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DEVELOPMENT OF A SEISMIC RATING SYSTEM FOR ARCHITECTURAL GLASS IN EXISTING CURTAIN WALLS, STOREFRONTS, AND WINDOWS

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SUMMARY

Past earthquakes have shown the vulnerability of architectural glass in curtain walls, storefronts, and windows. Damage in these nonstructural elements has ranged from dislodging of gaskets to glass cracking and glass fallout. Given that many building owners and other relevant parties are interested in learning about the vulnerability of such systems in their buildings, a procedure for seismic evaluation of this class of nonstructural systems in existing buildings is presented. This paper reports on a study undertaken to develop a seismic rating methodology for architectural glass. In this paper, first a brief review of available mathematical formulations for seismic rating of other systems such as bridges and building structural systems is presented. Then the mathematical formulation derived for a rating system suitable for architectural glass is discussed. Next, the parameters involved in the rating system are defined and the procedure to determine them is discussed. Finally, through a simple hypothetical example, the proposed rating procedure is further explained.

INTRODUCTION

Past earthquakes have revealed the vulnerability of architectural glass used in curtain walls, storefront, and windows (e.g., EERI [1-3]. Damage in these nonstructural elements has ranged from dislodging of gaskets to glass cracking and glass fallout. Although analysis and design methods for architectural glass curtain walls subjected to out-of-plane loads due to wind are relatively well-developed, analogous methods have not been developed for the analysis and design of curtain walls subjected to seismic loads. As a result, manufacturers of architectural glass curtain walls sometimes rely on full-scale mock-up tests (AAMA [4-5]) to aid in the design of architectural glass wall systems to withstand seismic loads.

During seismic interstory drifts, the typical rectangular curtain wall glazing frame becomes a parallelogram causing its glass panels to translate and rotate within the glazing frame pockets. Curtain wall designers typically use glass-to-frame clearances and glass panel aspect ratio to provide a geometry-

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based prediction for glass-to-frame contact (e.g., Bouwkamp and Meehan [6]; Sucuoglu and Vallabhan [7]). Experimental studies (e.g., Behr [8]; Memari et al. [9]) have shown that when the corners of one diagonal of a glass panel make contact with the corners corresponding to the shorter diagonal of the deformed frame, additional interstory drift leads to glass fracture and perhaps even glass fallout under the in-plane compression contact forces that are generated between the glass corners and the wall framing system corners. Thus, in cases where considerations of seismic effects are part of the design, curtain wall manufacturers typically try to satisfy seismic requirements by providing "adequate" glass-to-frame clearances so that the glass is able to "float" within the framing pockets (Beason and Lingnell [10]). Figure 1 shows the details of one example curtain wall. Typical clearances (usually ¼ in. (6 mm) to ½ in. (13 mm)) sometimes lead to curtain wall designs that are inadequate for building code design earthquakes since the interstory drift at glass panel level caused by such earthquakes can exceed the clearances and put the glass panel in compression along a diagonal. Moreover, inadequate consideration is often given to subsequent load interactions between the glass and frame in those cases where drifts are sufficient to overcome the glass-to-frame clearances. It is therefore clear that the possibility of glass-to-frame contact at corners due to deformation of aluminum framing during earthquakes cannot be ignored and a method is needed to evaluate such situations.

