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SEISMIC DAMAGE MITIGATION OF THE GLAZED BUILDING FAÇADE

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Danijela Đurić-Mijović, Jelena Savić,
Danijela Milanović, Aleksandra Cilić

Faculty of Civil Engineering and Architecture, University of Niš, Serbia

Abstract. *Glass as a material in architecture and civil engineering represents a challenge, and it is often a material of choice for designers, used both for the building interior elements as well as for cladding of building. The paper has addressed specifically the glazed curtain wall façades and the earthquake-induced issues related to them. A review of the standing standards and practice in this field are provided. The paper presents some of contemporary solutions for damage mitigation of glazed building envelopes caused by earthquakes, such as: solutions with clearances between glass and its frame, earthquake-isolated curtain wall system, modified geometry of glass corners and friction damping connectors.*

Key words: *facade, architectural glass, curtain wall, earthquake, facade damage mitigation.*

1. Introduction

Exterior building walls have a structural, environmental and architectural role. The structural role comprises not only resisting gravity and wind loads and transferring them to a structural frame but also withstanding the movements caused by earthquakes. The environmental role reflects in the protection of the building from weather effects, moisture as well as the capacity to provide the thermal comfort. Since they represent the building face, and they may have a decisive impact on the impression the appearance of the building leaves on an observer, they are paid great attention. Apart from the traditionally used materials of building façades, the hi-tech materials can be encountered nowadays. It is noticeable that a large part of the building envelopes is constituted by the glazed areas, be them the commercial, cultural buildings, or the storefronts.

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Corresponding author: Danijela Đurić-Mijović
Faculty of Civil Engineering and Architecture, Aleksandra Medvedeva 14, 18000 Niš, Serbia
E-mail: danijela.djuric.mijovic@gaf.ni.ac.rs

When natural disasters strike, whether they are earthquakes or strong winds, or man-made hazards, architectural glass as an integral part of the façade represents a sensitive component. Once the integrity of the building envelope is disrupted, rain, snow, wind but also debris can easily destroy the interior of the building. The price of envelope repair and lost time very often exceeds the repair cost of any of the structural elements. However, the greatest hazard is posed by the broken glass which can injure both passers-by or building residents.

Considering the previous statements, it is clear that architectural glazing and glazing components must be designed as structural components (Behr & Minor, 2006). The standards in this area are not numerous, and in designing, practical experience is used very often. Building envelope designers currently do not have comprehensive regulations concerning architectural glazing.

2. Architectural Glass Types Used for Facades

Glass production technology has advanced considerably, and nowadays there is a wide spectrum of glasses meeting the most diverse requirements regarding resistance capacity, blast protection, filtering of certain bands of Sun spectrum, etc. The following types of glass are used within each of the glazed exterior wall system: annealed, heat-strengthened, fully tempered, laminated glass and sealed insulating glass units (FEMA 356, 2000).

These different types of architectural glass (Savić et al., 2013) also belong to different strength categories. One of the most frequently used types of glass in architecture is *annealed glass*. This glass is not heat-treated, has good surface flatness and its downside is that when shattered, it would fall apart to numerous sharp shards. The glass characteristics are considerably improved if it is heat-treated. This procedure especially increases resistance to breakage. *Heat-strengthened glass* and *fully-tempered glass* belong to these glasses. Although *heat-strengthened glass* is no less than 2 times stronger than the ordinary annealed glass, after breakage, large, sharp shards are also formed, which represent a hazard for the building residents and passers-by. *Fully-tempered glass* is no less than 4 times stronger than annealed glass, so in terms of breakage resistance it is considered superior to the previously mentioned types of glass. Another favorable characteristic is that when broken, it would fall apart into numerous small pieces, so in some cases it can be used as a safety glass. *Laminated glass* consists of several layers of glass with a plastic interlayer in between. This glass is often used as a safety glass because plastic interlayer prevents pieces of glass from falling out. *Insulating glass units* (IG units) as well as laminated glass consist of two or more lites, but they are mutually connected with continuous spaces whose role is to enclose a sealed air space. IG units are in thermal and acoustic terms superior to the previously mentioned glasses, so the curtain walls and skylights are mostly made exactly of this type of glass (Vigener & Brown, 2009).

