EFFECT OF CONNECTORS ON IN-PLANE CYCLIC BEHAVIOUR OF MASONRY-INFILLED RC FRAMES

J S KUANG
Professor, Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong
cejkuang@ust.hk

Zhe WANG
PhD Candidate, Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong
zhewang@ust.hk

ABSTRACT: The instability of masonry infills in the out-of-plane direction has been recognised as one of the principle issues for masonry-infilled RC frame structures. Although most of seismic design codes have recommended the use of mechanical connectors to connect infill wall and bounding frame for mitigating the out-of-plane collapse of infill wall, it is still far from satisfaction with the insufficient commentaries in the codes, particularly neglecting the potential risk of connectors on the in-plane behaviour of masonry wall. The study is based on laboratory testing of three large-scale, single-bay masonry-infilled RC frame specimens. Two different infill configurations are adopted, which are named as “full contact infills” and “column-slitted infills”. The R6 reinforcing bars and ϕ4 steel wires are used to represent the strong and weak connectors, respectively. It is evident from test results that the specimen with weak connectors in slitted infills has displayed the preferable cyclic performance. In contrast, the specimen with strong connectors has appeared the shear sliding failure under the pronounced push-pull actions. The full contact specimen with strong connectors has emerged the severe local collapse of infills by in-plane bearing actions. It is concluded from the study that the weak connectors by preserving the sufficient flexible deformation capacity are recommended as mechanical connectors in the present seismic codes.

1. Introduction

Reinforced concrete frame buildings with masonry infills are the most popular structure system in the world. However, the out-of-plane collapse of masonry infills occurred repeatedly under investigations from past earthquakes. The most typical one is the Mw6.3 L’Aquila Earthquake, attacked the central Italy in 6th April 2009, where the double-leaf masonry infills are prevalent but without structural connections. As a result, an excessive amount of infilled frames experienced the substantial out-of-plane collapse focused on the outer-leaf under earthquake (Vicente, 2010).

The history of investigating the effect of connectors on masonry infills was early. The original connectors are functioned as “shear connectors” applied in moment-resisting frame structures with RC infill walls in early 1980’s, and are fabricated as “U hooks”, “J hooks”, or so-called “steel piece anchor” (Klingner and Bertero, 1976; Hayashi et al., 1980; Kwan and Liauw, 1984). The beneficial effect of connectors are acknowledged by transferring the lateral load and increasing the overall stiffness. The earliest experiments were recorded in 1985 to thoroughly compare with different anchorage conditions (Zarnic and Tomazevic, 1985). These connectors are in the true sense of “anchorage” by 6 mm smooth bars anchoring into columns and 8 mm deformed bars connecting to beam. It is noticed that the anchorage is capable of increasing the lateral resistance of structure. Throughout the 1990s, the studies were focused on connectors in improving of in-plane seismic performance, however, the so-called “column-to-panel ties” did not exhibit any of the particularly advantages to the cyclic behaviour of system, but rather induced the propagation of extensive off-diagonal random cracks to the adjacent masonry units (Dawe and Seah, 1989; Bennett, 1996). Studies coming to 2010s, the connectors are 6 ~ 10 mm smooth bars and only regarded as detailing measurement in securing against the out-of-plane actions of infills (Tasnimi and Mohebkhah, 2011; Leite et al., 2011; Al-Nimry, 2014).

On the other hand, the codes of practice have also noticed the favourable effect of connectors on preventing the out-of-plane collapse. The Chinese seismic code was the earliest code at nationwide level to mandate the detailing requirements of connectors in 1978. In the updated version GB50011-2010 by Clause 13.3.4, the 2φ6 smooth bars spaced at 500 mm ~ 600 mm along the height of infill panel shall extend into the over-length of mortar joints. The updated American masonry code MSJC (2011) has elaborated the connectors in the newly added chapter Appendix B. Specifically, the connectors shall be applied in the non-participating infills at a maximum spacing of 1.22 m along the supported perimeter.

