Collapse prevention of infill-brick wall of RC frames with FRP Stitching Technology

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SUMMARY:
With recent earthquakes occurred in the world, it is revealed that a great number of people are killed by the collapse of vulnerable buildings. With the objective of solely protecting human lives and without seeking any further performance objective for the structure, alternative economical collapse preventing strategies need to be developed. The authors presented an idea and the effectiveness of "sewing-bands" made from FRP bundle at 14WCEE in Beijing. As a continuation of that previous work, the scaled 1-story, 1-bay brick-infilled RC frames that were retrofitted with "sewing-bands" were tested by imposing out of plane load. The infill-brick walls of the test specimens sustained large deformations in and out of plane directions, but did not collapse. "Sewing-bands" successfully kept the infill-bricks intact by the help of a net made of FRP bundles, and the horizontal load carrying capacity of the frame was maintained. The proposed analytical model was validated by the test results. A simple design procedure to decide the amount of fiber reinforcement in a "sewing-band" was presented.

Keywords: Infill-brick wall, Collapse prevention, Life safety, FRP, Seismic retrofit

1. INTRODUCTION

The infill-brick walls are used generally as partitioning walls constructed inside the frame. During strong motions, the infill-brick wall may lose its stability in the out of plane direction (Fig. 1). Such sudden collapse of these walls may cause pancake type collapse of the building because of the non-ductile nature of existing RC frames of old construction (Fig. 2). Building collapses due to such collapses caused the death of more than 17,000 people in the 1999 Kocaeli earthquake (Architectural Institute of Japan 2001). In order to reduce the number of fatalities in future earthquakes, some measures to avoid the pancake collapse are absolutely needed. The objective of this study is to propose a possible collapse prevention scheme by keeping the infill walls intact during earthquake excitations. When the infill wall damage is eliminated, it is possible to keep the rigidity and lateral load capacity of some buildings equipped with substantial amount of infills during earthquakes. In this way, it is possible to contribute to the disaster mitigation studies by collapse prevention of buildings in countries where reinforced concrete frames buildings with infill-brick walls are commonly used.

Use of fiber reinforced polymers (FRPs) to upgrade the RC frames with infill-brick walls was developed as a part of an extensive research project (Ozcebe et. al. 2003 and Wasti et. al. 2003). In those studies FRP cross-braces that were bonded on the surface of infill-brick walls integrated to the boundary frame members with FRP anchors. Quasi-static cyclic tests were performed in order to validate the effectiveness of the system (Erduran 2002 and Akguzel 2003). Subsequently, an analytical model to estimate the nonlinear static response was proposed (Binici and Ozcebe 2006). The most important disadvantage of FRP cross-brace is the cost effectiveness. In order to overcome this deficiency, the ideas borrowed from FRP stitching of RC slabs for punching shear strengthening (Binici and Bayrak 2003) was applied to strengthen RC shear walls (Kobayashi 2005) and brick infilled RC frames (Kobayashi 2007). Most importantly, "sewing bands" can act as elements that can keep the wall intact for in and out of plane deformations. In order to apply "sewing bands" to the seismic retrofit design, a simple analytical model was also proposed in previous studies (Binici and Kobayashi 2008, Watanabe and Kobayashi 2009).

In this study, scaled one-story, one-bay brick-infilled RC frames retrofitted with "sewing-bands" were tested by imposing out of plane loads together with in plane deformation excursions. This study presents the summary of experimental findings and a procedure to calculate the required amount of FRP in a sewing band to keep the wall intact for in and out of plane deformations.

Figure 1. Collapse of infill-brick wall to out of plane

Figure 2. Pancake crush of RC frames with infill-brick wall

2. RETROFIT SCHEME BY FRP STITCHING

FRP stitching method previously explained in detail (Kobayashi 2005, Binici and Kobayashi 2008) is illustrated in Fig. 3. The application can be summarized as follows: First, small holes are drilled at some intervals on the brick joint line both horizontally and vertically without the need of any smoothening process on wall surfaces. A bundle of strands with resin are put through the holes as shown in Fig. 3. The end of strands is wound around the columns to secure the anchorage of the end of sewing-bands, to integrate the infill-brick wall and columns, and to increase the shear capacity of columns.