3. Curtain Wall Problems Caused by Structural Forces and Movements

Curtain walls belong to a group of lightweight façade systems, and they are a sublimation of all protective functions of a building into a lightweight, thin membrane which is permeable only to light. The curtain wall structure consists of a bearing structure, which is most often built of metal, and of the infill panels which, in addition to glass, can also be metal, stone, plastics, etc. Most of the problems of curtain walls arise from the wind action, however, earthquakes can also have destructive effects on them. The most curtain wall problems are caused by construction imperfections, inappropriate design and incompatibility with the primary building frame (Newman, 2001). Wind and earthquake action can cause considerable displacements of the primary bearing system of a building. This displacement must be entirely followed by a glazed curtain wall. During these displacements huge racking forces occur, which in addition to disintegration of sealants can lead to compromising the integrity of connections of the façade and the bearing building structure, but also to destruction of entire walls (Fig. 1). For these reasons, during designing curtain walls, a special attention must be paid to adequate connection design between the façade structure and main bearing system of the building.

3.1. Damage examples

After the San Fernando earthquake in California in 1971, the cost of damaged glass and of its replacement was higher than the cost of any other individual element damaged in the earthquake. Twenty three years later, as much as 60% of glazed shop-windows were damaged during the Northridge earthquake in Los Angeles in 1994 (Fig. 1b).

a)

b)

Fig. 1 Damages caused by Christchurch 2011 (a) and Northridge earthquake 1994 (b)

Figure 2 shows façade damages after Mexico earthquake in 1985. The deformations of metal curtain wall elements can be easily noticed (Fig. 2a) while glass panes are not damaged as it should be expected. Figure 2b shows a badly damaged curtain wall where the majority of glass areas are totally damaged but also deformations of metal mullions are visible. The meeting areas of different planes, such as corners, are particularly susceptible to displacements due to impact of seismic forces. The effects depend on the direction of movement and significant damage can be caused. There is also the risk of glass shards falling off of the structure.

a)

b)

Fig. 2 Damages caused by Mexico earthquake, 1985

4. Standing Standards

Protection of the glazing from seismic displacements in current practice varies from country to country and depends on numerous factors, primarily on the seismic zone and standing standards, but also the size of the building and importance of the structure, etc.

European standards, referring to earthquakes Eurocode 8 (EN 1998-1:2004) contain only general recommendations about non-structural elements including the curtain walls and their behavior during earthquakes. Glazed curtain walls or any glazing are not included in particular in this standard, but are generally considered with other non-structural elements. The standard EN 1998-1:2004 clearly emphasizes that curtain walls in case of failure may cause risk to persons or affect the main structure of building and that they should be verified to resist the design seismic action together with their connections and attachments or anchorages. A simplified procedure is also given, where seismic action may be determined by applying to the non-structural element a horizontal force F_a which is defined as follows:

$$F_a = (S_a W_a \gamma_a) / q_a \tag{1}$$

In equation (1) F_a is the horizontal seismic force, acting at the centre of mass of the non-structural element in the most unfavorable direction, S_a is the seismic coefficient applicable to non-structural elements, W_a weight of the element, γ_a importance factor of the element and for facade elements is assumed to be 1,0, and q_a is the behavior factor of the element which has the upper limit value 2,0 for the facade elements.

The practice in New Zealand considering architectural glazing is that during small earthquakes the glazing must remain protected and without damage. During the design-level earthquakes in the most flexible buildings, when the interstorey drift may reach as much as 90 mm, the glass panels must not fall out of their frames (Charleson, 2008).

The US code FEMA 450 stipulates that glass in glazed curtain walls, glazed storefronts and glazed partitions shall meet the relative displacement requirement shown by equation (2):

$$\Delta_{fallout} \geq 1{,}25\ ID_p \tag{2}$$

or 0,5 in. (13 mm), whichever is greater.

$\Delta_{fallout}$ represents relative seismic displacement causing glass fallout from the curtain wall, storefront or partition. It should be determined by an engineering analysis or in accordance with AAMA 501.6-2001 (AAMA, 2001). In equation (2) I is occupancy importance factor and D_p is the relative seismic displacement that the glazed curtain walls, glazed storefronts or glazed partitions component must be designed to accommodate and shall be determined over the height of the glass component under consideration (FEMA 450, 2003).