Although the effectiveness of connectors on resisting the out-of-plane load has been progressively acknowledged and mandated in code of practice in some countries, the potential detrimental effect of connectors in the in-plane direction has seldom been discussed. In this paper, the possible in-plane risk of connectors in both the full contact and isolated infill configurations has been thoroughly investigated. The possible change in the lateral load transfer mechanism owing to inclusion of connectors, and the corresponding cyclic performance and failure modes have been well recorded and discussed.

2. Experimental Programme

2.1. Test Specimens

Three large-scale, single-storey, single-bay specimens were tested under the reversed cyclic loading. The specimens were extracted from the ground-floor mid-span of a typical six-storey prototype building, which is designed to Eurocode 8 (CEN, 2004) with Ductility Class Medium (DCM). The dimensions equal to 2.4 m * 1.45 m under a centre-to-centre spacing, are illustrated in Fig. 1.

Reinforcement ratios of columns and beam are 2.57% and 1.16%, respectively, which are to guarantee the sufficient DCM demand. The concrete and mortar properties are summarised in Table 1, where the concrete strengths are in the range from 31.1 N/mm2 to 38.2 N/mm2, while the mortar strengths range from 8.62 N/mm^2 to 10.87 N/mm^2. In addition, the solid-clay brick units were chosen with the compatible size suitable to bounding frame as 205 mm * 98 mm * 50 mm to build the masonry infill walls.

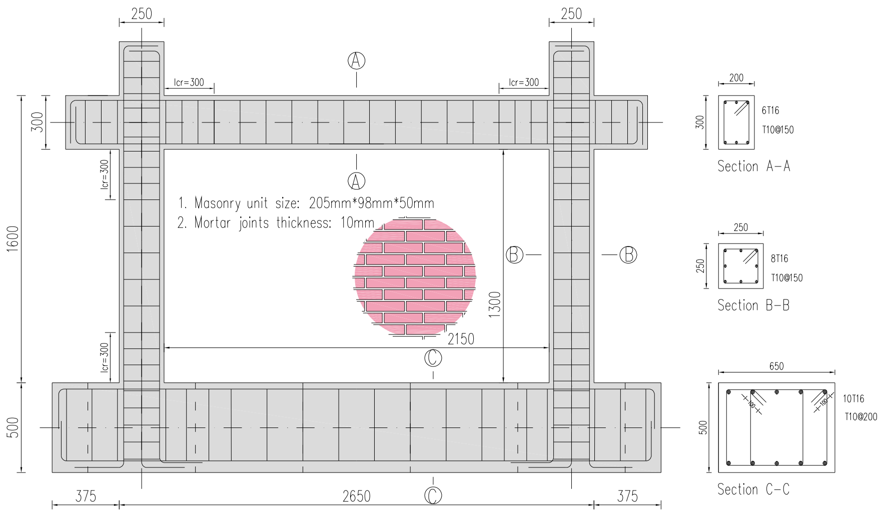


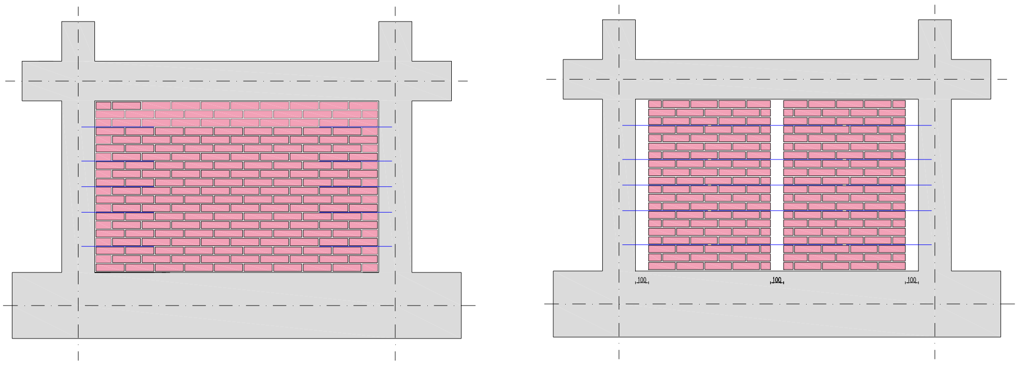
Fig. 1 – Geometry and Reinforcement Layout of Test Specimens (unit: mm)