The main advantages of this methodology are: i) There is no need to finish the wall surfaces or to apply primer to provide a flat surface for bonding, ii) The FRP bands are secured by proper wraps that are sufficient to develop a significant portion of tensile strength of FRPs, iii) The use of FRP bands that are much more economical compared to fabricated products minimizes the amount of FRP material resulting in economical retrofits.

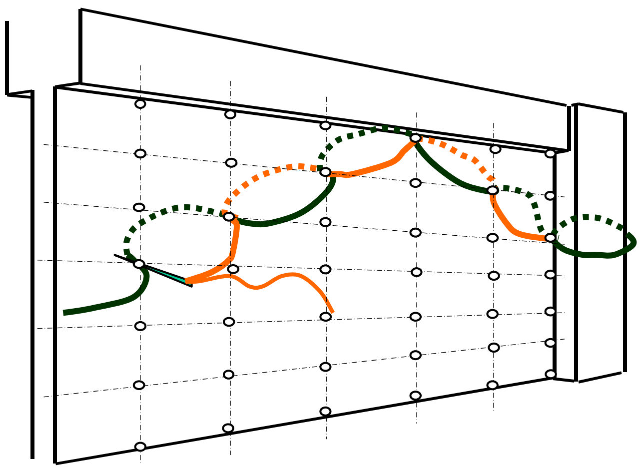


Figure 3. FRP Stitching technology

3. A LOAD-DEFLECTION MODEL FOR ONE STORY ONE BAY INFILLED RC FRAMES

The infill-brick walls resist earthquake induced lateral forces acting as compression struts as shown in Fig.4. The load-deflection relationship of RC frames with infill-brick walls can be described as the summation of the load deflection responses of the bare frame and the infill-brick wall acting as two springs connected in parallel.

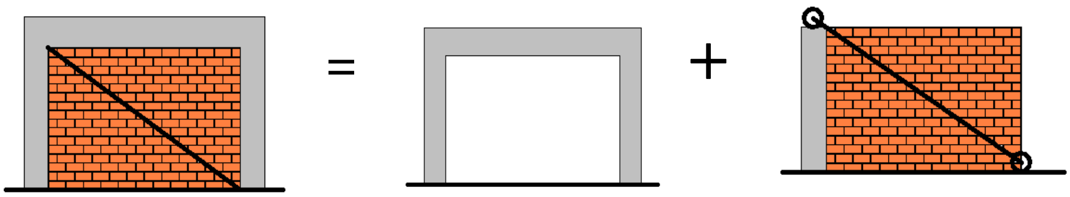


Figure 4. Concept of load deflection model of brick infilled RC frame

The load-deflection relationship of infill-brick wall strengthened by "sewing bands" is postulated from the prism test results (Binici and Kobayashi 2008, Watanabe and Kobayashi 2009) by using a simple load-deflection diagram as shown in Fig.5. The first region is the elastic region up to cracking (Q_{cr}) expressed by Eqn.3.1. At the cracking point, the shear deformation angle of the wall is approximately 1/1000 in the prism test results. At this stage, bed joint mortar reaches tensile strength and upon cracking there is a reduction in the stiffness of the system.

$$Q_{cr} = 0.19\sqrt{\sigma_m} \cdot t \cdot h_o \tag{3.1}$$

where σ_m is the compressive strength of joint mortar, t is the thickness of wall, h_o is the length of horizontal joint. Second region is the post cracking region. In the case of infill wall without sewing bands, strength can be maintained up until frictional resistance between bed joints is completely overcome. For the case of infill wall with sewing bands, further load carrying capacity that can be computed by Eqn.3.2 and Eqn.3.3 is available due to the contribution of tensile strength of fibers and their ability to limit crack openings in the mortar joints.

$$K = b \cdot 2 \cdot n_1 \cdot \frac{n_2}{l} \cdot A_f \cdot E_f \cdot \cos\theta \tag{3.2}$$

$$\Delta Q = c\sqrt{n_1 \cdot n_2 \cdot A_f \cdot E_f \cdot \cos\theta} \tag{3.3}$$

A_f is the sectional area of one strand, E_f is the Young's modulus of strands, n_1 is the number of strands in a sewing band, n_2 is the number of sewing bands that cross the diagonal line of wall panel, θ is the angle of sewing bands installed on wall panel, l is the diagonal line length of wall panel, and parameters b and c are 0.731, and 10.2 obtained from calibrations with experimental results.

