The 11th Canadian Conference on Earthquake Engineering
Canadian Association for Earthquake Engineering

ISOLATING STRATEGY FOR MITIGATING INTERACTION BETWEEN RC FRAME AND MASONRY INFILL PANEL: SHAKE TABLE TESTS

Hanhui Zhang
Ph.D student, The Hong Kong University of Science and Technology, Hong Kong
zhanghanhui@ust.hk

J.S. Kuang
Professor, The Hong Kong University of Science and Technology, Hong Kong
cejkuang@ust.hk

ABSTRACT: Unreinforced Masonry (URM) infill panels are widely used as partitions in RC frames and typically considered as non-structural elements in the design process. However, observations from the recent major earthquakes have shown that under seismic excitation the structural interaction between columns and infill walls can significantly alter the structural behaviour, thus causing catastrophic consequences. This paper presents shake table tests on 1/3-scale RC specimens with masonry infill wall under real earthquake excitation inputs, with the aim at verifying the effectiveness of proposed damage mitigation strategy, which isolates the infill panel and adds flexible connections at column-to-infill interface. Taking into account of similitude requirements, the first frame specimen was constructed by isolating the infill panel without steel wire connections, while the second and third specimens are constructed by separating the infill panel from columns with finite width vertical gaps. Infill wall are connected into columns with spaced mild steel bars in mortar layers, and the gaps are finally filled with polystyrene form. The test results indicates that the proposed details can effectively reduce the undesirable interaction between column and infill walls and improve the seismic performance of masonry-infilled RC structures. In addition, the energy dispassion capacity and displacement ductility can be considerably improved.

1. Introduction

The positive or negative effects of infill partitions on the seismic performance of RC structures still represent a controversial topic among the research community. The conventional tight-fit infill walls can considerably increase the frames' in-plane stiffness and beneficial for resisting wind load and minor earthquakes, however, under strong earthquake excitation the severe interaction of infill walls with bounding frame can introduce brittle shear failure in RC columns and thereby led to catastrophic failures and undesirable soft-storey mechanism. It has extensively been reported that in every single disastrous earthquake during the past decades poor seismic performance and severe damage of masonry-infilled frames have been observed, including many newly designed ones, particularly in the 1999 Izmit earthquake in Turkey, the 2008 Sichuan earthquake and 2013 Lushan-Ya'an earthquake in China, and the 2011 Christchurch earthquake in New Zealand. Even with dozens of lessons from past earthquake events with tremendous loss of human lives and property, the structural reliability and adequacy of infilled frame buildings are utterly not guaranteed by the current design and analysis methods. The intractable conflict between the expectations from engineers' computational analysis and the realistic observations of the seismic performance of infilled RC frame buildings remains unresolved.

The aforementioned contradiction has led to the formulation of two earthquake-resistant design philosophies. One requires the infill be tightly placed in the frame and behave as beneficial structural elements (Bertero & Brokken, 1983). The implementation of this philosophy is considering the unreinforced masonry infill (URM) behaviour as an equivalent diagonal strut. Some modelling techniques have then been proposed (Stafford-Smith, 1966; Saneinejad & Hobbs, 1995; Mehrabi & Shing, 1997; Flanagan & Bennett, 2001; El-Dakhakhni et al, 2003; Cavaleri, 2005) and practically presented in design pre-standards (FEMA 306, 1998; FEMA 356, 2000; ATC 40, 1996). However, the tightly placed strategy and strut model for URM infill walls cannot clearly define the complex interaction and reveal the inherent brittle properties of materials. As observed in most of these studies, the brittle nature of infill partition walls could not be prevented. As a result, under moderate and high earthquakes, the tight fit URM infilled frames exhibit poor performance due to premature shear failure of frame, or rapid degradation of stiffness, strength and energy dissipation capacity of infill wall.