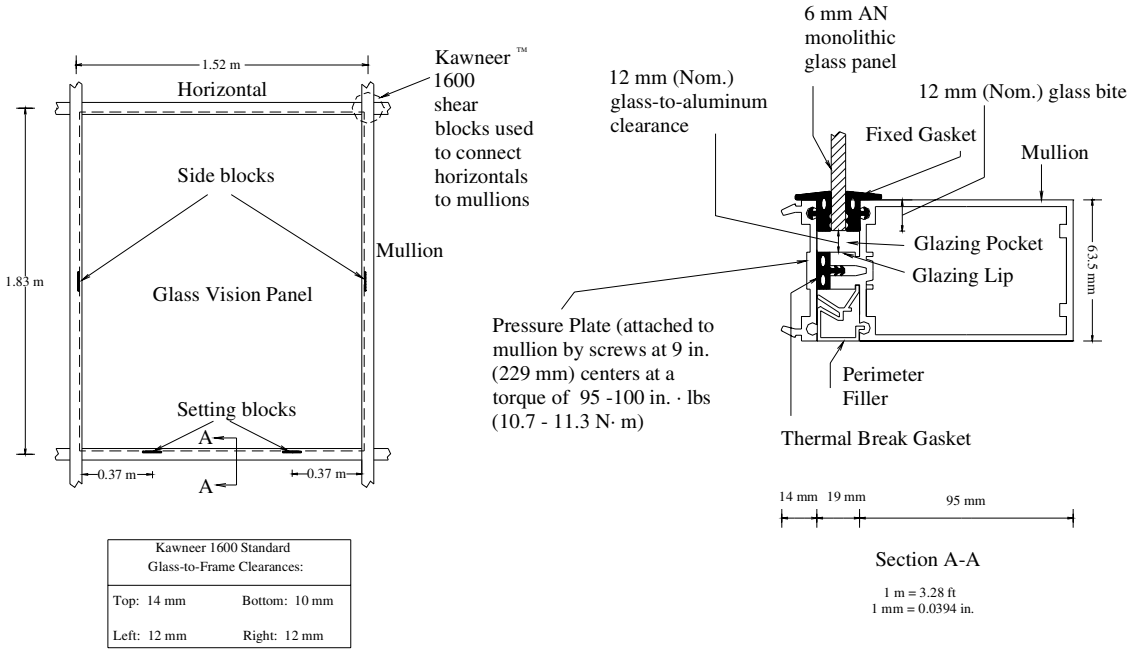

Figure 1. Typical detail for a glass curtain wall

The need for such an evaluation is more critical for existing curtain walls since seismic codes in the U.S. have only recently devised provisions for safeguarding curtain walls with architectural glass during earthquakes. It is desirable to develop a rating system that can evaluate architectural glass used in existing curtain walls and windows and express the glass curtain wall overall condition by a score to help owners decide whether any retrofit work for the curtain wall system is needed. In this method, the primary input data would be gathered from existing curtain walls by inspection. The responsible professional can use the proposed equations to compute the score. The score for each curtain wall would represent the degree of its

seismic vulnerability. Based on this score, building owners can make their decisions regarding taking further retrofit actions.

LITERATURE REVIEW OF SEISMIC RATING METHODOLOGIES

Rating systems are developed to investigate the seismic vulnerability of structures and in some cases to determine the retrofit prioritization. The rating can be based just on a visual inspection or based on more detailed study of the building conditions. The method based on visual inspection (e.g., FEMA [11]) involves surveying the building to collect data on the structural and nonstructural systems and assigning scores according to the conditions of these systems (some basic score for the structural system and modification scores depending on parameters that affect the response). The final score is then used to determine whether existing conditions of the building are acceptable for the considered (design/evaluation) earthquake (with respect to life-safety) or whether the building needs to be further studied. In case a more in-depth study is needed, an engineer would conduct a more detailed estimation of the seismic capacity using structural drawings, design calculation, and perhaps inspection of the structure itself. The visual inspection method is usually used to develop or establish the retrofit prioritization.

In the second method, which can be a follow up approach to the first one, each building is considered for a more in-depth evaluation. In this method, detailed studies may be conducted in order to have a more accurate earthquake vulnerability evaluation. An example of the second method for buildings is described in FEMA 178 [12]. The procedure in this document involves seismic analysis of the structure to determine demand forces and calculation of capacities to be compared with demand forces to identify any deficiencies. The procedure also requires qualitative answers to some evaluation statements related to various aspects of structural and nonstructural systems. Each evaluation statement describes a certain building characteristic that is essential to minimize the risk of earthquake damage. The final evaluation would be a statement about the condition of the building and what needs to be done to avoid life-safety hazards.

Most rating systems used for bridge evaluation have components of both approaches (visual inspection and detailed study). A literature review performed shows that there is no identical definition for the score in these studies. Filiatrault et al. [13] used a rapid screening procedure for existing bridges in Canada. They computed seismic vulnerability index (SVI) in term of multiplication of structural and nonstructural indeces and also foundation factor and seismic risk coefficient. Dicleli and Bruneau [14] proposed a rating index, IR, which consists of multiplication of the importance index and the overall damage index. Damage indices are expressed as demand/capacity ratios for these components; values less than 1.0 indicate that the corresponding component is unlikely to fail during the site earthquake, whereas values greater than 1.0 denote possible failure. Babaei and Hawkins [15] introduced a priority index (I) as the multiplication of criticality factor and seismic vulnerability factor. Criticality factor depends on the criticality of the route carried by the bridge as a lifeline, criticality of the utility lines carried by the bridge, criticality of the route crossed by the bridge as a lifeline and criticality of the bridge as a structure. Seismic vulnerability factor represents vulnerability of the bridge to seismic failure. Mander et al. [16] represent a damage index as a proportion of the absorbed hysteretic energy to the total energy absorption capacity to failure for bridges. Anderson and Gruendler [17] used bridge score (risk) in their approach. Bridge score is defined as the product of bridge vulnerability factor and importance factor. The bridge vulnerability factor is defined in term of the structure vulnerability factor, i.e., bridge geometric rating, superstructure rating and substructure rating. What seems to be common in the most of these methods is that some form of vulnerability index is defined as a product of a series of indices that represent influential parameters. A similar approach was used to derive appropriate relationships for seismic rating of architectural glass in this study.

