TOWARD DEVELOPMENT OF A PREDICTIVE MODEL FOR DRIFT LIMITS IN ARCHITECTURAL GLASS UNDER SEISMIC LOADINGS

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SUMMARY

This paper outlines current efforts at the Building Envelope Research Laboratory at The Pennsylvania State University toward the development of a predictive model for seismic design/evaluation of curtain walls containing architectural glass components. One suggested approach is based on diagonal load to failure tests performed on 305 mm x 305 mm (12 in. x 12 in.) glass plates and third point compressive loading tests on 305 mm (12 in.) mullion segments. These stroke rate controlled small-size tests were performed in a manner that would permit comparisons with the existing limit state data from tests performed on full-size curtain wall assemblies. Small-size and full-size test results are presented, and correlations between small-size test results and full-size test results are established. A simple relation is suggested for the prediction of ultimate drift capacity of full-size curtain walls containing architectural glass based on the failure load of a small-size glass plate. The proposed approach provides an alternative to the costly full-size (mock-up) testing approach currently being used and advocated for seismic performance verification of curtain wall systems.

INTRODUCTION

Damage to curtain walls and storefront walls containing architectural glass components in recent earthquakes [EERI, 1990 and 1995] has prompted model building code writers to consider new provisions for the satisfactory performance of these nonstructural elements in future earthquakes. In fact, International Building Code 2000 [ICC, 1997] now requires architectural glass curtain walls to accommodate the maximum allowed building story drifts. These new code provisions imply that the architectural glass cladding should either be designed for in-plane lateral loads to have sufficient drift capacity or that satisfactory seismic performance be demonstrated by means of full-size testing of wall systems constructed with architectural glass.

Currently, the only practical approach to demonstrate acceptable seismic performance is based on costly full-size testing. Recently, the American Architectural Manufacturers Association (AAMA) has recommended the use of a static full-size test approach as a standard testing procedure for the seismic performance of curtain walls and storefront walls [AAMA, 1999]. The AAMA seismic test method requires that a full-size section of the curtain wall with similar material, detailing, and connections as in the real building be tested for three cycles of static racking displacements at an inter-story drift magnitude equal to at least 0.01 times the story height (h). Performance of the wall system mock-up is then evaluated by the design professional based on its observed response and comparisons with pre-established seismic performance criteria. Of course, this approach is costly, especially for small building projects. Thus, alternative procedures for the seismic design of architectural glass cladding are urgently needed.

An analytical method for the seismic design of architectural glass cladding under seismic loading has also recently been proposed [Sucuoglu and Vallabhan, 1997] to estimate the ultimate drift capacity of the architectural glass panels. This method considers the rigid body motion of the glass panel within the aluminum frame and the in-plane shortening of the glass panel due to buckling.

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The failure stress is assumed to correspond to flexural stresses at the geometric center of the glass panel during buckling. In-plane dynamic racking tests on full-size curtain wall test assemblies constructed with architectural glass and aluminum frames [Behr et al., 1995], however, have shown that crack propagation starts along the edges near diagonally opposed corners of glass panels where glass-to-aluminum contacts are made during in-plane racking of the curtain wall frame. Moreover, observation of the aluminum frame during dynamic racking tests and inspection of the frame glazing pockets after the tests indicate that the glass plate can cause significant plastic deformations of the aluminum frame, especially in the corners, as a result of these contacts. Accordingly, it is clear that a seismic design method for architectural glass, whether experimentally based or analytically based, should take into account the realistic physical behavior observed in laboratory experiments.

A predictive model approach is outlined in this paper that is based on low cost testing of small-size glass plate and aluminum frame segments. This approach utilizes available experimental data on full-size glass failure load and aluminum frame deformation. According to this approach, in-plane tests to failure of 305 mm (12 in.) x 305 mm (12 in.) glass plates can be used in conjunction with third point loading tests on segments of aluminum frame to estimate the ultimate drift capacity of full-size curtain walls constructed with architectural glass panels and aluminum frames of the small-size type being tested.

