SEISMIC BEHAVIOR OF UNITIZED GLAZED CURTAIN WALLS IN A LOW-DAMAGE STRUCTURAL STEEL BUILDING

C. Chen (1), P. Xiang (2), L. Jia (3), X. Zhao (4), R. Dhakal (5), G.A. MacRae (6), J. Bhatta (7) and C. Clifton (8)

(1) Graduate Student, College of Civil Engineering, Tongji University, Shanghai, China, can_chen@tongji.edu.cn
(2) Associate Professor, College of Civil Engineering, Tongji University, Shanghai, China, p.xiang@tongji.edu.cn
(3) Associate Professor, College of Civil Engineering, Tongji University, Shanghai, China, lj_jia@tongji.edu.cn
(4) Professor, College of Civil Engineering, Tongji University, Shanghai, China, x.zhao@tongji.edu.cn
(5) Professor, Department of Civil & Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand, rajesh.dhakal@canterbury.ac.nz
(6) Professor, Tongji University, Shanghai, China, and Associate Professor, Department of Civil & Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand, gregory.macrae@canterbury.ac.nz
(7) PhD Candidate, Department of Civil & Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand, Jitendra.bhatta@pg.canterbury.ac.nz
(8) Associate Professor, Department of Civil & Environmental Engineering, The University of Auckland, Auckland, New Zealand, c.clifton@auckland.ac.nz

Abstract

In reconnaissance reports on some recent large earthquakes, it is reported that economic losses due to non-structural elements considerably exceed those related to earthquake-induced structural damage. Unitized Glazed Curtain Walls (UGCWs) which have been increasingly used for facades in modern buildings play an important role. Research on seismic performance evaluation of UGCWs is limited. There is possibility of cosmetic and weather tightness failures but not life-threatening for seismic risk of UGCWs. Deformation behavior of UGCWs depends on factors such as the width of clearance between glass panels and aluminium frames, gasket friction and degradation of structural glazing tapes. These factors should be calibrated through dynamic tests. Specifically, corners of UGCWs are more vulnerable under seismic excitations, while limited studies have been conducted to evaluate seismic behavior of corners of UGCWs, which is in lack of information.

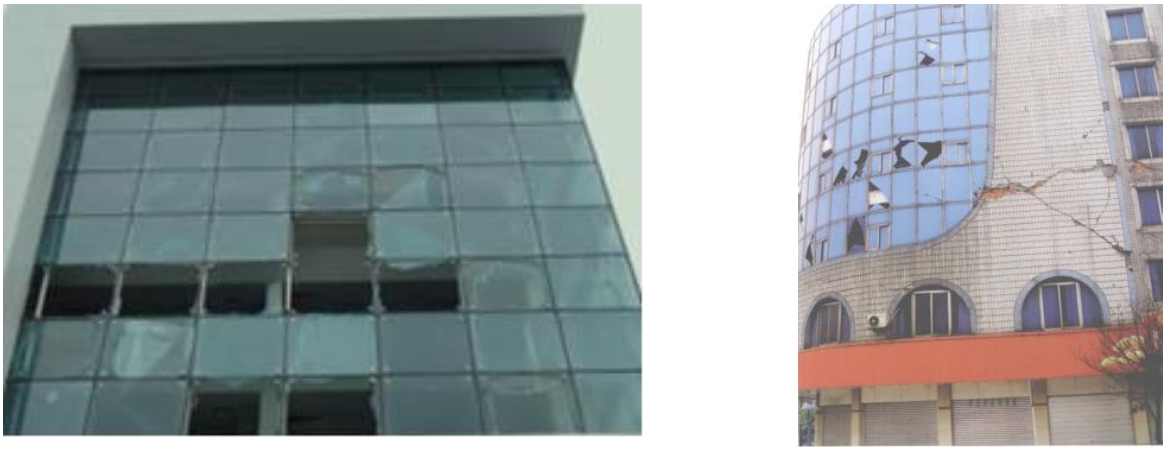
This study aims to investigate in-plane and out-of-plane deformation behaviour of UGCWs employing low-damage connection details. The overall deformation behavior of UGCW system is characterized, and specifically the seismic behavior at the low-damage corner condition is discussed. Bidirectional shaking table tests will be conducted at the International joint research Laboratory of Earthquake Engineering (ILEE) facilities, Shanghai, this year. The specimen is a 9 m tall three-storey steel building equipped with UGCWs on the top two floors at the opposite two corners. The UGCWs configuration includes three side-by-side primary panels in the longitudinal direction and two adjacent panels in the transverse direction at the corner of each floor. Displacement transducers such as Linear Variable Differential Transformers LVDTs as well as high-resolution cameras will be employed to record or capture deformation behavior of UGCWs within stack joints and hooks.

