected at design drifts. The overall conclusion is that four-sided SSG curtain wall systems can be designed to satisfy the seismic provisions of the building code even in a stick-built construction system. However, since four-sided SSG systems are generally shop-glazed and mostly unitized system is employed, the seismic code provisions with respect to glass fallout are expected to be satisfied more readily and sealant damage (if any) is expected to be much less compared to stick-built systems.

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