DEVELOPMENT OF A PREDICTIVE MODEL

Observations of the glass and frame behavior during dynamic racking tests on full-size specimens of curtain wall assemblies constructed with architectural glass were used to devise small-size glass and frame segment tests for the purpose of developing a model to predict the behavior of full-size specimens from small-size tests. Development of a robust predictive model would offer several advantages for curtain wall design professionals including: (1) a less costly and time consuming method of obtaining seismic performance data for curtain wall designs, and (2) an analytical framework for designing new curtain wall systems. The framework for a model that could potentially meet these criteria is outlined below. It should be noted that the predictive model concept presented below is based on correlations between small-size and full-size tests on a particular aluminum curtain wall system, but further small-size and full-size tests will be needed to provide the necessary data to calibrate the model such that future test efforts can be limited to small-size tests only.

Previous dynamic racking tests on full-size curtain wall systems constructed with several architectural glass types have provided information on the drift limit states and loads at which first glass-to-frame contact, first crack formation, and glass fallout occurs for each architectural glass type. Since these load-displacement relations are relatively linear, they can be modeled by a spring equation with the stiffness of the curtain wall system being represented by the slope of this relationship. However, the displacement used to develop these full-size specimen load-displacement relations is the total displacement (drift). This total displacement includes displacement attributed to rigid body motion ($\Delta_{\text{Rigid Body}}$) of the glass panel within the curtain wall frame before contact occurs between the glass corners and the frame glazing pocket in addition to all other displacements that occur after glass-to-glazing pocket contact ($\Delta_{\text{Deformation}}$). The latter component can be thought of as the deformation beyond contact which leads to glass failure, and consists of in-plane deformation of the glass plate, elastic deformation of the aluminum frame, and plastic deformation of the frame glazing pocket (especially in the corners). Thus, through tests on small-size glass plates and segments of curtain wall frame designed to simulate the observed loading that occurs in full-size tests, it may be possible to obtain a correlation between the small-size tests and the expected behavior of the curtain wall frame and glass combination in full-size tests. It is hypothesized that this correlation can be established by superimposing the load-displacement relation from the small-size glass plate on the load-displacement relation from the curtain wall frame segment tests. Since this combined small-size load-deformation relation can also be modeled with a spring equation, the correlation between the small-size and full-size specimen tests may be possible by simply relating the two spring equation expressions. With such a relation available, one can then use the failure load from a small-size glass plate test to estimate the drift capacity of a given full-size curtain wall constructed with the same architectural glass type as the small-size glass plate. More details on the proposed method are discussed in the sections that follow.

SMALL-SIZE GLASS TESTS

Relative story displacement of a curtain wall under lateral drift typically causes frame deformation and translation and rotation of the glass panels within the frame. Laboratory studies suggest that if these relative story displacements are large enough, a significant, nearly diagonal force can be induced on the glass panels as opposing diagonal glass corners are forced into contact with the glazing pocket of the frame mullions and horizontals [Behr et al., 1995; Behr, 1998]. As previously mentioned, the small-size glass tests were developed to approximate the glass panel loading that occurs in full-size tests. The small-size glass test apparatus used and a specimen under test is shown in Figure 1. The glass specimens were mounted in a custom-built test fixture attached to the crossheads of an MTS 880 electrohydraulic testing machine. The test fixture ensured pure diagonal loading of the glass plate, although it should be noted that somewhat less than pure diagonal loading of the glass panels has been observed in full-size dynamic racking tests. Hardened steel was used to construct that portion of the test fixture in contact with the corners of the glass plate during loading so that only the load-deformation relation of the glass plate under test was acquired. The tests were performed at a constant stroke rate of

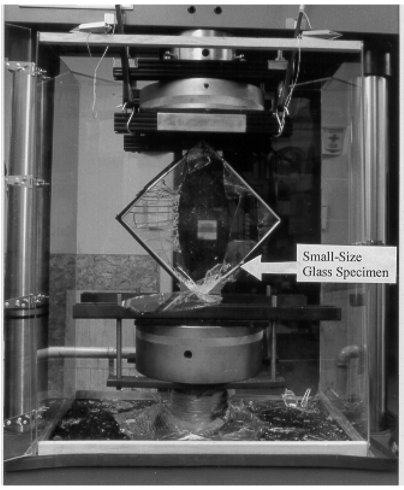

Figure 1: Small-size glass test apparatus and typical small-size glass specimen. (Note: Specimen under test is a two pane insulating glass unit.)