The third region is the softening region of the load-deformation response. At this stage frictional strength of the mortar bed joints tends to decrease and crack opening and propagation are observed. For infill frames without sewing bands, load carrying capacity reduces to zero. On the other hand, infill walls with sewing bands, the wall can further carry load due to tensile strength of fiber strands leading to available residual carrying capacity (Q_r) that can be assumed to be same as (Q_{cr}) for all practical purposes.

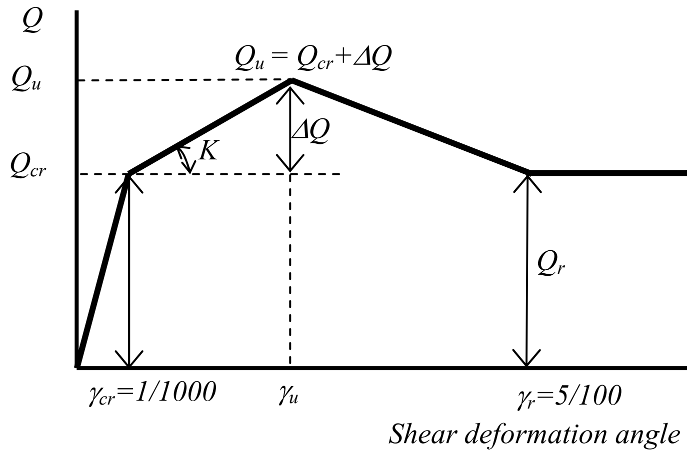


Figure 5. Load-deflection model

4. SEWING BANDS REQUIRED FOR OUT OF PLANE RESISTANCE

Assuming that the out of plane horizontal force ($F = k \cdot w \cdot h_o \cdot l_o$) that acts on the wall is known (h_o and l_o are the length and the height of infill-brick wall respectively), *F/2* acts on the sewing bands that were wound around one column as shown in Fig.6. The number of strands required in a sewing band (n_1) to resist *F/2* can be calculated as:

$$n_1 \cdot n_3 \cdot A_f \cdot \sigma_{fe} \geq F/2 \tag{4.1}$$

n_3 : Number of sewing bands wound around one column
n_1 : Number of strands for a sewing band
σ_{fe} : Effective tensile strength of fiber
A_f: Sectional area of a strand
k : Response seismic shear coefficient