The other design philosophy requires that infills be isolated from the structural system so that their structural effect and interaction can correctly be neglected. Nevertheless, difficulties lie on lack of convenient and satisfactory solutions for fire and acoustic protection of the gap. On the other hand, lessons from past earthquake events showed that isolating of infills without proper connection detailing led to catastrophic out of plane throw-off failure, which blocked the crucial escape/rescue channel and endanger people inside or outside the structure. In addition, recent researchers have found that the costs relating to failure of masonry infill panels may exceed cost of the replacement of the whole building. It is clear that no technological solutions and design guidelines have been developed to reflect the severe interaction under biaxial seismic actions and to model the major possible failure modes of both infill and frame. Therefore, there is an urgent need for proposing innovative technical solution and conducting experimental investigations to fill the gap.

Recognising the aforementioned poor seismic performance of tight-fit unreinforced masonry-infilled RC frame structures and the fact that the current code provisions for the seismic evaluation are far from satisfactory in terms of completeness and reliability, it is necessary to study and propose proper detailing and arrangements in the construction phase to assure no or low undesirable interaction of frame and infill. To address the aforementioned issues, a research project, including reversed cyclic load and shake table tests on scaled infilled RC frames, has been being carried out at the Hong Kong University of Science and Technology. The primary objective of the research is to develop an innovative damage mitigation system for infilled frames where the infill panel is isolated from bounding frame while appropriate flexible connections at column-to-infill interface are provided. This proposed optimum solution targets to utilise certain degrees of the beneficial strengthening effect of infill wall by reducing storey drift during low to moderate earthquakes, while under strong seismic excitations, infill walls are effectively isolated and the reliable in-plane stability are still maintained by the flexible steel connections. This paper presents the shake table tests results on 1/3 scale one storey-one bay specimens. The emphases are placed on the observations of failure modes, in-plane and out-of-plane stability, as well as global ductility.

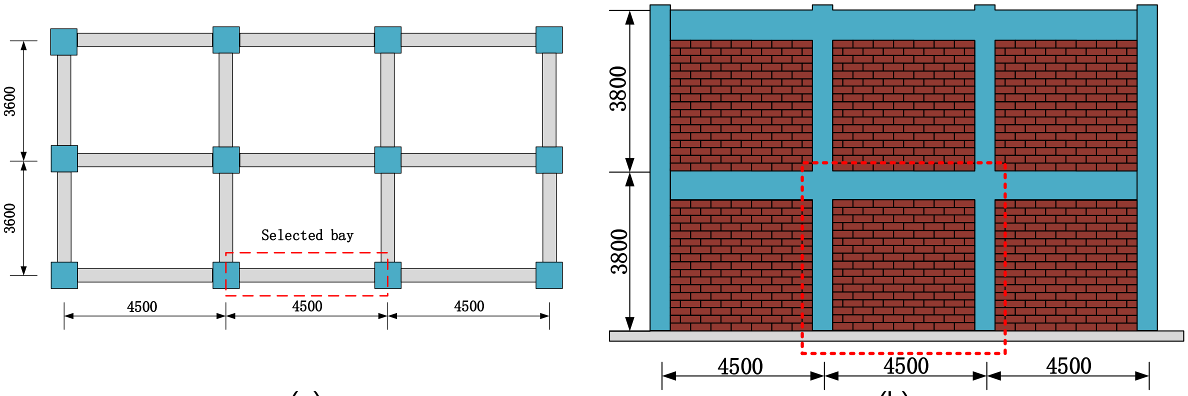
2. EXPERIMENT PROGRAMME

2.1. Prototype structure

The prototype structure chosen in this study is a typical 2-storey residential, reinforced concrete frame building in rural areas in China, which was designed to the Chinese seismic code (GB50011-2010) with the seismic precautionary intensity of 7 in Category 1, corresponding to the design peak ground acceleration of 0.15g. In this study, following a realistic situation the effect of infill panels is ignored and the building is modelled as a bare frame structure at the initial stage of design analysis. The ‘grade’ of the structure, which determines the reinforcement design and detailing requirements is evaluated based on the configuration, functionality and expected level of seismic influence of the building, is Class 3 according to the code of practice, which means the displacement ductility factor is approximately between 2 to 4. The design strengths of concrete, longitudinal and transverse reinforcement adopted are 20.1 MPa, 400MPa and 300MPa, respectively. The plan and elevation view of prototype structure are shown in Figure 1. The model structure is taken from first storey and middle bay of prototype structure and then scaled down to one-third scale.