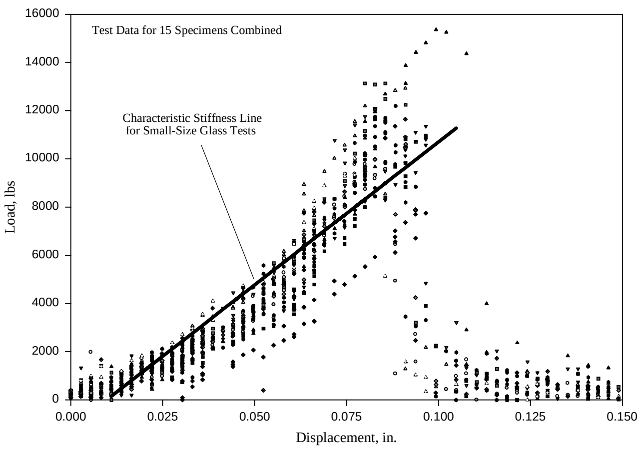

Figure 2: Small-size glass load-deformation data for ¼ in. annealed monolithic glass.

51 mm/s (2 in./s). This characteristic stroke rate was determined from an analysis of the load-displacement profile from full-size dynamic racking tests on a curtain wall constructed with 1524 mm (60 in.) x 1829 mm (72 in.) glass panels within an aluminum curtain wall framing system. Further details of full-size testing will be discussed subsequently.

Fifteen 305 mm (12 in.) x 305 mm (12 in.) specimens of several glass types over a range of thickness commonly employed in practice were tested. The purpose of this paper is to outline a suggested method for predicting the ultimate drift limit of architectural glass under seismic loading; thus, discussion of the results of these tests will be limited to just the 6 mm (1/4 in.) annealed monolithic glass specimen tests. The load-deformation data for the fifteen 6 mm (1/4 in.) annealed monolithic specimens are shown in Figure 2. As expected for a brittle material such as glass, the plotted data indicate a sharp increase in load with displacement up to some maximum load level where glass failure occurred, followed by a sudden drop in the load. The maximum load points are the glass failure loads for different tests. Since the load-deformation plots for each specimen are quite linear up to the failure load, a line can be drawn as shown in Figure 2 to represent the stiffness relation for that glass type. The representative line drawn through the load-deformation data in Figure 2 for annealed monolithic glass will be assumed to represent the load-deformation (stiffness) relation for this glass type and thickness in the following development. The load-deformation line from the frame segment tests discussed in the next section will be superimposed on this line to provide a measure of support flexibility. This is necessary to take into account the contribution of frame flexibility in estimating the drift capacity of the glass components.

ALUMINUM FRAME SEGMENT TESTS

As the full-size curtain wall is laterally loaded, a normal load is exerted on the frame glazing pocket near the corners of the frame each time glass-to-frame contact occurs. This contact occurs as the glass panel translates and rotates within the deforming glazing pocket, and inspection of the glazing pocket after many of the full-size tests has shown that plastic deformation can occur over a foot or more of frame length along the ends of the frame horizontals. In addition, gouge and scrape marks caused by glass-to-frame contact along the ends of the frame verticals has also been observed. Thus, a small-size frame segment test employing third point loading was conceived to approximate the triangular load distribution imposed in the corner regions of the frame glazing pocket by the glass panel during glass-to-frame contact and to develop a load-deformation relationship to simulate the support flexibility of the frame during full-size dynamic racking tests. The frame type (Kawneer 1600™ shear block) used for full-size dynamic racking tests on a mid-rise curtain wall [Behr, 1998] was chosen for the initial small-size frame segment tests. A decision was made to use steel plates rather than glass plates to transfer the third point load to the lip of the frame segment glazing pocket during the frame segment tests so that the load-deformation relationship for the frame even beyond the failure load of glass could be obtained.