PROPOSED RATING SYSTEM FOR ARCHITECTURAL GLASS

Identification of Parameters for the Rating System

Available building seismic rating systems have been developed to mainly evaluate the vulnerability of the structural systems for life-safety hazards. In the case of new architectural glass curtain walls, designers rely on full-scale mock-up tests to check the appropriateness of seismic design. After installation and with passage of time, the condition of the curtain wall components would not remain the same as the newly manufactured architectural glass curtain walls. This is the case because of environmental effects on glass and sealing material (including aging) or changing in the initial clearance between the glass and frame due to wind or (past) seismic induced drifts. Therefore, even a well designed architectural glass curtain wall or window could potentially pose some seismic hazard after many years in service.

Inspection of the existing architectural glass curtain walls or windows by a curtain wall professional is an essential part of the evaluation process. A suitable rating system for architectural glass would be one that can evaluate the existing condition of curtain walls or windows by considering their manufactured properties and current conditions and can express the vulnerability by a score. This score should represent a measure of the condition of the glass, frame and connections to building structural system.

Different parameters are involved in this evaluation. Figure 2 shows most of the parameters that can be considered in the rating system. Drift in the building forces the curtain wall frame to deform and leads to rotation of glass panel within the frame. The initial gap between the edge of the glass and frame can prevent the glass corner region from touching the frame pocket under small drift magnitudes. However, with increasing drift, the clearance will be overcome and the corner region of the glass, usually at opposite diagonal corners, will contact the frame leading to glass panel stress increase. Therefore, the relationship between the applied drift and the stresses that arise in the glass can be divided into two parts, first before contact between the glass corner regions and the frame and second after the contact is made. By developing the relationship between story drift and the stresses in glass panel, the stresses due to the application of a drift equivalent to the code specified allowable building drift could be computed. The next question is whether the glass would crack under this stress. The crack initiation stress in the glass panel depends on the manufactured glass crack initiation stress, other conditions of the glass in use, e.g., age, flaw, residual stresses, the conditions of the frame, e.g., frame type, member connection type, glazing frame-to-building structural system connection and apparent conditions, and the conditions of the gaskets e.g., sealing material, gasket pressure and the age of gasket rubber or silicon sealant.

The overall score for the curtain wall depends on three major tasks. First, the story drift should be predicted by the use of building properties and seismic hazard maps as prescribed in building codes. Alternatively, the maximum allowable drift specified in the building code can be considered. Computing the cracking initiation stress at the edge of the glass, which depends on the conditions of glass, frame, connections and glass panel boundary conditions, is the second part of this study. Finally, the relationship between the applied drift and the resulting stress in the glass panel should be developed as the third task. Consequently, stresses due to input earthquake action and ultimate crack initiation stress can be compared and expressed as a score. This score would present the vulnerability of architectural glass for earthquake.

Proposed Mathematical Formulation to Determine the Rating Score

In order to represent the conditions of the curtain wall glass by a score, parameters relevant to glass, frame, boundary conditions and building drift should be considered. Figure 3 shows the flowchart that illustrates the procedure for the score calculation. Building properties are used to calculate the maximum