2.2. Similitude requirements and specimen design

For earthquake-simulated shake table test, the design of specimens should fully consider the capacity of facilities and then derive the scale factor which based on the similitude law. In model testing, the ‘similitude requirements’ relating the reduced scale model to prototype structure can be derived from the dimensional analysis (Harris, 1979). In fact, the “true replica model”, which satisfies simultaneously the replication of inertial, gravitational and restoring forces, is difficult to be created because of severe restrictions imposed on material properties. As a consequence, the Artificial Mass Simulation model (AMS model) is developed, in which additional structurally uncoupled masses (Artificial Masses) are attached to the reduced scale model in order to augment the density of the model structure and satisfy the uniform vertical compressive strain. The summary of scale factors for the shake table tests is presented in Table 1.



(a) (b)

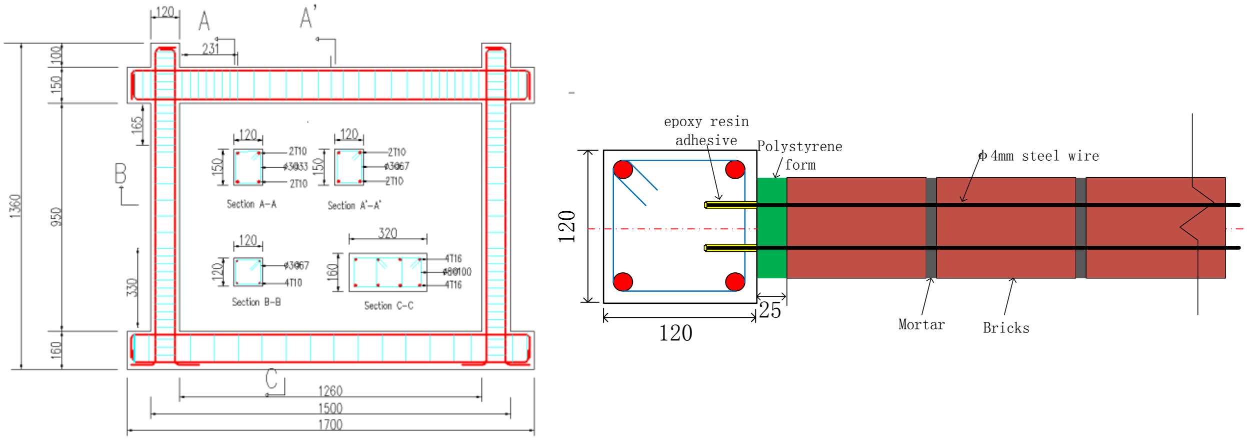
Figure 1. (a) Plan view of prototype structure (b) vertical view of prototype structure

Table 1. Summary of scale factors for shake table tests.