305 mm (12 in.) long segments of aluminum frame were loaded using the same electrohydraulic testing machine as that used for the small-size glass tests. However, the custom-built test fixture used for the aluminum frame segment tests differed from that used for the glass tests. The fixture was constructed to allow third point loading of the aluminum frame section with a 6 mm (¼ in.) steel plate for frame sections used to accommodate 6 mm (¼ in.) glass and a 25 mm (1 in.) steel plate for frame sections used to accommodate 25 mm (1 in.) architectural glass such as insulating glass units. Roller bearings were used along the sides of the plate to ensure normal loading of the aluminum frame by the steel plate. Figure 3 shows the test apparatus and a frame segment under test. Results for five Kawneer 1600™ frame segment tests are shown in Figure 4. The initial displacement at very small loads shown in the figure is due to the adjustment of the specimen in the setup. The rising portion of the plotted data clearly identifies the stiffness provided by the frame and is the part that will be superimposed on the small-size glass test load-deformation curves.

Comparison of Figures 2 and 4 indicates that for a load level of, say, 44,480 N (10,000 lb) the glass deformation varies from 1.8 mm (0.07 in.) to 2.3 mm (0.09 in.), while the deformation of the frame varies from 5.6 mm (0.22 in.) to 7.6 mm (0.3 in.). In other words, the frame deformation is on the order of three times that of the glass deformation.

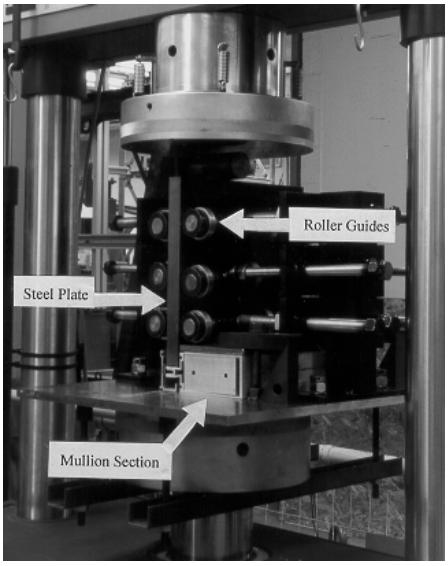

Figure 3: Aluminum frame test apparatus. Note: The end piece representing a vertical attached to the horizontal in the foreground was removed to enhance the cross-section view.

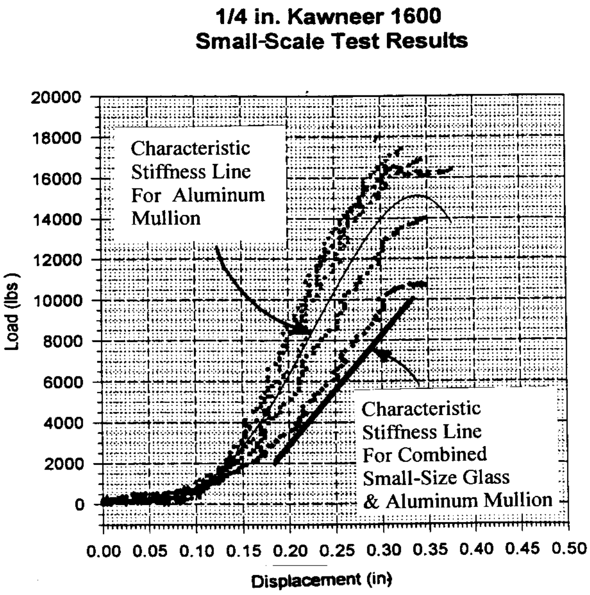

Figure 4: Load-deformation data for Kawneer 1600™ shear block aluminum frame test.