It is theoretically shown that the connection details of UGCWs can provide low-damage behavior under the maximum allowable 3.4% inter-storey drift of the steel building. Additionally, simplified calculation model of UGCWs without and with shear keys are introduced in this paper, and a method is suggested for prediction of ultimate drift capacity of full-size UGCWs based on some assumptions. This calculation method of the deformation of UGCWs can help improve decision making regarding resilient seismic retrofit options of UGCWs.

Keywords: non-structural elements, glazed curtain walls, low-damage, seismic performance, inter-story drift.

1. Introduction

In recent development, due to aesthetic, thermal and lightening advantages, Unitized Glazed Curtain Walls (UGCWs) are widely used in building structures. The UGCWs belong to non-structural facade components, often covering one or more stories. Previous earthquake events have shown frequent damages to UGCWs and attested that failure may provoke significant economic loss and pose a life-threatening to pedestrians and occupants (Fig. 1). However, previous research based on experimental tests or numerical simulations on this issue is insufficiently developed. Hence, there is a need to investigate seismic performance of UGCWs.



(a) (b)

Fig. 1 – Glazed curtain wall damage observed in past earthquakes: (a) 2011 Christchurch Earthquake [1], (b) 2008 Wenchuan Earthquake [2].

The principal cause of damage of a curtain wall is the in-plane displacement rate caused by inter-storey drifts, more than the acceleration demand for the curtain wall itself [1]. In order to assess the performance of the existing glazed curtain walls on buildings during earthquakes, different experimental tests have been conducted over the past few decades. Studies focus on the in-plane behavior of glazed curtain walls, and a number of experimental in-plane racking tests have been carried out on the full-size glazed systems [3, 4, 5]. Common mechanism of damage recognized are gasket dislodgement, glass crush at corners and fall-down of glass panels. On the other hand, it is observed that unitized glazed systems attached to buildings are effective in resisting horizontal motions [6].

Shaking table tests were also performed by some researchers to evaluate seismic performance of UGCWs. Wang et al. [7] conducted a multi-modal shaking table test on inner-skin curtain wall system of Shanghai tower, aiming at investigating its seismic performance, in which the seismic inputs to the system including multi-dimensional accelerations as well as inter-story drifts. Alustet Company [8] designed a low-damage UGCWs capable of resisting seismic forces induced by major earthquakes. Such new glazed system was tested on a shaking table for earthquake resistance at the National Technical University of Athens with excellent results. Following these shaking table testing studies, no visible damage was observed in the glass panels, and the glass panels returned to their exact initial position, with no permanent displacements [9, 10].