Quantity	Unit	Dimension	Artificial Mass Model	
Length	m	L	S_L	1/3
Displacement	m	L	S_L	1/3
Velocity	m/sec	LT^{-1}	$S_L^{1/2}$	0.577
Acceleration	m/sec^2	LT^{-2}	1	1
Time	sec	T	$S_L^{1/2}$	0.577
Frequency	Hz	T^{-1}	$S_L^{-1/2}$	1.732
Modulus	kN/m^2	FL^{-2}	1	1
Stress	kN/m^2	FL^{-2}	1	1
Strain	--	--	1	1
Force	kN	F	S_L^2	1/9
G-acceleration	m/sec^2	LT^{-2}	1	1
Model weight	kN	F	S_L^2	1/9

Two one-third-scaled masonry-infilled RC specimens with different frame-to-infill connection configurations were designed and tested under real earthquake record excitations. The geometry and reinforcement detailing of test specimens are shown in Figure 2. Detailing requirements in the Chinese code of practice require that in seismic areas, the infill panels should be anchored into columns with equally spaced 6-mm reinforcing bars deployed to the column/infill interface, with vertical spacing of 500 mm and extending into 500 mm into infills. Although this detailing requirement improves the integrity of the frame, it is still considered as strong connection which enlarges the undesirable infill-frame interaction and causes shear failure in frame members. Hence, flexible connections at infill-column interface using mild steel as anchorage are adopted; then the gaps are filled with structural polystyrene foam, which is fire proof, acoustic insulated, and environmental friendly. The first test specimen INC has no connections and tested as benchmark, while the second specimen IFC1 has isolated infill wall and 2 layers of full length flexible connections, as illustrated in Figure 3. The third specimen IFC2 has isolated infill panel and 3 layers of one-third length steel wire connections.

The mean values of concrete strength of INC, IFC1 and IFC2 obtained from 150-mm cubes are 37.1 MPa and 40.8 MPa and 36.6MPa respectively. Solid-clay brick units with dimensions of 205×98×50 mm were used for masonry infill panels. The characteristics of mortar layer are important parameter in masonry infill frame experimental tests. In this series of study, the mortar strength was designed corresponding to Type N mortar (ASTM C270, 2006). The mass ratios of cement to lime putty to sand to water are 1:1.134:9.073:1.585. The mean value of compression stress at 28 days is 4.73 MPa according to 100-mm cubes.



(a) (b)

Figure 2. (a) Geometry and reinforcement detailing of test specimen (unit: mm), (b) layout of proposed flexible connection

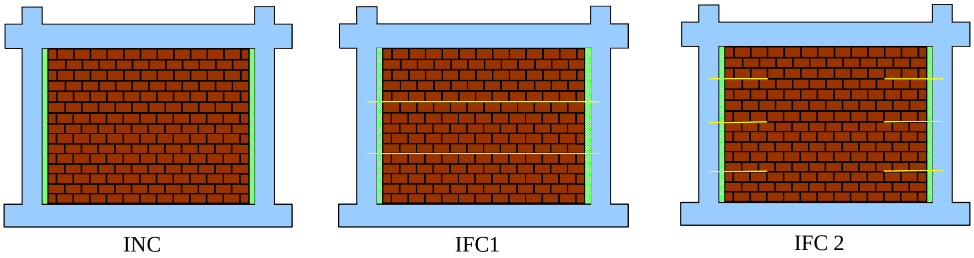


Figure 3. Masonry infill configurations

2.3. Test setup and instrumentation

All the shake table tests were carried out at the Structural Engineering Laboratory in the Department of Civil and Environmental Engineering, HKUST. The power unit system of the shake table is a hydraulic actuator with force rating of 10 tonnes and the maximum stroke is 150mm (±75mm). The payload of the whole shake table system was designed to 2 tonnes corresponding to the hoist capacity of the crane in the lab. The operational frequency is 0-50 Hz. The test setup and instrumentation is shown in Figure 4. A 1-ton steel mass was placed to serve as artificial attached mass and vertical load.

Test measurements mainly include three parts: (1) the overall lateral displacement and lateral force, (2) strain changes of reinforcement in bounding frame, and (3) crack development during loading process. To accomplish these measurements, accelerometers and laser transducers were arranged at the different locations of frame to record the lateral displacement. Strain gauges were placed at critical sections of frame to capture the local response. The crack development of infilled frame was carefully recorded by a camera during tests.