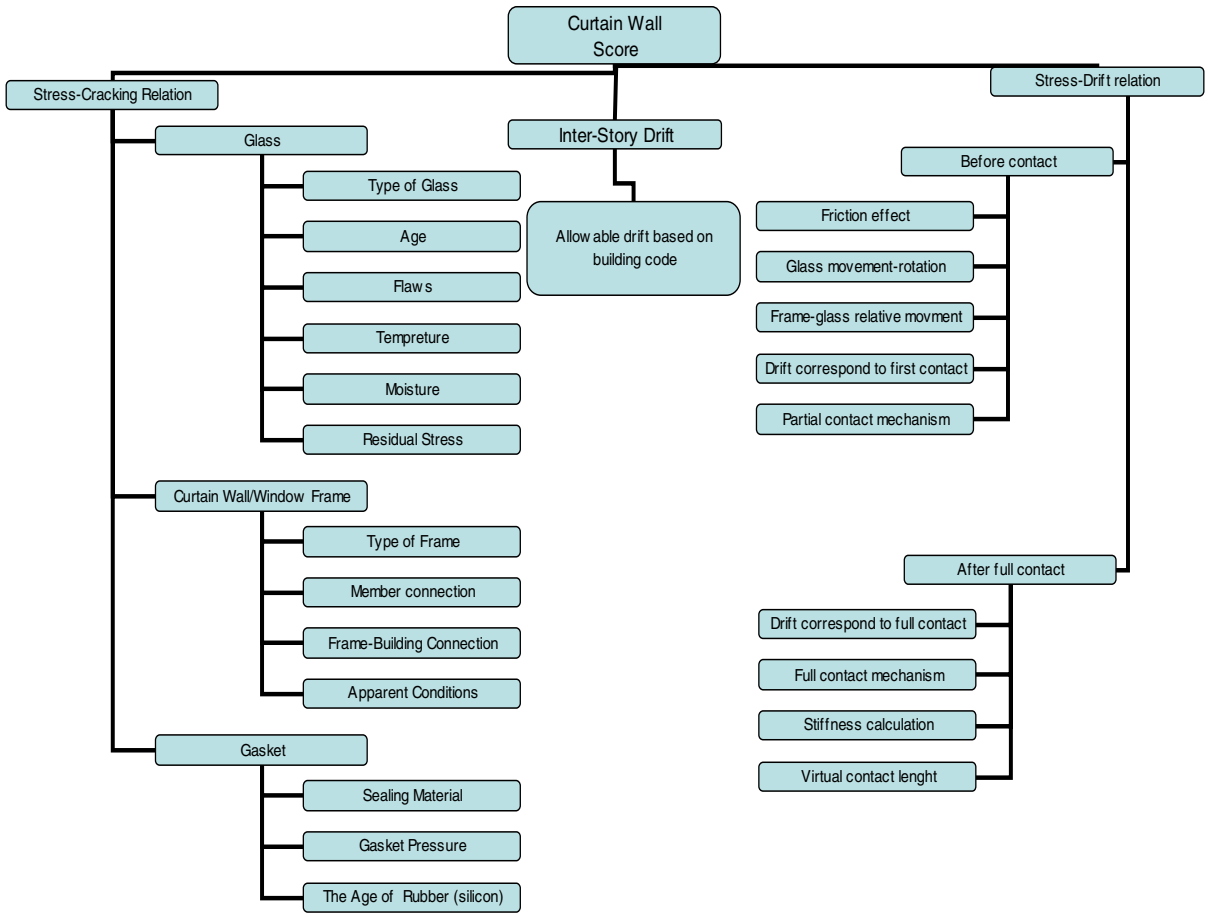

Figure 2. Parameters defined in the curtain wall glass rating system

interstory drift. The stress in the glass panel induced in this drift can be computed by the use of displacement-stress relationships, which along with the equation for $F_{c\ Max}$ are expressed in term of the gasket, frame and glass properties. The maximum crack initiation stress ($F_{c\ Max}$) is the stress corresponding to the crack initiation in the glass panel. Cracks usually initiate at or close to the corners of the glass panels where the glass panel comes in contact with the frame due to the drift in the curtain wall. The maximum crack initiation stress depends not only on crack initiation stress of manufactured glass but also on other conditions such as flaws and imperfections in the glass. By the use of ultimate manufactured glass stress and other curtain wall conditions, i.e., the conditions of the frame, glass panel, and the boundary conditions of the glass, the maximum stress that would correspond to crack initiation can be computed. From the crack initiation stress specified for new glass, the following equation is proposed to determine the crack initiation stress for a glass panel in use:

$$F_{c\ Max} = F_C^{'} \times C_G \times C_F \times C_B \tag{1}$$

where

$F_{c\ Max}$: Predicted crack initiation stress for glass panel in use

$F_C^{'}$: Crack initiation stress for manufactured glass (new glass)

C_G: Coefficient that corresponds to the following glass parameters:

- C_{G1}: Glass type (annealed, heat-strengthened, fully-tempered)
- C_{G2}: Edge flaw
- C_{G3}: Imperfections
- C_{G4}: Age
- C_{G5}: Residual stress
- C_{G6}: Temperature

C_F : Coefficient that corresponds to the following frame parameters:

- CF1: Type of frame
- CF2: Frame members connections
- CF3: Frame-to- building connections
- CF4: Apparent condition of curtain wall

C_B : The coefficient that corresponds to the boundary of the glass panel i.e.