This standard also emphasizes three exceptions. The first relates to the glass with sufficient clearances from its frame which facilitates that there is no physical contact between the frame and the glass, even in the cases of design drift. This is presented by the equation (3) and should be exempted from the provision of equation (2):

$$D_{clear} \geq 1{,}25 D_p \tag{3}$$

$$D_{clear} = 2c_1\left(1+\frac{h_p c_2}{b_p c_1}\right) \tag{4}$$

In the previous equations D_{clear} designates a relative horizontal displacement between the upper and the lower edge of the glass panel. Height and width of the rectangular glass are marked with h_p and b_p while c_1 and c_2 represents the gap between the vertical and horizontal glass edges and the frame, respectively.

The second and the third exception relate to fully tempered monolithic glass in seismic groups I and II located maximum 3 meters above the ground and annealed or heat-strengthened laminated glass in single thickness which is mechanically captured in a wall system glazing pocket.

5. Seismic Damage Mitigation of Glazing Systems

On the glazed building facades, the glazed panels themselves are fitted into the metal frames which are fixed on the bearing structure of buildings. Glass, as a material, has considerable in-plane strength and out-of-plane flexibility. However, glass panels, in addition to the external loads, are also exposed to the impact of the forces which are transferred from the metal frame on its corners and edges, and in this way they can be partially or fully damaged (Fig. 3).

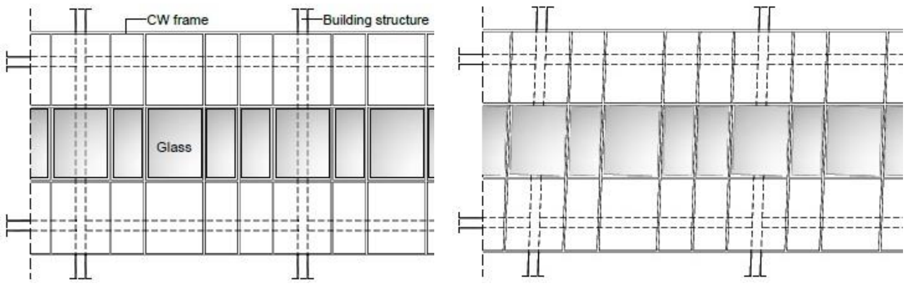


Fig. 3 Building structure and curtain wall frame before and after deformation

For stiff buildings, such as those with numerous shear walls, if the interstorey drift is very small (up to 2 mm) it is not necessary to design any special seismic separation details. However, interstorey drift for multi-storey buildings is much greater, e.g. $\pm$20 mm is typical movement to accommodate during small earthquakes and even up to 90 mm for very flexible structures during strong earthquakes (Massey & Charleson, 2007). Such large displacements cannot be easily designed, regarding that a good design must keep out wind and water, allow thermal movement, meet acoustic requirements, be durable but also to meet high esthetic criteria. Further in the text is the review of the contemporary solutions allowing mitigation of seismic damage to glazing systems of building envelope.

5.1. Mitigation using clearance

In the cases, where due to the earthquake action, small displacements are expected, it is common to implement such solutions where clearances are provided on all 4 sides of the glass pane. Clearances (marked as c on Fig. 4) or gaps facilitate prevention of glass panel corner and edge damage as a result of rotations and displacements caused by earthquakes. Very often such solution is not sufficient, so in cases of larger interstorey drifts it is recommended to implement the so called seismic mullions (Fig. 5a). This element is built in the bearing elements of curtain wall, and it provides the isolation of the glass panels from the metal elements of the frame by allowing larger clearances.