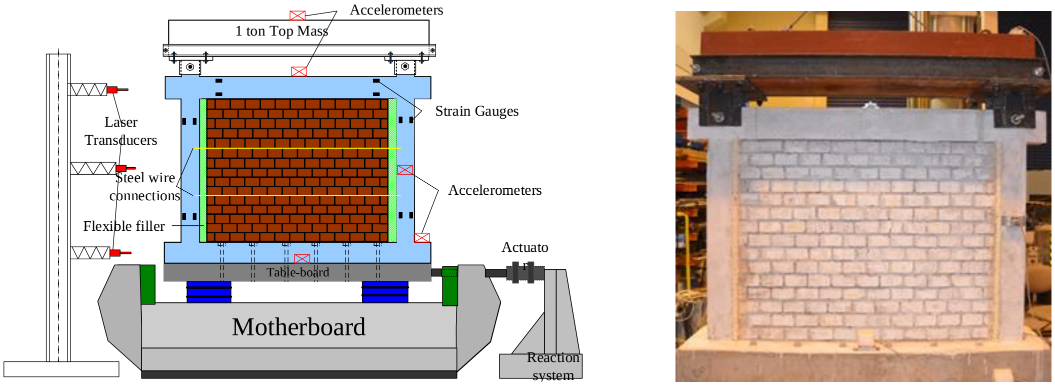


Figure 4. Test setup and instrumentation of frame specimens

2.4. Test protocol

All the three specimens are subjected to a series of dynamic tests, including white noise excitations and scaled earthquake record motions. The 2008 Wenchuan earthquake with PGA 0.58g, 1989 Loma Prieta earthquake with PGA 0.76g and 1987 Superstition Hill earthquake with PGA 0.96g are selected and scaled according to similitude requirements. Each of the specimen is subjected to a sequence of 37 dynamic tests and the main goal of which is to gradually damage the structure by subjecting it to earthquake ground motions with increasing intensity.

The dynamic loading protocol is shown in Table 2. The sequence of 37 dynamic tests can be categorised into 4 series. Series A are low amplitude tests to study the structural behaviour in the elastic range. Series B and C are moderate to high amplitudes to study the crack pattern and failure modes of structure. After the aforementioned three series of tests, sustained and visible damages of the specimens were induced. In order to estimate the ultimate failure modes, series D was conducted which included strong sine wave ground excitations and 100% input of selected earthquake ground motions. The white-noise tests were conducted before and after each trial of test to give the estimation of modal parameters including natural period, damping ratio and modal shapes, which can be used to indicate the damage evaluation.

Table 2. Dynamic loading protocol for all tests

Test Series	Description	Target PGA	Intensity according to Chinese Code
A	Low amplitude	0.056g	Intensity 7, frequent
		0.112g	Intensity 8, frequent
		0.15g	Intensity 7,moderate
		0.32g	Intensity 7, rare
B	Moderate	0.4g	Intensity 9, moderate
		0.52g	Intensity 8, rare
C	High amplitude	0.63g	Intensity 9, rare
		0.7g	
		0.8g	
		0.9g	
D	Sine wave and full amplitude excitation	1g Sine wave	-
		0.58g	Wenchuan
		0.76g	Loma Prieta
		0.96g	Superstition Hill