FULL-SIZE TESTS ON GLASS AND ALUMINUM CURTAIN WALL SYSTEMS

The full-size test data that will be used to establish a correlation with the small-size glass and frame segment test data were derived from dynamic racking tests on sections of Kawneer 1600™ shear block curtain wall glazed with a single panel of architectural glass [Behr, 1998]. The dynamic racking tests were performed using the apparatus shown in Figure 5 and are referred to as "crescendo tests" [Behr and Belarbi, 1996; Behr, 1998], in which the step-shaped swept sine function shown in Figure 6 is applied to the curtain wall section through the use of an MTS electrohydraulic actuator with a capacity of 100 kN (22 Kips). More details on the facilities used for the crescendo tests are described by Behr and Belarbi [1996]. A load versus displacement (drift) hysteresis loop was plotted for each step of the crescendo tests using the acquired load cell and LVDT (displacement) readings from the MTS actuator during the test. Procedures for the crescendo tests, including the recording of glass-to-frame contact, first glass cracking and glass fallout data are described by Behr [1998]. Figure 7 shows the average peak load and corresponding deformation data, including first glass-to-frame contact, glass cracking and glass fallout for six panels of 6 mm (¼ in.) annealed monolithic glass with dimensions of 1524 mm (60 in.) width and 1829 mm (72 in.) height.

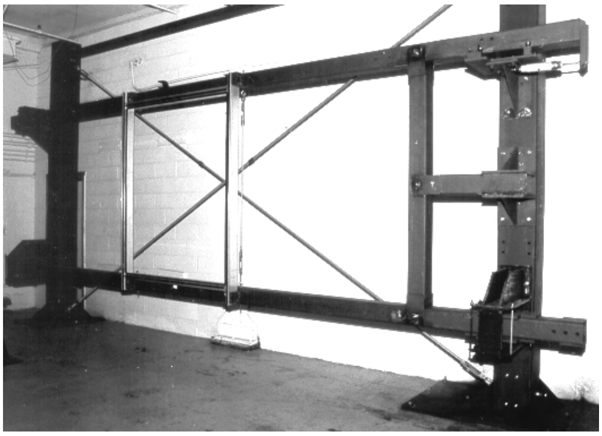

Figure 5: Facility used for dynamic racking tests of full-size curtain wall panels.

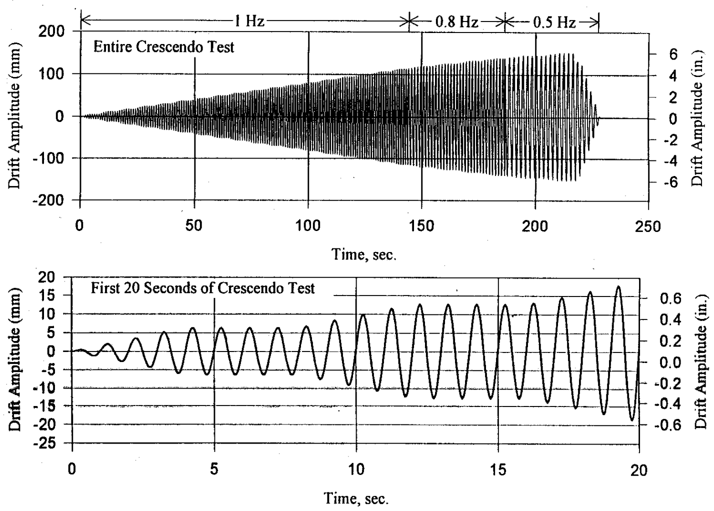

Figure 6: A typical drift time history for performing dynamic racking crescendo tests.