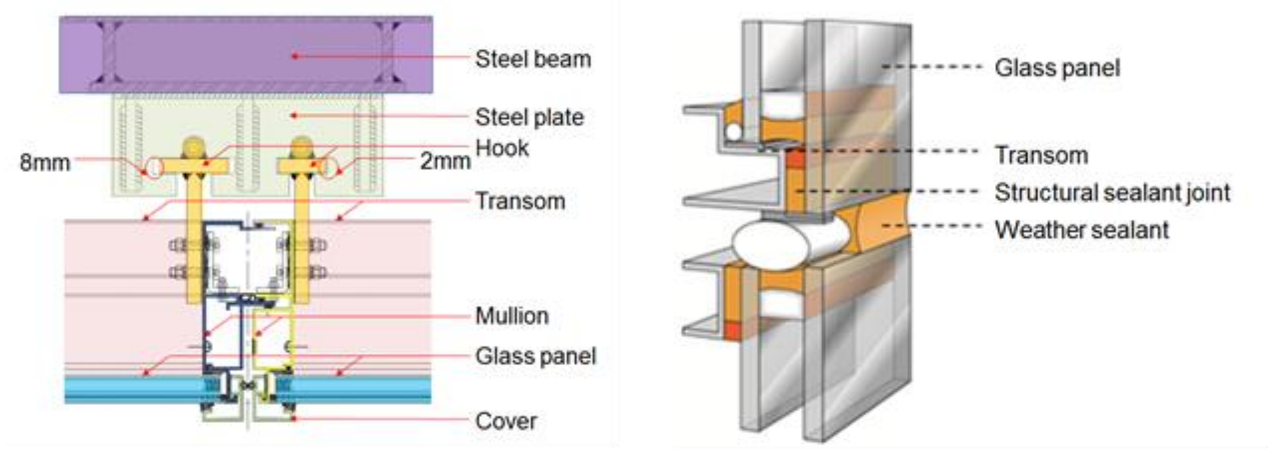
Even if the benefits offered by UGCWs exposed to world are widely used, no official regulation currently provided clear explanations on deformation mechanism of UGCWs under large inter-storey drifts. Recent seismic design provisions (e.g. Code for Seismic Design of Buildings [11]) provide specific limitations to the Inter-storey Drift Ratio (IDR) of structural frame to avoid damage to non-structural components.

This study focuses on UGCWs. In UGCWs, glass panels and aluminum frames are commonly bonded with structural silicone sealants. The connection between the upper and lower panels is known as a "stack joint" and allows panels at each level to slide horizontally [6]. Furthermore, the UGCWs are often thoroughly hung to the primary structure by means of connections at the beam/slab level. In such construction method, the panels are expected to "sway" but not actually "rack" as in the stick-build systems [6].

Very few studies have been conducted to evaluate the actual seismic performance of UGCWs, especially, considering the in-plane and out-plane behavior at corners. The objective of this paper is to theoretically analyze the seismic performance of UGCWs from its deformation mechanism.

2. UGCW components and test plan

UGCWs typically consist of pre-assembled modular panels consisting of several panels of glass held within metal (often aluminum) frames with vertical elements (mullions) and horizontal elements (transoms) by structural silicone sealants. Soft material is also placed between panels to provide protection of the building from the external environment. It may be seen that there are 3 barriers to air movement (with 2 internal chambers). The glass, frame, and soft material (silicone or rubber), together provide lateral force resistance (Fig. 2). Generally, the upper panels are attached to the lower panels using a continuous length horizontal stack joint, and panels are then clipped together along the vertical edges.



(a) (b)

Fig. 2 – Captured view of unitized GCW: (a) Plan view of mullion, (b) 3D view of transom [13].

The typical hooking connections of UGCWs in steel structure are shown in Fig. 2(a), incorporating common anchorage components such as adjusting bolt, steel hook and steel plate. As curtain wall must fit the building, the hooking connections are designed to accommodate construction tolerances in three orthogonal directions and ensure rotation about the three axes. Vertical tolerance is accommodated using adjusting bolt, while horizontal tolerance is commonly the clearance between the steel hook and the steel plate. One panel of UGCWs requires two hooks to anchor on the building. For one of the hooks, the clearance with the steel plate is 8 mm, and for the other, the clearance is 2 mm (Fig. 2(a)). The width of the clearance is mainly concerned with the construction tolerance and the effect of temperature variation. Regarding to one panel with a width of 1 m, the deformation caused by the temperature variation of 80 ℃ is approximately 2 mm.