3. EXPERIMENTAL OBSERVATIONS

3.1. Observations

The cracks development and failure modes of specimen INC and IFC1, IFC2 during four test series are summarised in Figure 4. The initial phase of testing involved low amplitude excitations to study the structural behaviour in elastic range. The three selected ground motions were scaled to the peak ground acceleration of 0.056g, 0.112g, 0.15g and 0.32g and were used as input excitations. As can be seen from Figure 5, after test series A, no visible cracks were observed on infill panels. After test series B, some flexural cracks developed on frame members, however, because the panel wall was isolated and the flexible connection detailing was used, the interaction between infill panel and bounding frame was effectively mitigated and no brittle shear failure was observed on infill panel and beam-column joints. Test series C contains four groups of high amplitude excitations. Since the maximum displacement of Wenchuan earthquake would exceed the displacement stroke of the shake table system, only Loma Prieta and Superstition Hill earthquake records were used and scaled to peak ground acceleration from 0.63g to 0.9g. As shown in Figure 5(c), after the 0.9g Superstition Hill excitation, some shear sliding occurred and flexural cracks were developed on infill panel of INC. Although the storey drift of the three specimen reached 2.71%, 1.73%, and 1.88% respectively, all the specimens showed good seismic performance and only limited damage and cracks were observed, which indicates that the undesirable interaction was effectively reduced while at the same time the connections improved the integrity of infill walls. Test series D contains two parts, the 1-g sine wave excitation and full amplitude of selected ground motions. The purpose of this test series is to study ultimate failure mode of infilled RC frame specimen. As shown in Figure 5(d), during test series D, the specimen INC indicate that even in-plane excitation may trigger out-of-plane failure if no reliable connections are provided at column-infill interface. This phenomenon has been observed during the past earthquake events and the afterward out of plane throw off failure of infill panel usually caused catastrophic consequence. For specimen IFC1, three shear sliding failure surfaces were observed on infill panel, the general stability of infill panel were kept well. For specimen IFC2, flexural cracks were observed on critical region of bounding frame, however the in-plane stability of masonry wall is quite well. The mild steel connections in mortar layer provided satisfying in-plane integrity and prevented the out-of-plane throw off failure effectively.

Test series Specimen INC Specimen IFC1 Specimen IFC2

A

(a). INC, IFC1, IFC2 after 0.32g, 54% Wenchuan earthquake, drift ratio 1.02%, 0.71%, 1.14% respectively

B

(b). INC, IFC1 and IFC2 after 0.52g, 88% Wenchuan earthquake, drift ratio 1.68%, 1.1%, 1.25% respectively

Figure 5. Seismic performance and damage evaluation of specimens INC, IFC1 and IFC2

C

(c). INC, IFC1 and IFC2 after 0.9g, 94% Superstition Hill earthquake, drift ratio 2.71%, 1.73% and 1.88% respectively

D

(d). INC, IFC1, IFC2 after 1-g sine wave excitation

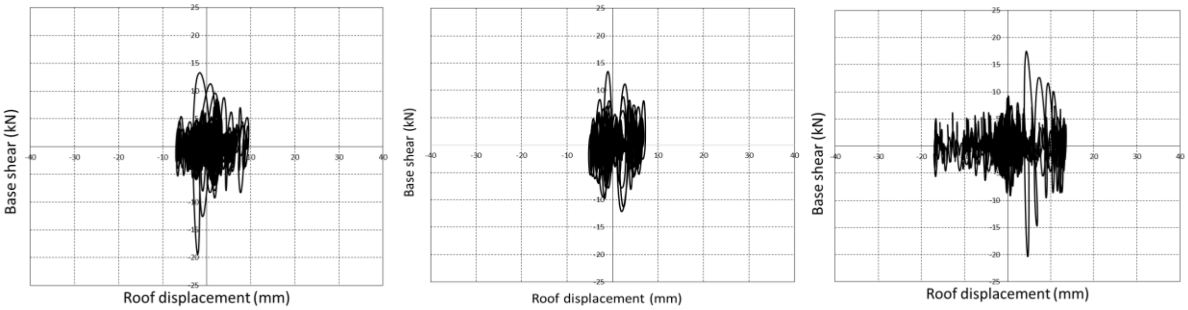
Figure 5. Seismic performance and damage evaluation of specimens INC, IFC1 and IFC2

3.2. Hysteresis behaviour

The hysteretic response of three specimens in test series A, B and C are presented in the form of top displacement plotted against corresponding horizontal base shear force, as shown in Figure 6. According to the hysteretic plots, all the three specimens have good global ductility and energy dispassion capacity. The frame specimen with flexible isolation can prevent the frame system from premature shear failure and reliable mild steel connections can improve the in-plane integrity of infill panel and avoid out-of-plane throw out failure at early stage of excitation. For specimen IFC1 and IFC2, the full-length connections and one-third length connections have similar performance under low amplitude excitation, however under high amplitude excitations, the full length connections may prevent the crack development in masonry panel along vertical direction and finally form horizontal shear sliding cracks, which potentially cause instability.