- CB1: Gasket
- CB2: Sealing material (rubber or silicon)
- CB3: Gasket pressure
- CB4: Sealant age

The following equations show how each of the three main coefficients is formed as a function of relevant parameters:

$$C_G = \prod_{i=1}^{6} C_{Gi} \tag{2}$$

$$C_F = \prod_{i=1}^{4} C_{Fi} \tag{3}$$

$$C_B = \prod_{i=1}^{4} C_{Bi} \tag{4}$$

Quantitative values for the effect of each of these parameters should be determined based on experimental studies and/or statistical analysis using data gathered through questionnaires or analytical methods.

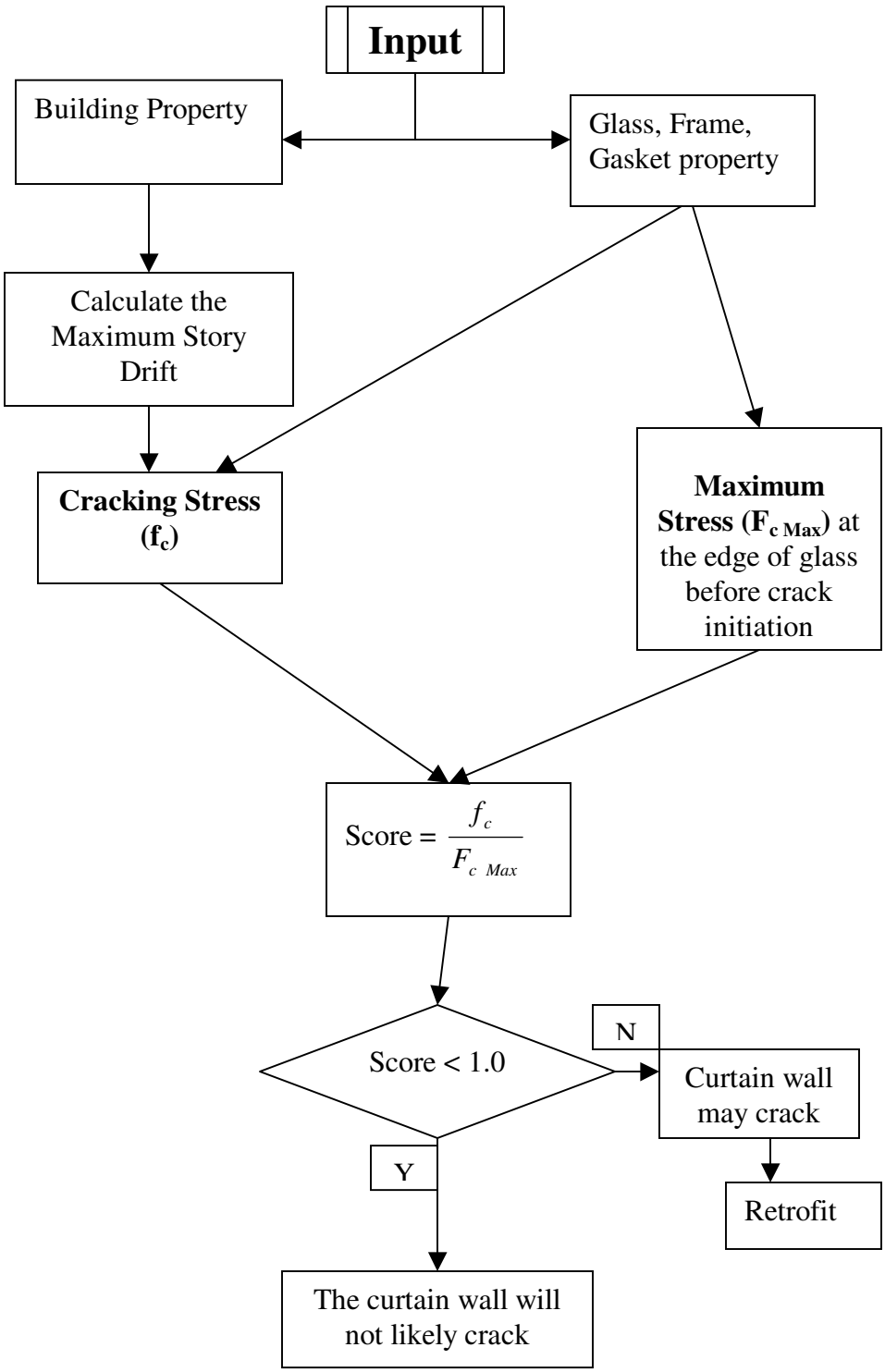

Figure 3. Flowchart for score calculation

The score check shown in the flowchart of Figure 3 and also as Eq. (5) below expresses the vulnerability of the glass panel in earthquakes. If the stress in the glass panel exceeds the crack initiation stress, the glass will likely crack. In other words, glass would crack if the score is equal to or greater than one.

$$\text{Score} = \frac{f_c}{F_{cMax}} \tag{5}$$

In the above equation, f_c is the stress in the glass caused by drift.

Load-Displacement and Stress-Displacement Relationships

With the score defined in terms of stresses, next, the relationship between the lateral load applied to the glass panels and the associated displacement on the one hand, and the relationship between the displacement (drift) and the resulting stresses on the other hand should be established. From the available test results ((Memari et al. [18]), the relationship between the lateral force and displacement can be estimated by four straight lines as shown in Figure 4. Test results show that in both push-over static tests and also dynamic cyclic-displacement tests the relationship between load and displacement can be estimated by straight lines. In Figure 4, D1 is a drift, which corresponds to the first contact between