Actually, the corners of the UGCWs are more likely to be damaged under earthquake excitations. Accordingly, it is of great significance to understand the seismic behavior of UGCWs at corners. Details of vertical split corner mullion is show in Fig. 3. Different from the nesting connections of mullions or transoms, a plug-in board combined two aluminum veneers through bolts is embedded in the middle of UGCWs' corner in order to assist waterproof and heat preservation. The plug-in board and the mullion are connected with the Ethylene Propylene Diene Monomer (EPDM) sealant, and the clearance between the plug-in board and the corner vertical mullion is 20 mm.

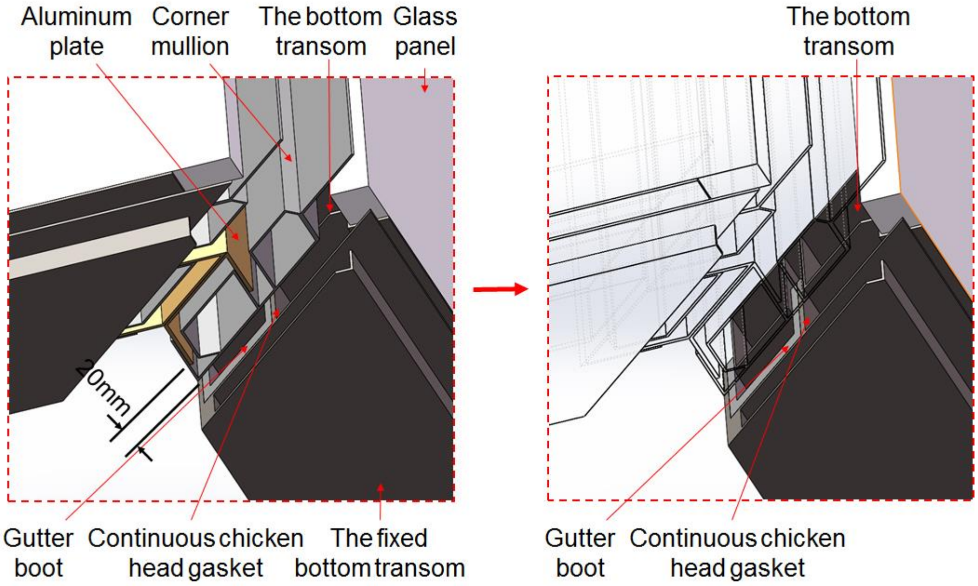


Fig. 3 – Corner details of UGCWs

For severe earthquakes, adjacent panels in curtain wall corners may contact with each other. A common practice is to employ "shear key" to avoid this trouble. As shown in Fig. 4, the shear key is usually fixed in the middle span of the top transom of the panel, and the described slot is extruded at the middle span of the bottom transom of the panel, aiming to restrict the upper and lower panels from horizontal sliding when the shear key is inserted into the slot. In doing so, following design standard regulation, shear key plays a key role to allow the upper panel rotate around itself, and hence being responsible of maximum deformation achievable in the UGCW components under larger inter-storey drifts. However, no specific considerations are given by most of existing standards to its real performance under seismic loads using the shear key on the top transoms. Research efforts and case studies need to be conducted further.