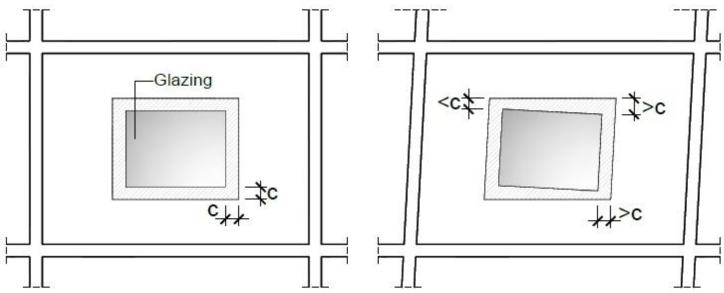


Fig. 4 A single façade unit before and after building movement

Some of the most frequent approaches for prevention of the damage of glass panes during earthquakes are presented on Fig. 5. A detail where besides the frame into which glass is fitted, there is also an additional seismic frame (Fig. 5b) which is connected to the building frame and it moves in unison with it. If there are no additional frames, then the glass is fitted and sealed with a gasket into the frame, so that the glazing pockets are sufficiently deep to allow the designed glass displacements (Fig. 5c). This approach is most frequent in case of stick systems. In case of the unitized systems almost as a rule, individual units which interlock are used (Fig. 5d). This system became common for multi-storey building, because the displacement between (units) is facilitated both along the horizontal and vertical axes (Massey & Charleson, 2007).

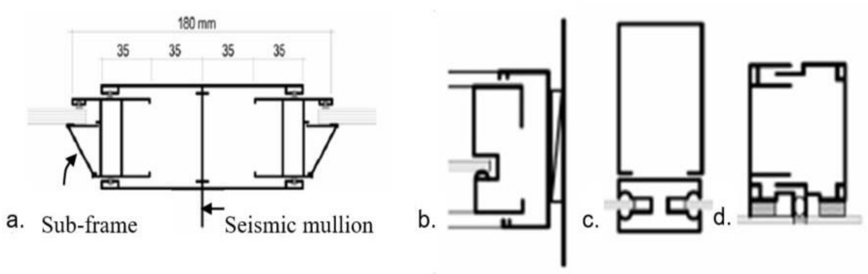
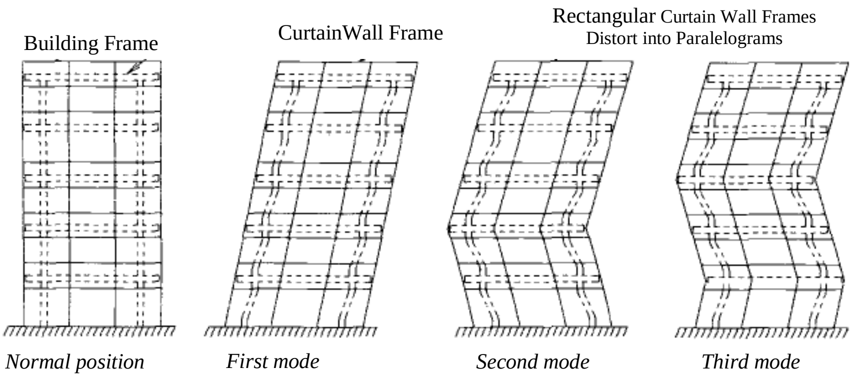


Fig. 5 Aluminium seismic mullion (*a*); Seismic frame (*b*); Glazing pocket (*c*); Unitized system (*d*)

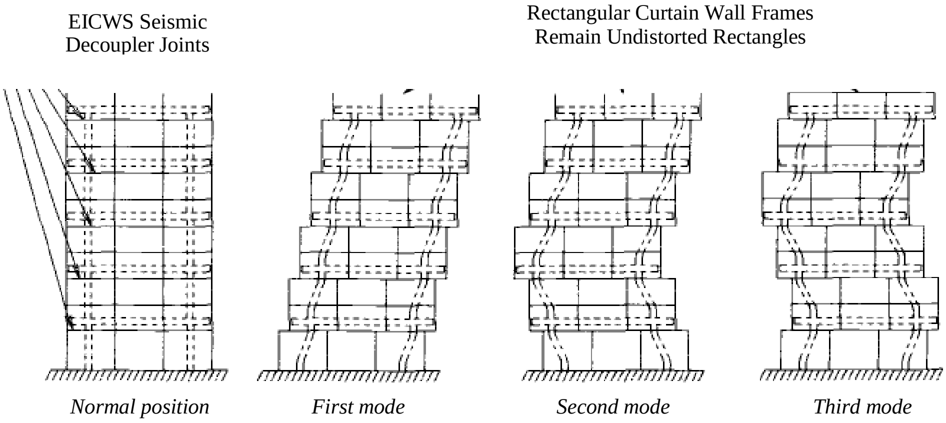
5.2. Earthquake – Isolated Curtain Wall System