glass corner region and glazing frame pocket wall. By increasing the drift, two opposite-diagonal corners of the frame move toward the two corners of glass panel, which will result in full contact with increased drift. At full contact, both vertical and horizontal members of the frame will come in contact with the glass corner regions at both opposite side diagonal corners of frame. In Figure 4, D2 represents the drift for full diagonal contact and Dc denotes the drift at which crack initiation occurs.

The following equations show the load-displacement relationships:

$$F = B \quad \text{if} \quad D < D1 \tag{6}$$

$$F = K1\,(D-D1) + B \quad \text{if} \quad D1 < D < D2 \tag{7}$$

$$F = K2\,(D-D2) + K1\,(D2-D1) + B \quad \text{if} \quad D2 < D \tag{8}$$

where F is the lateral load on the curtain wall. K1 and K2 are the slopes of lines 2-3 and 3-4, respectively in Figure 4 and B is the resisting friction force between glass panel edges and perimeter gaskets. K1, K2 and B can be computed based on test results and D is the applied drift to a curtain wall glass or window.

Strain measurement test results and also finite element model analyses show that stress-drift relationship can be estimated linearly before crack formation (Memari et al. [18]). Because both load-drift and stress-drift relationships are both linear in this proposed procedure, the effective area of the glass panel along the diagonal region for the stress can be considered constant and it would not be changed by the magnitude of the drift applied to a curtain wall.

The glass panel stress due to an applied drift can be expressed in the following form:

$$f = B/Aef \quad \text{if} \quad D < D1 \tag{9}$$

$$f = K1\,(D-D1)/Aec + B/Aef \quad \text{if} \quad D1 < D < D2 \tag{10}$$

$$f = [K2\,(D-D2) + K1\,(D2-D1)]/Aec + B/Aef \quad \text{if} \quad D2 < D \tag{11}$$