Test series Specimen INC Specimen IFC1 Specimen IFC2

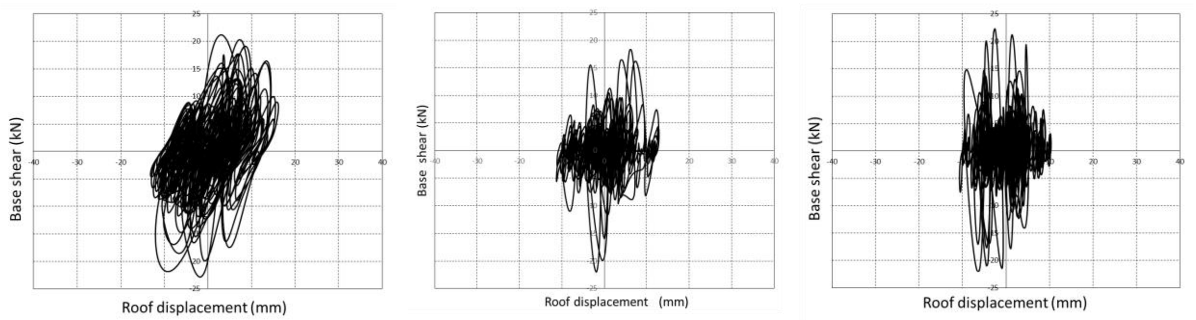
A



(a). INC, IFC1, IFC2 after 0.32g, 54% Wenchuan earthquake

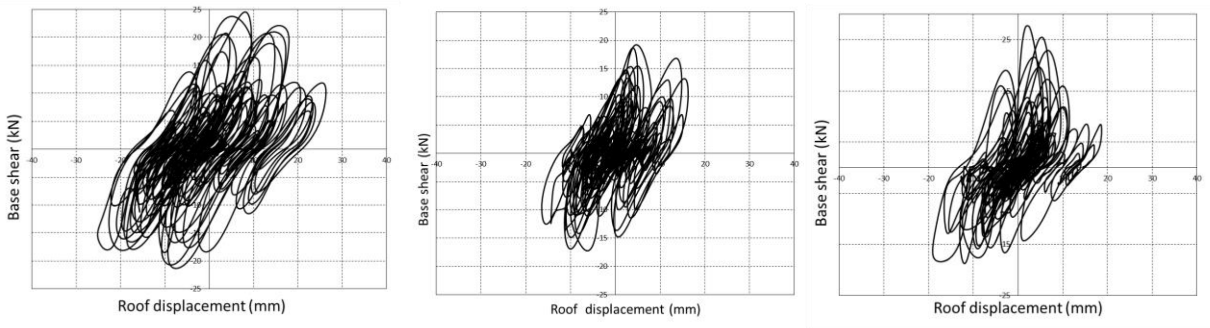
Figure 6. Base shear vs. top displacement hysteresis curves

B



(b). INC, IFC1 and IFC2 after 0.52g, 88% Wenchuan earthquake, drift ratio 0.65%, 1.1%, 1.3% respectively

C



(c). INC1, IFC1 and IFC2 after 0.9g, 94% Superstition Hill earthquake, drift ratio 2.71%, 1.73%, 1.88% respectively