A curtain wall system called Earthquake-Isolated Curtain Wall System (EICWS) (Behr & Wulfert, 2003; Brugemann, 2000) provides high resistance to earthquake-induced building motions. The essence of this system is that the curtain wall façade on the multi-storey building is constructed in such a way that each floor is decoupled, both from the façade on the upper floor, and from the one on the lower floor. In order to allow this EICWS system utilizes a specially developed „seismic decoupler joint“ whose fundamental role is to isolate vertical mullions at each floor from the mullions on the floor above and below. In order to accomplish this, a specialized structural support system is necessary. In this way, large interstorey displacements are allowed, both in horizontal, vertical and out-of-plane directions so no intensive forces can occur in curtain wall frame as a consequence of earthquake action. The difference in behavior of the classic curtain wall and EICWS system during earthquakes is presented in figure 6.

The basic difference of EICWS systems in comparison with the classic curtain wall systems available on the market is that the mullions have exclusively the height of one floor, while in case of classic curtain walls, they can have the height of 2 and 3 floors. For that reason precisely, due to the displacement of the main bearing system of the building, distortion of curtain wall frame occurs. By using the decoupling of vertical mullions, this is avoided. The seismic decoupler joint (Fig. 6c till 6f) which apart from its lore to facilitate and accommodate large interstorey displacements, must also provide water tightness. An advantage of this system is that it provides a great freedom of design, because it can be used irrespective of the floor plan.



(a) clad with a conventional curtain wall system



(b) clad with an Earthquake-Isolated Curtain Wall System

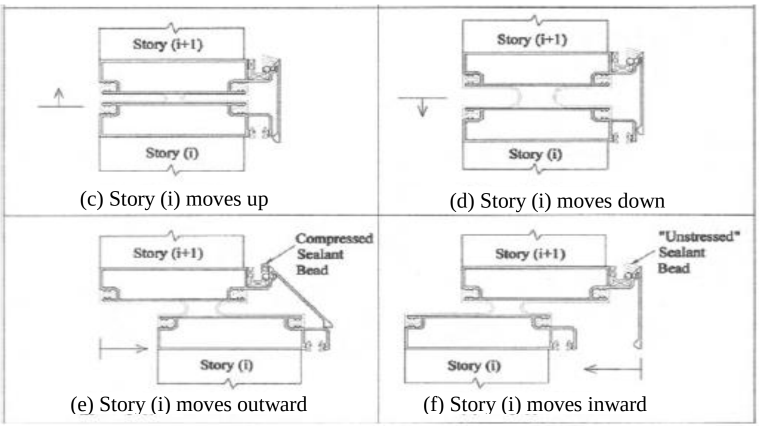


Fig. 6 Fundamental vibration modes of a typical building frame (a, b);
joint behavior at various displacements (c, d, e, f) (Behr & Wulfert, 2003)

5.3. Modified glass corner geometry

The fact is that the majority of seismically isolated wall systems designed to resist earthquakes are not envisioned for building retrofit but primarily for application on new buildings, and that their cost is considerably higher than the cost of conventional systems which are not specifically designed for earthquake resistance. However, some of the existing solutions, aimed at achieving as favorable behavior of curtain walls in earthquakes as possible, effectively represent a limiting factor in terms of esthetic design of building facades. One of such examples is a wide mullion wall system which allows and increased clearance so as to avoid glass-to-frame contact during earthquake displacements.

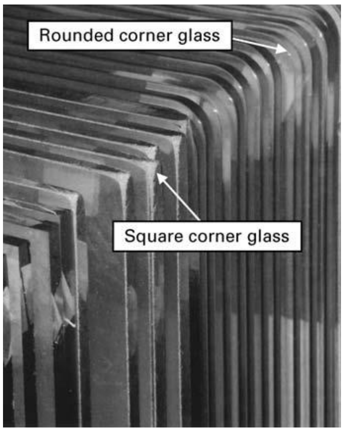


Fig. 7 A stock of squared corner glass and rounded corner glass panes (Memari & Schwartz, 2003)

The fact is that the damage and breakage of glass panels as façade elements firstly occur at their corners. Considering this Memari and Schwartz proposed a change of corner geometry in order to reduce the damage. The proposed design (Memari and Schwartz, 2006) comprises usage of rounded panel edges instead of regular straight angles (Fig. 7). In this way a grater rotation of glass panels in metal façade frames is allowed, and the most favorable effect is achieved using the corner rounding radius of 25 mm.