Table 1 Material properties for specimens (Unit: N/mm2)

Specimen	Concrete strength	Steel yield strength	Mortar strength
FC-R6	35.7	500	10.87
CS-R6	38.2	500	8.62
CS-W4	31.1	500	9.59

2.2. Classification of Specimens

The three specimens are separated into two categories: the "**F**ull **C**ontact infills" by specimen FC-R6 (standard one) and "**C**olumn-**S**litted infills" by specimen CS-R6 and CS-W4. The objectives of study are to investigate the in-plane influence of connectors on different infill configurations, and analyse different failure mechanisms under different connectors: R6 steel bars or φ4 steel wires. The connectors are anchored into columns on one side, and effectively embedded into mortar bed joints on the other side with the sufficient length ⩾ 450 mm, as shown in Fig. 2.



(a) Specimen FC-R6 (b) Specimen CS-R6 / CS-W4

Fig. 2 – Classification of Specimens

2.3. Experimental Set-up and Procedure

The test set-up and loading arrangement are shown in Fig. 3. The specimen is subjected to both the vertical and horizontal loads, where the vertical load is first applied to the two column ends by the loading frames with the axial load ratio of about 10% of the column squash capacity, to simulate as a practical axial load ratio in real buildings, while the lateral load reversal is then applied to the end of the top beam by a 440-kN servo actuator. In the test, the displacement controls are adopted through the whole loading stages. The test specimens are subjected to two cycles of reversed loading until specimen experiences a significant loss of capacity (80% of maximum applied load).

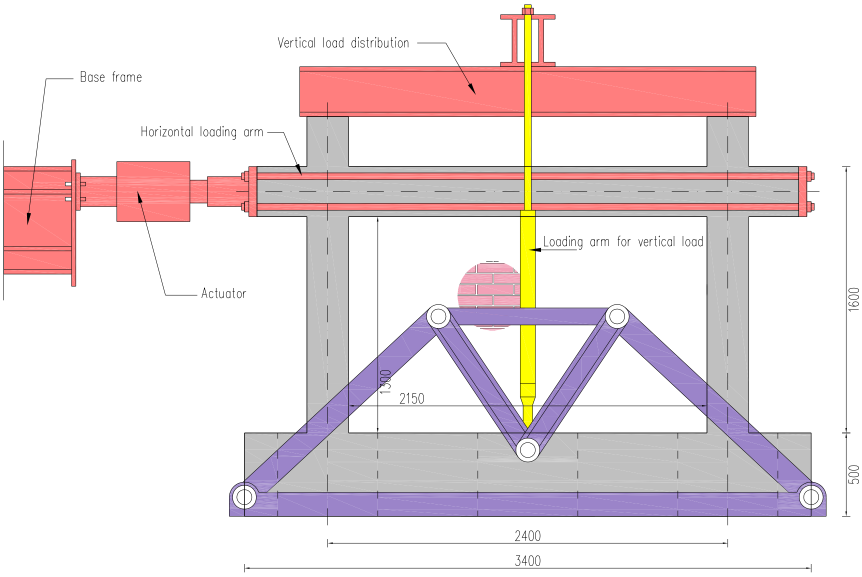


Fig. 3 – Test Set-up and Loading Arrangement (unit: mm)