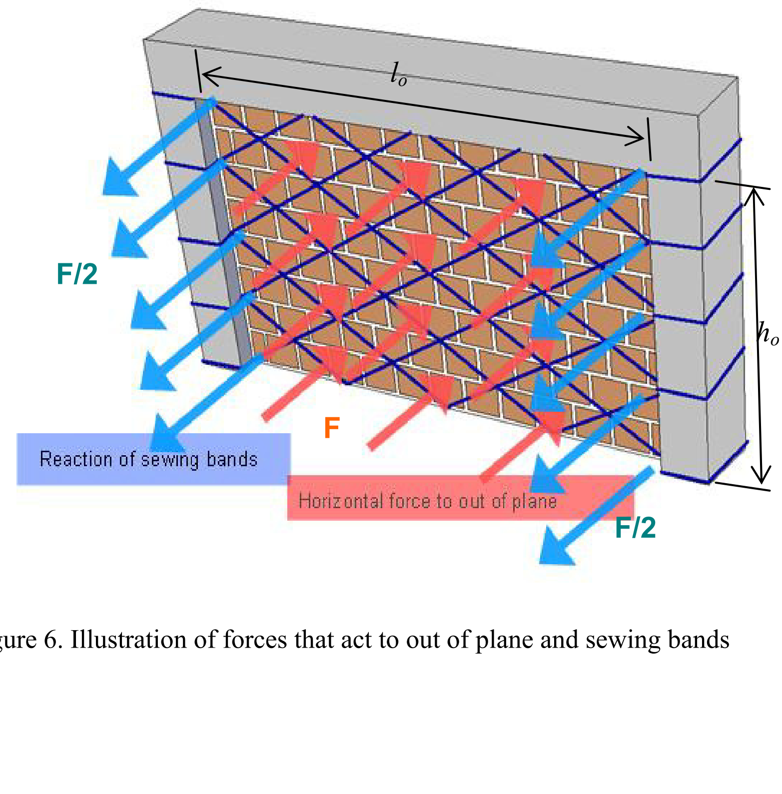


Figure 6. Illustration of forces that act to out of plane and sewing bands

From the prism test results (Binici and Kobayashi 2008, Watanabe and Kobayashi 2009), we observe that a positive stiffness, (i.e. no softening in the load-deflection response) in the load deflection curve of infill-brick walls can be obtained when:

$$\sqrt{n_1 \cdot n_2 \cdot A_f \cdot E_f \cdot \cos\theta} \geq 250 \tag{4.2}$$

and

$$2 \cdot n_1 \cdot \frac{n_2}{l} \cdot A_f \cdot E_f \cdot \cos\theta \geq 110 \tag{4.3}$$

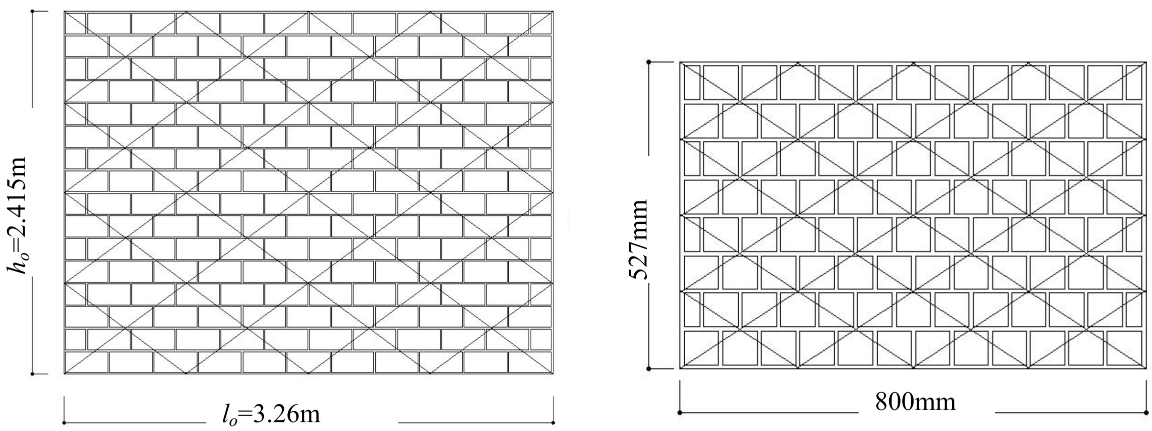
In addition, it was proved from the prism test that a minimum volume of strands in a sewing band is required to get the strengthening effect. From the prism test results, the strengthening effect was obtained when more than the following number of strands (n_{1min}) in Table 1 was provided.

Table 1. Required minimum number of strands in a sewing band

	n_{1min}
Carbon	2
Aramid	2
Glass	5
PVA	8
Nylon	16
Polyester	16

5. COMBINED IN AND OUT OF PLANE TESTING OF RC FRAMES WITH INFILLS

The dimensions of the scaled test frames were decided based on the dimensions of a prototype full scale RC frame as shown in Figure 7. The self weight of the infill wall is 1.876kN/m^2 considering both the bricks and the joint mortar. Possible candidates for FRP strands are listed in Table 2. The efective tensile strength of a strand was defined as 2/3 of the tensile strength or the stress at 2% strain as shown in Table 3. From Eqn.4.1 to Eqn.4.3 and Table 1, the required number of strand in a sewing band ($n_{1req.}$) was calculated as shown in Table 4. Here, the response sesmic shear coefficient k was assumed to be 0.7.



a) Full scale prototype model b) ¼ scaled model

Fig.7 Infill-brick wall specimen and prototype dimensions

Table 2. Properties of fiber strand

	Tensile strength (N/mm^2)	Young's modulus (N/mm^2)	Section area (mm^2)
Carbon	5000	23500	0.917
Aramid	2916	98000	0.594
Glass	2162	81000	0.289
PVA	1300	28500	0.154
Nylon	992	3100	0.165
Polyester	1090	3000	0.159