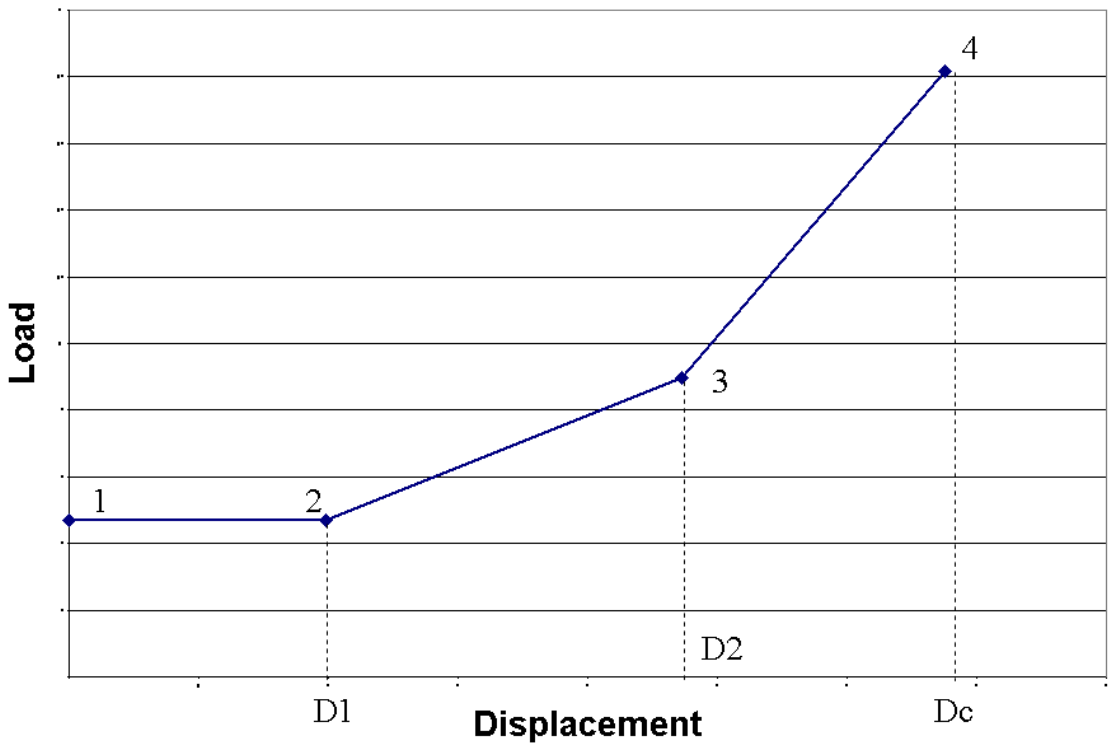

Figure 4. Simplified load-displacement relationship after frame stiffness effect elimination

where the Aef is the effective stress area for friction including gasket and setting block friction before glass-to-frame corenr contact and Aec is the effective stress areas corresponding to conditions after contact. These effective areas can be estimated by the use of available test results. Finally the score can be expressed by the following equations:

$$\text{Score}= \frac{B}{(F_{c\ Max})A_{ef}} \quad \text{if} \quad D< D1 \qquad (12)$$

$$\text{Score}= \frac{K_1(D-D_1)}{(F_{cMax})A_{ec}} + \frac{B}{(F_{c\ Max})A_{ef}} \quad \text{if} \quad D1<D < D2 \qquad (13)$$

$$\text{Score} = \frac{K_2(D-D_2)}{(F_{c\ Max})A_{ec}} + \frac{K_1(D_2-D_1)}{(F_{c\ Max})A_{ec}} + \frac{B}{(F_{c\ Max})A_{ef}} \quad \text{if} \quad D2< D \qquad (14)$$

To use these equations, among other geometrical and material related parameters that need to be determined, one would need to have values for the drift at which assessment is being made (e.g., structural analysis result or code allowable drift), predicted crack initiation stress based on Eq. (1), and effective stress areas. For a better explanation of the proposed seismic rating approach, an example is next developed.

EXAMPLE APPLICATION

In this section, a numerical example is presented to show how the method can be applied to a hypothetical case. The values of the parameters chosen in the example are only for illustration of the method. For a real building example, the values of parameters will be different depending on the condition. The architectural glass curtain wall system considered in this example is a dry-glazed, Kawneer 1600™ wall system with a detail as in Fig. 1. This wall system is commonly used in mid-rise building construction. The Kawneer 1600™ wall system uses rubber gaskets between the glass and the aluminum curtain wall frame and rubber gasket lined pressure plates to clamp the glass panel perimeter. Setting blocks along bottom horizontals (transoms) and side blocks along the mullions are designed to cushion the glass panel and maintain the glass-to-frame edge clearance as the glass and frame move relative to one another during in-service conditions. The glass panel used in this curtain wall is assumed to be a single ply, 6 mm (1/4 in.) thick annealed monolithic architectural glass panel. The building is a mid rise, steel-resisting frame building with 8.0 cm design earthquake interstory drift. The clearance between glass panel edge and frame pocket is 6 mm on all sides. The age of curtain wall glass is 20 years. The curtain wall frame is attached to the building structural frame through connections fully restrained against sliding. No obvious damage or imperfection is assumed in the glass panels. Pressure plates that provide the pressure on the perimeter gasket are attached the curtain wall frame members by using screws 23 cm c/c with 11.3 N.cm torque. Glass panel dimensions are183 cm high and 152 cm wide.