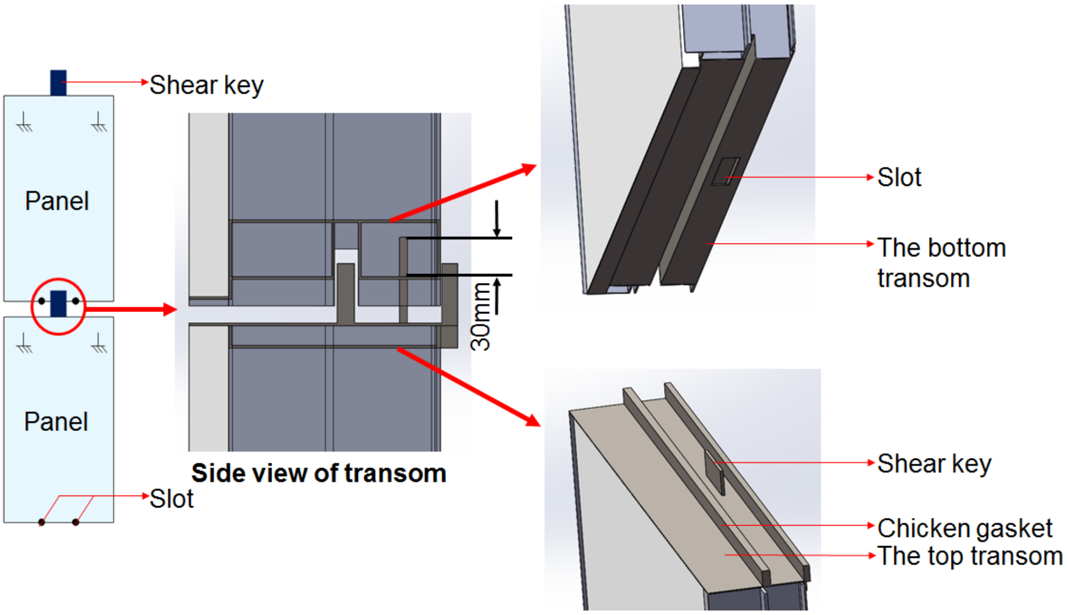


Fig. 4 – The details of shear key in UGCWs

Shaking table tests on a low-damage steel building equipped with UGCWs will be conducted at the International joint research Laboratory of Earthquake Engineering (ILEE) facilities, Shanghai, China. The proposed structure is a 9 m tall three-storey steel building equipped with UGCWs on the top two floors at the opposite two corners. The UGCWs configuration includes three side-by-side primary panels in the longitudinal direction and two adjacent panels in the transverse direction at the corner of each floor (Fig. 5). For the specific tests described herein, all steel plates are rigidly connected to the steel beam, and each panel hangs on the steel plate by means of two steel hooks. In order to compare the seismic performance of UGCW system with and without shear keys, the panels at one corner are equipped with shear keys, while the other corner is not. Earthquake input energy is designed to be dissipated by friction where the moment resisting frames (MRFs) use SHJ-AFCs, and braced frames use SFCs. Connections of this structural steel building are made with and without Belleville springs. Beams and columns are designed to remain elastic during an earthquake event, with all non-linear behavior occurring through stable sliding frictional behavior. In this context, the structural building may induce large inter-story drifts under earthquakes.

Displacement transducers such as Linear Variable Differential Transformers (LVDTs) as well as high-resolution cameras will be employed to record or capture deformation behavior of UGCWs within stack joints and hooks. The test is to be conducted in August 2020.