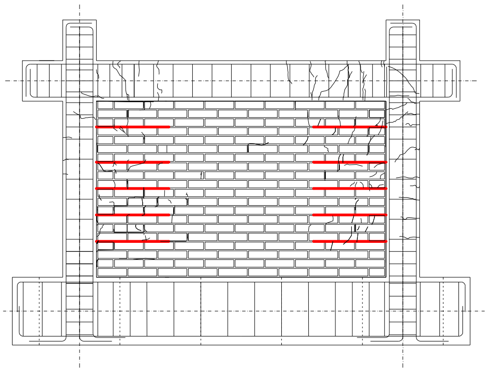
3. Test Results

3.1. Effect of Connectors on Specimen FC-R6

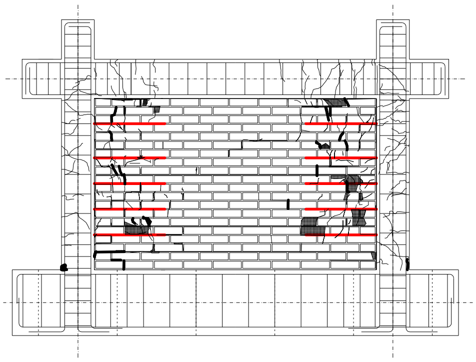
The Specimen FC-R6 is presented as a standard infilled frame with the full contact infills. The 2R6 mild bars with 450-mm embedded length are anchored into columns with spacing of each three or four masonry courses. It was observed that the typical bearing failure of infills occurred on the lower mid-height connector regions, as shown in Fig. 4.

The in-plane bearing effect of connectors was pronounced even at relatively low lateral drifts. It has been seen from Fig. 4 (a) that the clearly visible off-diagonal random cracks were focused on the connector regions at drift ratio of 1.2%. The anchored connectors induced the unexpected compressive action repeatedly to the adjacent masonry units accompanied with the reversed lateral movement of columns, which led much stronger bearing action to masonry units than the diagonal shear / tension actions.

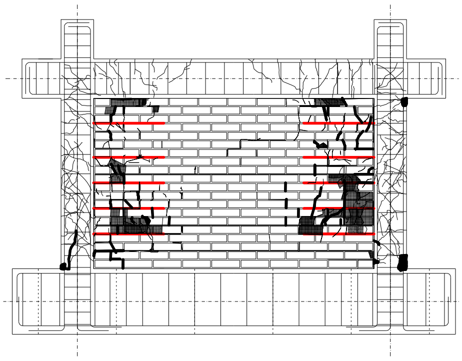
It is observed that the masonry units at lower mid-height region cross the connectors were suddenly fractured around the peak load drift of 2.6% (Fig.4 (b)). After that, the masonry infills begun to progressively collapse, and eventually turned into a large “opening” near the right column side. It can be seen from Fig. 5 that the undesirable opening dramatically decreased the supporting length of column and concentrated the deformation at lower mid-height area, eventually caused the short column failure.



(a) 1.2% drift



(b) 2.6% drift



(c) 3.6% drift

Fig. 4 – Failure Modes of Specimen FC-R6 under Different Lateral Drifts

(a) short column failure of right column

(b) local collapse of masonry infills

Fig. 5 – Final Stage of Specimen FC-R6

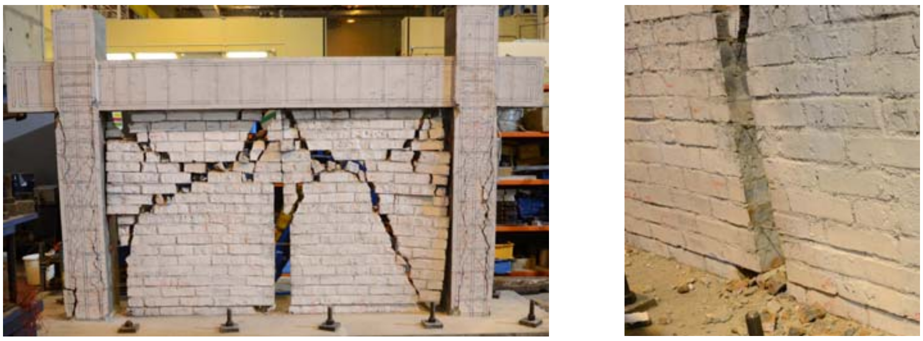
3.2. Effect of Connectors on Specimen CS-R6 / CS-W4

The Specimen CS-R6 and CS-W4 were tested the identical column-slitted infill walls but with different types of steel connectors. From an overall perspective, it can be recognised that the application of isolated infill condition can effectively eliminate the in-plane bearing ations of connectors. However, the shear sliding failure induced by the push-pull action of connectors is undesirably substantial in Specimen CS-R6, as shown in Fig. 6. It was observed that the two subpanels of masonry infills were adversely separated into several portions, particularly concentrating at the connector embedded mortar layer, which indirectly damage the integrity of infill panel.