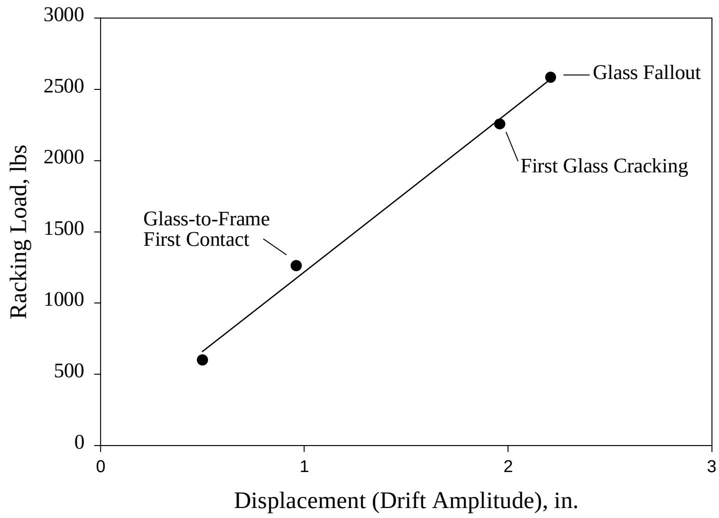

Figure 7: Average load-displacement relation from full-size tests on sections of curtain wall glazed with 6 mm (1/4 in.) annealed monolithic glass and Kawneer 1600^{TM} shear block aluminum frames.

The data plotted in Figure 7 correspond to the total lateral displacement or drift, which includes rigid body movement (translation and rotation) of the glass panel within the aluminum frame, glass panel in-plane deformation (due to diagonal compression from corner contact points), aluminum frame elastic deflection, and plastic deformation of the frame. Separation of the contribution of each of these racking displacement components is complex, and the sophistication required would be incompatible with other simplifications and approximations made in this developing design procedure. Having said that, it should also be mentioned that after the first (corner) contact between the glass and the frame, the stiffness of the entire system is expected to increase further. Since the objective here is to estimate the ultimate drift capacity of glass panels within a given curtain wall system, it is necessary to determine the stiffness of the system after glass-to-aluminum contact. It is then appropriate to separate the rigid body movement component (racking displacement before glass-to-aluminum contact) of the glass plate from the total displacement. The lower bound horizontal displacement component of this rigid body movement of the glass panel, which occurs at small loads (e.g., 2700 N (600 lb)), can be assumed to be equal to the clearance between the glass edge and the frame glazing pocket. To separate a measure of the rigid body horizontal displacement of the glass panel from the total horizontal displacement corresponding to the glass cracking and fallout points in Figure 7, one can subtract the glass-to-frame clearance distance from the displacement values at those two points. This clearance distance in the full-size specimen was 12.7 mm (0.5 in.). The slope of the best fit line through the 12.7 mm (0.5 in.) point representing the estimate for rigid body movement at 2700 N (600 lb) (before glass-to-aluminum contact) and the glass cracking and fallout points then provides an estimate for the stiffness of the full-size specimen at failure. This line can then be assumed to represent a characteristic stiffness relation for the full-size specimens, and a correlation will be established in the next section between this relation and the glass stiffness relation from the small-size tests.

6. CORRELATION BETWEEN SMALL-SIZE AND FULL-SIZE TESTS

The information provided by the load-deformation relations for the full-size test specimens and the combined glass and frame segment small-size tests was used to establish a correlation between the small-size and the full-size test results. The correlation was established by relating the slopes (stiffness) of the lines representing the respective load-deformation relations (Figures 4 and 7) and also the average peak failure loads for both the small-size glass tests and the full-size tests. An outline of the procedure used to establish a correlation between the small-size tests on 6 mm (¼ in.) annealed monolithic glass and Kawneer 1600^{TM} shear block frame segments and the full-size tests on 6 mm (¼ in.) annealed monolithic glass in a section of the Kawneer 1600^{TM} shear block curtain wall is given below.

With reference to Figure 4, the equation for the line representing the combined effect of small-scale glass and frame was assumed to be modeled adequately by the linear spring constant expression, $P_S = K_S\Delta_S$, where P_S and Δ_S represent the combined small-size test load and deformation, respectively, and K_S represents the slope (stiffness) of the relation. The slope K_S for the line in figure 4 is approximately 8,364 N/mm (47,760 lb/in.). With reference to Figure 7, the equation for the line representing the full-size load-deformation behavior was assumed to be modeled adequately by the linear spring constant expression, $P_F = K_F\Delta_F$, where P_F and Δ_F represent the full-size test load and deformation, respectively, and K_F represents the slope (stiffness) of the relation. The slope K_F for the line in Figure 7 is approximately 196 N/mm (1,120 lb/in.). Thus, the ratio of the full-size stiffness value and the combined small-size stiffness value was determined as $m_1 = K_F/K_S = 0.0235$, and the ratio of the average value of the six full-size failure loads, P_F, and the average of the fifteen small-size glass failure loads, P_S, was determined as $m_2 = P_F / P_S = 2{,}583/11{,}423 = 0.2261$.