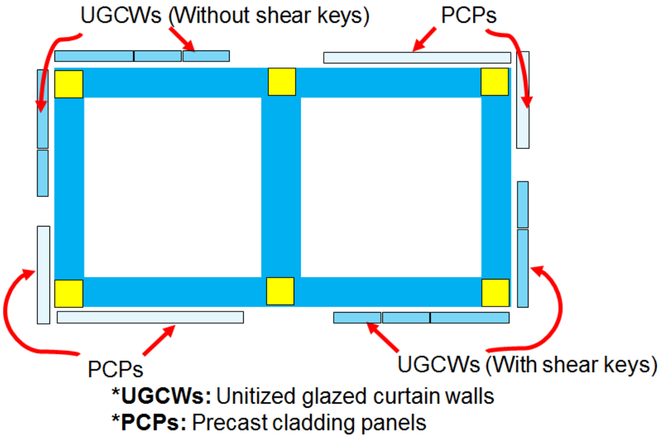


Fig. 5 – UGCWs test configuration

3. Analysis of simplified model of UGCWs

The drift ratio demands to curtain walls are relatively simple in current code provisions [14]. As summarized by Huang [15], the IDR of curtain walls varies among different codes where the Chinese standard as per Curtain wall for building [14] is the most conservative (IDR = 0.006 for concrete building), while the American code as per Minimum Design Loads for Buildings and Other Structures [12] is the least conservative (IDR = 0.0225 for design level). Actually, the drift demand relates to the physical parameters of the main structure, such as the building height, structural type, and ground motions. More analytical and experimental studies are required to justify the existing codes. In particular, it is recommended that the in-plane peak drift of curtain walls should be no less than three times the elastic deformation limit of the main structure as per Technical code for building curtain wall [16]. The deformation limits of the main structure are specified both in China national seismic design code and Shanghai local seismic design code [11, 16]. This means that the IDR of UGCWs should be larger than $1/300\times3 = 0.01$ for structural steel building from Chinese provisions [14, 16]. Nevertheless, testing objective of this study is that UGCWs can provide low-damage behavior under the maximum inter-storey drift as much as 3.0% of the steel building, and to meet such demand, the drift capacity of UGCWs in our test should be close to 3.0%.

In this study, the deformation mechanism of the UGCW system without or with shear keys is based on the following several assumptions or conditions: (a) Inter-storey drifts of the steel building are distributed in the first mode along the structural height. (b) The storey height for each level is 3000 mm. (c) The size for each UGCW panel is 1350 mm×2980 mm (width×height). (d) UGCW panels rotate in the same direction and achieve the maximum rotation angle at the same moment. (e) The vertical clearance between two adjacent panels in the longitudinal or transverse direction is 12 mm. (f) The corner clearance between the plug-in board and the corner vertical mullion is 20 mm. (g) The maximum allowable compression deformation of sealant is 50%. (h)Within one panel, the distance between the hooks and the surface of the top transom is 350 mm. (i) The thickness of the structural silicone sealant between the glass and the aluminum frame is 6 mm. (j) The horizontal clearance between the upper and lower adjacent panels is 20 mm. (k) Within one panel, the horizontal distance between the right (left) hanger and the right (left) side of the panel is 55 mm. (l) The in-plane clearance between the shear key and slot is 2 mm on each side.

3.1 UGCW system without shear keys

Generally, there are two main types of the typical existing UGCW systems in China. One is without shear keys which is suitable for small deformation cases, and the other is with shear keys aiming to resist large deformation. Regarding the deformation mechanism of UGCW system without shear keys, UGCWs firstly slide horizontally and then rotate around the hinge joint to accommodate in-plane inter-storey drifts. In this context, the total horizontal drift of one UGCW panel consists of three parts: (a) $\triangle_1$ is the corner clearance between the plug-in board and the corner vertical mullion, (b) $\triangle_2$ is the shear deformation of structural silicone sealant within the panel, and (c) $\triangle_3$ is the deformation due to the rotation of the panel.

For sake of clarity, Fig. 6 describes the deformation mechanism of UGCW system without shear keys when the floor of the structural frame move horizontally. More specifically, Fig. 7(a) shows the rotational deformation of one panel. Taking Panel 11 (P11) as an example, in order to adapt to the inter-storey drift of the structural frame, in the first step, P11 slides horizontally until the bottom right side of panel contacts the bottom left side of the orthogonal panel C1. As previous shown in Fig. 3, the collision at the corner actually refers to the collision between the plug-in board and the right mullion of P11. Thus, the absorbed horizontal displacement of P11 is $\triangle_1 = 20$ mm. Next, the structural silicone sealant between the glass and the aluminum frame occurs shear deformation to resist the inter-storey drift, and the shear deformation within the panel can be calculated by Chinese curtain wall provisions [16], which is 3 mm. Finally, P11 rotates around the right hanger to absorb the remaining inter-storey drift. The required relative horizontal displacement at the bottom left side of C1 (C2) is

$(2980 - 350) \times 3\% = 78.9$mm.

Because $\triangle_2$ is too small and the shear deformation may recover during panel rotation, the required horizontal displacement at the bottom right side of P11 (P21) induced by rotation is

$\triangle_3 = 78.9 - \triangle_1 = 78.9 - 20 = 58.9$mm.

Thus, the drift capacity of P11 (P21) can be calculated as

$58.9 / 2630 = 2.24\%$.

For P12 (P22), the horizontal clearance between P11 (P21) and P12 (P22) is filled with sealant, and the gap can be squeezed up to $12\times50\%=6$ mm, and then the drift capacity of P12 (P22) can be roughly calculated as

$(58.9-6) / 2630 = 2.01\%$.