The following values are assumed for the parameters:

$F_C^{'}$ = 60 MPa

C_G: calculated below using the following glass parameters:

- C_{G1}=1.0 (Glass type)
- C_{G2}= 0.9 (Edge flaw)
- C_{G3}= 1.0 (Imperfection)
- C_{G4}= 0.9 (Age)
- C_{G5}= 1.0 (Residual stress)
- C_{G6}= 1.0 (Temperature)

C_F: calculated below using the following frame parameters:

- C_{F1}= 1.0 (Type of frame)
- C_{F2} = 1.1 (Frame members connections)
- C_{F3}= 1.0 (Frame-to- building connections)
- C_{F4}= 1.0 (Apparent condition of curtain wall)

C_B: calculated below using the following gasket and sealant parameters:

- CB1= 0.95 (Gasket)
- CB2= 1.0 (Sealing material (rubber or silicon))
- CB3= 1.05 (Gasket pressure)
- CB4= 0.9 (Sealant age)

$$C_G = \prod_{i=1}^{6} C_{Gi} = 1.0 \text{ x } 0.9 \text{ x } 1.0 \text{ x } 0.9 \text{ x } 1.0 \text{ x } 1.0 = 0.81$$

$C_F = \prod_{i=1}^{4} C_{Fi}$ = 1.0 x 1.1 x 1.0 x 1.0= 1.1

$C_B = \prod_{i=1}^{4} C_{Bi}$ = 0.95 x 1.0 x 1.05 x 0.9= 0.898

$$F_{c\ Max} = F_C^{'} \times C_G \times C_F \times C_B$$

$F_{c\ Max}$ = 60 x 0.81 x 1.1 x 0.898 = 48.0 MPa → $F_{c\ Max}$ =48.0 MPa

The score can be computed using equations (12)-(14). The term D_2 in Eq. (14), which corresponds to the state when glass-to-frame contact occurs at two points on a diagonal, can be determined using the equation provided in ASCE 7-02 [19] and shown below:

$$D_2 = 2c_1\left(1+\frac{h_p c_2}{b_p c_1}\right) \quad \text{\{ASCE 7-02 [14])} \qquad (15)$$

In Eq. (15), h_p is the height of rectangular glass, b_p is the width of rectangular glass, c_1 is the clearance (gap) between the vertical glass edge and frame, and c_2 is the clearance (gap) between the horizontal glass edge and frame. Based on the assumed values for various parameters, the score can be calculated as follows:

D_1=c = 0.6 cm (assumed to be the glass-to-frame clearance)

D_2= 2x 0.6 (1+ 1.2) =2.6 cm

K_1= 155 N/cm, K_2= 454 N/cm, B= 470 N, A_{ef} = 0.702 cm^2 and A_{ec}= 0.468 cm^2 (all assumed to be obtained from available test results)

$$\text{Score} = \frac{454(8.0-2.6)}{(4800)0.468} + \frac{155(2.6-0.6)}{(4800)0.468} + \frac{470}{(4800)0.702}$$

Score= 1.36

Score is greater than 1.0, which indicates that the glass would likely crack if the building experiences the interstory drift as a result of the design earthquakes.

CONCLUDING REMARKS

The seismic rating system introduced in the paper for evaluation of architectural glass in existing curtain walls, storefronts, and windows has been developed considering the available knowledge related to seismic rating systems for building and bridge structural systems. Development of the proposed procedure, however, has been more complicated for the glazing systems than for a typical structural system because of the involvement of many parameters including some at the interface of structural and nonstructural systems and the environmental effects on the material performance with time. The objective of the study, however, has been met by the formulation of a mathematical procedure to determine a score

based on stresses in the glass panel caused by seismic induced drifts. For a meaningful determination of the values of the parameters, follow-up studies based on a combination of experimental techniques, survey of practitioners in the fields of curtain wall and window industries, and statistical methods are needed. The proposed mathematical formulation may be refined based on the availability of new information in the follow-up studies. The procedure developed could be particularly of interest to the curtain wall and window industries, building owners in seismically active regions, and insurance companies providing earthquake damage coverage.

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