Figure 6. Base shear vs. top displacement hysteresis curves

4. CONCLUSIONS

In this paper, an innovative damage mitigation system, where infill panel is isolated from bounding frame while adding flexible connections at column-to-infill interface, is proposed. Three one-third scale, one-storey one-bay masonry infilled frames were constructed and tested on one directional shake table with real earthquake ground motions. The test results showed that isolating the infill panel from RC columns with finite length can effectively prevent direct shear failure at beam column joint and rapid stiffness degradation in infill panel. After moderate amplitude excitations, some shear sliding occurred and flexural cracks were developed on infill panel of INC. Although the storey drift of the three specimen reached 2.71%, 1.73%, and 1.88% respectively, all the specimens showed good seismic performance and only limited damage and cracks were observed. It should be noted that in-plane ground excitation may also trigger the out-of-plane throw-off failure of infill panel and endanger peoples' life and properties, consequently, reliable connection is essential for isolating design strategy. The full length and one-third length steel wire connections showed no obvious difference under low amplitude excitation, however, in order to prevent potential shear sliding failure, the detailing method of IFC2 is recommended. Generally, the proposed flexible connection detailing method can effectively mitigate the interaction between infill-panel and bounding frame. In addition, the ductility and energy dispassion capacity, and integrity of the frame system are generally improved.

5. ACKNOWLEDGEMENTS

The support of the Hong Kong RGC under grand number 16204214 is greatly acknowledged.

6. REFERENCE

Applied Technology Council (ATC) (1996). Seismic Evaluation and Retrofit of Concrete Buildings, Volumes and 2, Report No. ATC-40, Redwood City, CA.

ASTM C 270, Standard Specification for Mortar for Unit Masonry, Annual Book of Standards, Vol. 04.05, ASTM International, West Conshohocken, PA, 2006

Bertero, V.V. and Brokken, S.T. (1983). "Infills in seismic resistant buildings", *Journal of Structural Engineering*, ASCE, 109(6), 1337-1361

Chopra, A. K. (1995). "Dynamics of Structures: Theory and Applications to Earthquake Engineering". PrenticeHall. Inc., Upper Saddle River, NJ.

Cavaleri, L., Fossetti, M., and Papia, M. (2005). "Infilled frames: developments in the evaluation of cyclic behaviour under lateral loads." *Structural Engineering and Mechanics*, 21, 469-494.

El-Dakhakhni, W.W., Elgaaly, M. and Hamid, A.A. (2003). "Three-strut model for concrete masonry-infilled steel frames." *Journal of Structural Engineering*, ASCE, 129(2), 177-185.

Flanagan, R.D. and Bennett, R.M. (2001). "In-plane analysis of masonry infill materials." *Practice Periodical on Structural Design and Construction*, ASCE, 6(4), 176-182.

FEMA (1998). Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings. FEMA 306, Federal Emergency Management Agency, Washington, D.C.

GB 50011-2010 (2010) Code for Seismic Design of Buildings, Architecture & Building Press, Beijing, China.

Harris, H.G. and Sabnis, G.M. (1999). "Structural Modelling and Experimental Techniques, 2nd Edition, CRC

Kuang J.S. and Zhang H.H. (2014). "Shake table tests of infilled RC frames with different column-to-infill connections" Proc., 2nd European Conf. on Earthquake Engineering and Seismology, Istanbul, Turkey Press.

Mehrabi, A.B. and Shing, P.B. (1997). "Finite element modeling of masonry-infilled RC frames." *Journal of Structural Engineering*, 123(5), 604-613.

Priestley, M.J.N.(2000). "Performance based seismic design." *Proc.,12th World Conf. on Earthquake Engineering*, Auckland, New Zealand

Stafford-Smith, B. (1966). "Behaviour of square infilled frames." *Journal of Structural Division*, ASCE, 92(ST1), 381-403.

Saneinejad, A. and Hobbs, B. (1995). "Inelastic design of infilled frames," *Journal of Structural Engineering*, ASCE, 121(4), 634-650.