Likewise, it is easy to calculate the drift capacity of P13 (P23) is

$(58.9-6-6) / 2630 = 1.78\%$.

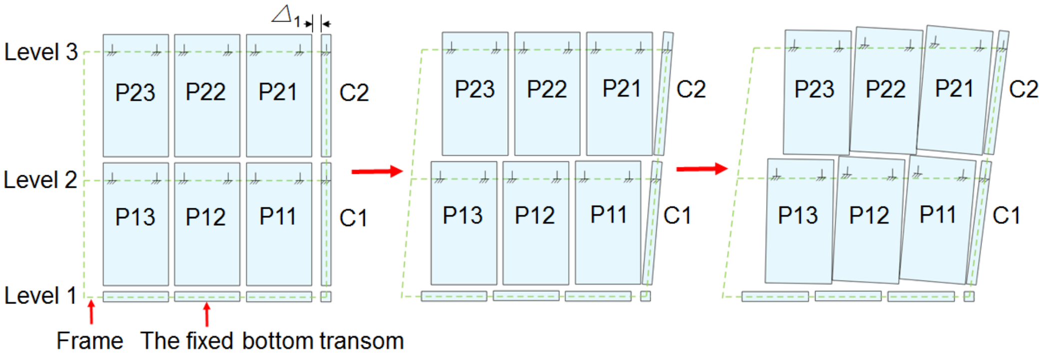
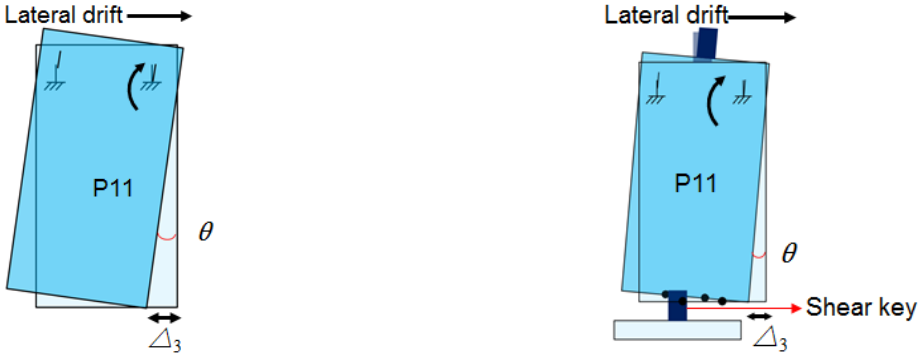


Fig. 6 – Deformation mode of UGCW system without shear keys



(a) (b)

Fig. 7 – Rotation mode of one panel: (a) Panel in UGCW system without shear keys, (b) Panel in UGCW system with shear keys.

The final rotation angle of each panel in Fig. 6 can be calculated, and the results are listed in Table 1. It should be noted that adjacent panels contact one by one from right to left, and the closer to the panel at the corner, the greater the rotation angle itself. The final uplift height of the left side of P11 can be roughly calculated as

(1350 – 55) × 2.24% = 29.01mm.

Since 29.01 mm>20 mm, the upper left side of P11 will contact with the lower right side of P22. The IDR of C1 and C2 are both 3.00%, which is the same as the IDR of the building because C1 and C2 move together with frame columns.

Table 1 – The IDR for each panel in UGCW system without shear keys

No.	P11	P12	P13	P21	P22	P23	C1	C2
IDR	2.24%	2.01%	1.78%	2.24%	2.01%	1.78%	3.00%	3.00%
	1/45	1/50	1/56	1/45	1/50	1/56	1/33	1/33