In Specimen CS-W4, the much weaker connectors 2φ4 wires were utilised to anchored into bounding columns. It has been shown from the results that no obviously push-pull action from connectors was observed and the two subpanels were failed by the typical shear cracking along the diagonal directions, as shown in Fig 7. It should be cautioned that the bond condition between the beam bottom and wall panel interface is significantly important. The bond should be weak enough to develop the shear-friction mechanism by releasing the deformation capacity of infills, rather than the diagonal shear mechanisms.

(a) overall view (b) shear sliding failure

Fig. 6 – Final Stage of Specimen CS-R6



(a) overall view (b) integrity of infill panel

Fig. 7 – Final Stage of Specimen CS-W4

4. Conclusion

Experimental investigations are conducted on large-scale masonry-infilled RC frame specimens to study the effect in-plane connectors which connect infill walls and bounding frame on the seismic behaviour of infilled RC frames. It reveals from the test results that under R6 reinforcing bars, the in-plane bearing effect of connectors is extremely remarkable in the standard specimen (full contact infills), while the push-pull action of connectors is also pronounced in the isolated one. Comparatively, the weak ϕ4 steel wires achieved better cyclic behaviour than the R6 connectors. It is concluded that the weak connectors but having enough flexible deformation capacity are highly recommended to use in practice, and steel the connectors should be strictly required to constrain the transfer of in-plane forces.

5. Acknowledgements

The support of the Hong Kong RGC under grand number 613712 is gratefully acknowledged.

6. References

AL-NIMRY, H.S. “Quasi static testing of RC infilled frames and confined stone-concrete bearing walls”, *Journal of Earthquake Engineering,* Vol. 18, 2014, pp. 1-23.

BENNETT, R.M., ET AL. “Evaluation and analysis of the performance of masonry infills during northridge earthquake”. Oak Ridge, Tenn., 1996.

CEN (European Committee for Standardization) (2004). EN 1998-1: 2004: Eurocode 8: Design of Structures for Earthquake Resistance-Part 1.1: General Rules, Seismic Actions and Rules for Buildings, European Commission, Brussels.

DAWE, J.L. and SEAH, C.K. “Behavior of masonry infilled steel frames”, *Canadian Journal of Civil Engineering*, Vol. 16, 1989, pp. 865–876.

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

HAYASHI, Y., NIWA, H., and FUKUHARA, M. “The strengthening method of the existing reinforced concrete buildings”, *Proceedings of the seventh world conference on earthquake engineering, Istanbul*, Turkey, Vol 4, 1980, pp 89-96.

KLINGNER, R.E. and BERTERO, V.V. “Infilled frames in earthquake-resistant construction”, Report No. EERC 76-32, University of California, Berkeley, CA., 1976.

KWAN, K.H. and LIAUW, T.C. “Non-linear analysis of integral infilled frames”, *Engineering Structures*, Vol 6, No 3, 1984, pp 223-231.

LEITE, J., PAULO PEREIRA, M.F., LOURENÇO, P.B. “Infill masonry: Seismic behavior of reinforced solutions”, *Proceedings of the 7th International Conference, Analytical Models and New Concepts in Concrete and Masonry Structures*, Cracóvia, Polónia, CD-ROM, 2011.

MSJC (Masonry Standards Joint Committee) (2011). Building Code Requirements for Masonry Structures and Specification for Masonry Structures, (TMS 602-11 / ACI 530.1-11 / ASCE 6-11), the American Concrete Institute, Farmington Hills, Michigan.

TASNIMI, A.A. and MOHEBKHAH, A. “Investigation on the behavior of brick-infilled steel frames with openings, experimental and analytical approaches”, *Engineering Structures*, Vol. 33, 2011, pp. 968-980.

VICENTE, R. RODRIGUES, H., COSTA, A., VARUM, H., SILVA, J.A.R.D.d. “Masonry enclosure walls: lessons learnt from the recent Abruzzo earthquake”, *14th European conference on earthquake engineering*, Ohrid, Republic of Macedonia, 2010.

ZARNIC, R. and TOMAZEVIC, M. “Study of the behaviour of masonry infilled reinforced concrete frames subjected to seismic loading”, *proceeding of the 7th International Conference on Brick Masonry*, Australia, 1985, pp. 1315–1325.