This research demonstrated that using this design increases both serviceability and ultimate drift limit, i.e., reduces glass cracking as well as fallout of glass panes. This design is simple, and its advantage is the potential for application both on the newly built structures and during retrofitting of the existing buildings.

5.4. Friction Damping (FD) connectors

As an alternative to the existing seismic solutions comprising clearance between the glass panel edges and the frame, the idea of isolating the façade from the main structure using advanced connectors has been proposed within Action COST 25. The use of advanced connectors was proposed by many researchers earlier especially for heavy cladding systems. The fixed elements of a cladding system are vulnerable to damage during an earthquake due to deformation occurring in the bearing structure. The advanced connectors provide isolation between the light-weight cladding system and the bearing structure by dissipating energy. Energy dissipation systems can be used for lightweight façade systems to provide a degree of isolation which would ensure the least damage possible. Friction damping connectors are implemented as connecting devices between the glazed façade and the main bearing structure of the building. Friction behavior of those devices reflects in the friction coefficient between two sliding surfaces and force perpendicular to them (Afghanikhorasgani et al., 2011). Friction damping connectors are simple devices, both to produce and to install into curtain walls. Their advantage is also the possibility to transfer the set force intensity. When the force intensity is higher than the set one, the device no longer transfers the force but starts to displace in the force direction. Friction damping brackets are presented in Figure 8.

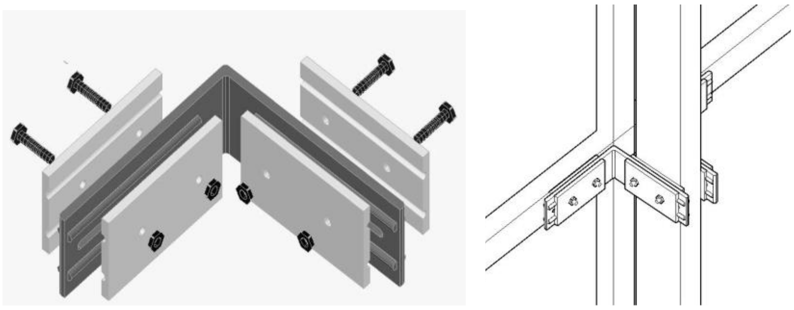


Fig. 8 Friction connector bracket (Afghanikhorasgani et al., 2011)

6. CONCLUSION

Glazed curtain wall facade system consists of large glass panes, long aluminium mullions and steel anchorages which connect curtain wall to structural building frame. All applied materials, elements and connections have to be designed in such a way to withstand all lateral movements. Any failure, such as falling glass or falling wall system components, presents potentially serious life safety hazard. From dual perspective of injury prevention and reducing economic loss, glazing and glazed facade systems are worth protecting. The paper presents some of the designs whose aim is the reduction of glass panel damage due to earthquakes, where glass panels are a part of glazed curtain wall facades. Each design has certain advantages, and some can be implemented both on the newly built structures and on the retrofitted building. Considering that the behavior of lightweight façade structures due to the earthquake action cannot be observed separately from the main bearing structure and other loads (dead loads and wind loads), only good knowledge of the systems for seismic damage mitigation can lead to the selection of adequate designs. Therefore, it is important that earthquake design criteria of facade systems are established at an early stage.

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REDUKCIJA ŠTETE NA STAKLENIM FASADAMA ZGRADA USLED ZEMLJOTRESA

Staklo kao građevinski materijal predstavlja stalan izazov za projektante i njihov je čest izbor kako za primenu unutar objekta tako i za njegovo oblaganje. Rad se bavi staklenim fasadama tipa zid zavesa i njihovim ponašanjem usled dejstva zemljotresa. Dat je pregled aktuelnih standarda kao i rešenja koja su našla primenu u praksi. Predstavljena su sledeća savremena rešenja za redukciju štete staklenih fasada izazvanih zemljotresima: rešenje sa međuprostorom između stakla i rama, EICWS sistem, modifikovanje geometrije uglova staklenih panela i FD konektori.

Ključne reči: *fasada, staklo, zid zavesa, zemljotres, redukcija štete.*