3.2 UGCW system with shear keys

Additional analytical efforts were made in this work to analysis the deformation mechanism of UGCW system with shear keys. Fig. 8 depicts deformation progress of each panel. When unitizing the shear keys for a UGCW system, C1 (C2) can avoid corner crash with P11 (P21). The earlier rotation around the hooks happens once the contact between the shear keys and slot happens. The total horizontal drift of one UGCW panel with shear keys comprises three main parts: (a) $\triangle_1$ is the in-plane clearance between the slot and shear keys, (b) $\triangle_2$ is the shear deformation of structural silicone sealant within the unit, and (c) $\triangle_3$ is the deformation due to the rotation of the panel. Because of the previous assumptions, all panel movements are the same, and P11 is taken as an example for the following detailed analysis. The deformation mechanism of P11 is also summarized in Fig. 7(b). P11 firstly slides horizontally until it hits the lower shear key, which is $\triangle_1 = 2$ mm. $\triangle_2$ is also ignored here. P11 continues to move horizontally following with the main structure, and then rotates around its right hanging point without crash with C1 owing to the restriction of the shear key. And the left side of its bottom slot always keeps contact with the shear key when P11 rotates. With the requirement that the drift capacity of P11 is 3%, the rotation deformation of P11 should be

$$\triangle_3 = 3000 \times 3\% - \triangle_1 = 90 - 2 = 88\text{mm}.$$

Under the previous assumptions, the deformation mechanism of other panels is in accordance with P11.

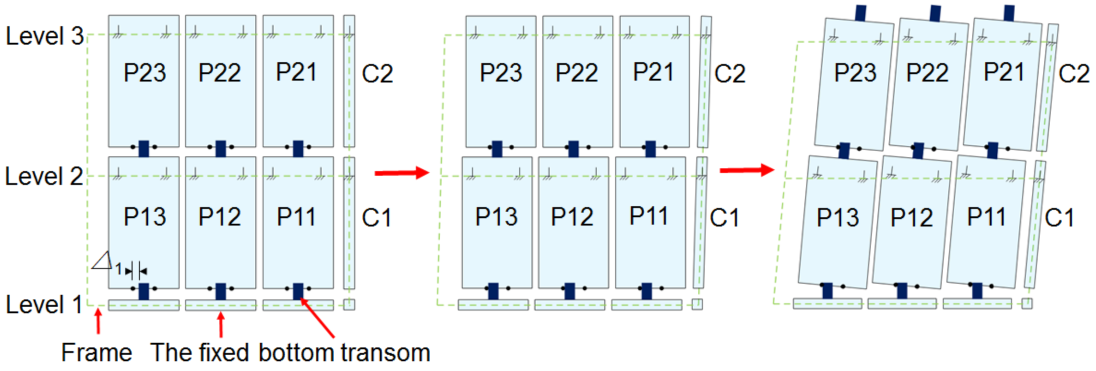


Fig. 8 – Deformation mode of UGCW system with shear keys

It is predicted that for the UGCW system without shear keys, crash usually occurs when the clearance between the plug-in board and corner mullion decreases to zero, whereas for the UGCW system with shear keys, collisions at the corners can be avoided. Accordingly, when the horizontal drift of the main structure is a constant, the number of rotating panels is limited for the UGCW system without shear keys, and the other panels only horizontally slide but without rotation; whereas for the UGCW system with shear keys, each panel rotates uniformly.

4. Conclusions

The following conclusions can be made for UGCW systems employed in this study: (a) For the UGCW system without shear keys, drift capacity is generally determined by the clearance between adjacent panels and the clearance between the plug-in board and the nearby mullion. (b) For the UGCW system with shear keys, crash between the corner panels can be avoided.

Further developments of this research will concern: (a) A verified computational model should be developed to predict reliable drift capacity of UGCWs when considering other factors such as glass panel size effect, and the distance between the hooks and the top surface of the panels. Giving critical design variables and predicting drift limits of cracking or fall down of glass panels, are challenging problems. (b) UGCWs consisting of different sizes of panels should be proposed for drift capacity. Thus, UGCW systems that qualify as exceptions to the governing design equation would avoid the necessity of undergoing laboratory mockup testing. (c) Future code provisions should continue to emphasize life safety in UGCW design, but they should also consider low-damage design as part of performance requirements for UGCWs.

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