Given the average failure load from a series of small-size glass specimen tests, P_S, and using the ratios m_1 and m_2, one can then find an estimate for the drift capacity of the full-size curtain wall system by relating the equations for the two representative lines:

$$\Delta_F = \frac{m_2}{m_1 K_S} P_S \tag{1}$$

Equation (1) describes the general form of the predictive model. Thus, to estimate the ultimate drift capacity for a given architectural glass component within a given curtain wall system, parameters m_1, m_2 and K_S corresponding to the type of glass and mullion used must be available. Initially, this would entail the systematic generation of appropriate values of m_1, m_2 and K_S for commonly used architectural glass types and aluminum frame types for a particular aspect ratio. Then, prediction of the ultimate drift capacity for various glass panel aspect ratios glazed within a particular curtain wall frame can be made. For example, substitution of the values for m_1, m_2 and K_S, determined earlier in this section, gives the following approximate relation to predict the ultimate drift capacity of 6 mm (¼ in.) annealed monolithic glass glazed in Kawneer 1600™ shear block curtain wall:

$$\Delta_F(in.) = 0.0002 P_S(lb) \tag{2}$$

According to this relation, the ultimate drift capacity for a dry glazed Kawneer 1600™ shear block curtain wall system containing 6 mm (1/4 in.) thick annealed monolithic glass with dimensions of 1524 mm (60 in.) width and 1829 mm (72 in.) height and a 12.7 mm (0.5 in.) glass-to-frame clearance is approximately 0.02 percent of the load at failure of a small-size glass plate tested as specified in this paper.

To show an application of this approach, the failure load for a small-size glass test (P_S) has been shown to vary between 40,000 N (9,000 lbs) and 53,000 N (12,000 lbs) for 6 mm (1/4 in.) annealed monolithic glass from the test results in Figure 2. Based on Equation (2), the glass fallout drift capacity of a full-size Kawneer 1600™ curtain wall containing this glass type is then between 46 mm (1.8 in.) and 61 mm (2.4 in.). Crescendo tests on Kawneer 1600™ curtain wall sections containing this type of glass [Behr, 1998] indicated a value of 57 mm (2.24 in.) as the average value of the glass fallout drift capacity. Thus, in this specific case, the specified predictive model yields a reasonable estimate of the glass fallout drift limit. However, as in any other design situation, a factor of safety (yet to be determined) will probably need to be applied to make the approach consistent with design practice. The relation given in Equation (2) is expected to be slightly different for other glass thicknesses and types, different mullion types, and different glass aspect ratios. This design procedure is currently undergoing further development in the Building Envelope Research Laboratory at The Pennsylvania State University. The results presented in this paper should be regarded merely as a preliminary indicator of the potential viability of this simplified predictive model for the seismic design of architectural glass.

CLOSING REMARKS

A seismic design procedure similar to that presented in this paper could become a practical alternative to full-size mock-up testing of curtain walls containing architectural glass components. Preliminary results indicate that the approach could be practicable for estimating the glass fallout drift capacity of a given architectural glass component within a given aluminum curtain wall system frame. The estimated glass fallout drift capacity can then be compared with the model building code's drift limits to evaluate the seismic performance of a specific curtain wall system. Additional efforts are underway to establish a more accurate correlation between small-size and full-size test results. Further study is also needed to investigate the optimum dimensions of the small-size glass plate as a “standard test specimen”, the optimum load orientation for loading the small-size glass plate (pure diagonal loading versus adding a side load component to the diagonal component), and the optimal specimen dimension and loading requirements for the frame segment tests. The significance of the suggested approach lies in the relative economy of the small-size laboratory specimen tests and the simplicity of estimating glass fallout drift capacity in terms of a simple percentage of the small-size glass failure load.

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