Table 3. Effective tensile strength of fiber

	Effective strength (N/mm^2)	Strain (%)
Carbon	3290	1.4
Aramid	1862	1.9
Glass	1377	1.7
PVA	570	2
Nylon	62	2
Polyester	60	2

First, the number of strand for a sewing band is decided for the full scale model of Fig.7. Next, the number of strand in a sewing band for the scaled test specimen was determined so that *K* of Eqn.3.2 is equal to that in the full scale prototype frame model. For the test specimen, the number of strands in a sewing band was determined as shown in Table 5 for the possibly applicable fiber strands. Nylon was selected for the two test specimens (No.2 and No.3 specimens), and glass was selected for No.4 specimen (Table 6) owing to their economical nature. No.1 specimen, on the other hand was the control specimen, with no retrofit. No.3 specimen had double the number of strands of No.2 specimen. The RC frame of No.4 specimen was the reuse of No.1 specimen, after the failure of the infill wall as no major damage was observed in the RC frame of No.1 specimen.

Table 4. Required number of strand in a sewing band

	$n_{1req.}$
Carbon	2
Aramid	2
Glass	5
PVA	8
Nylon	63
Polyester	68

Table 5. Applicable number of strands for specimen

	$n_{1,test}$	Remarks
Carbon	2	Minimum volume of strands
Aramid	2	Minimum volume of strands
Glass	5	Minimum volume of strands
PVA	8	Minimum volume of strands
Nylon	16	Effective tensile strength
Polyester	17	Effective tensile strength

Table 6. List of test specimens

Specimen	Sewing band
No.1(N00)	No sewing bands
No.2(N16)	Nylon-16 strands
No.3(N35)	Nylon-35 strands
No.4(G5)	Glass-5 strands

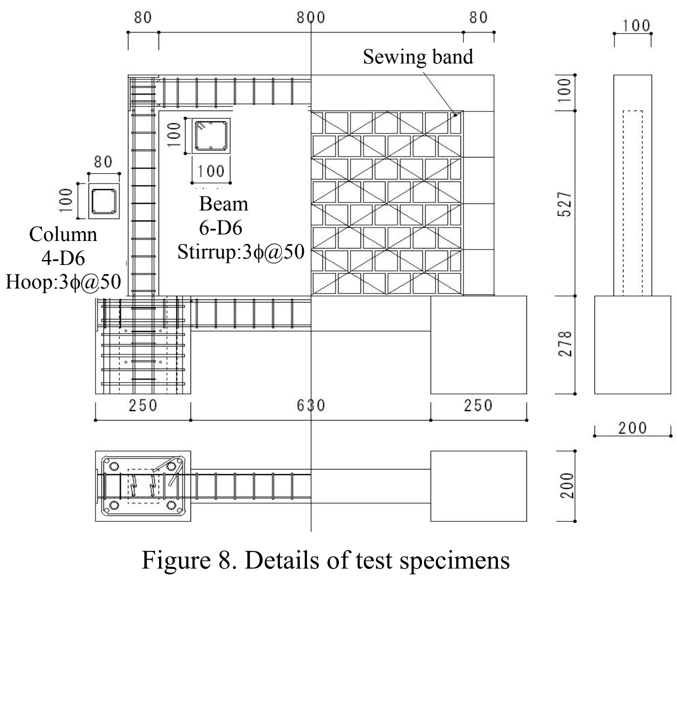


Figure 8. Details of test specimens

The detail of specimen is shown in Fig.8. The compressive strength of concrete for frame was 29N/mm^2. The yield strength of steel bars was 270N/mm^2 for both D6 and 3ϕ. The compressive strength of bricks and the joint mortar was designed to be 10N/mm^2.

Keeping the wall panel horizontal, the footings were fixed to the reaction frame and the upper beam of specimen was horizontally supported by rollers as illustrated in Fig.9. The load to direction outside of plane was given by dead weight. The actual magnitude of applied load was 2,838N. The cyclic horizontal load in plane was given by the 100kN oil jacks. The loading setup is shown in Fig. 9.

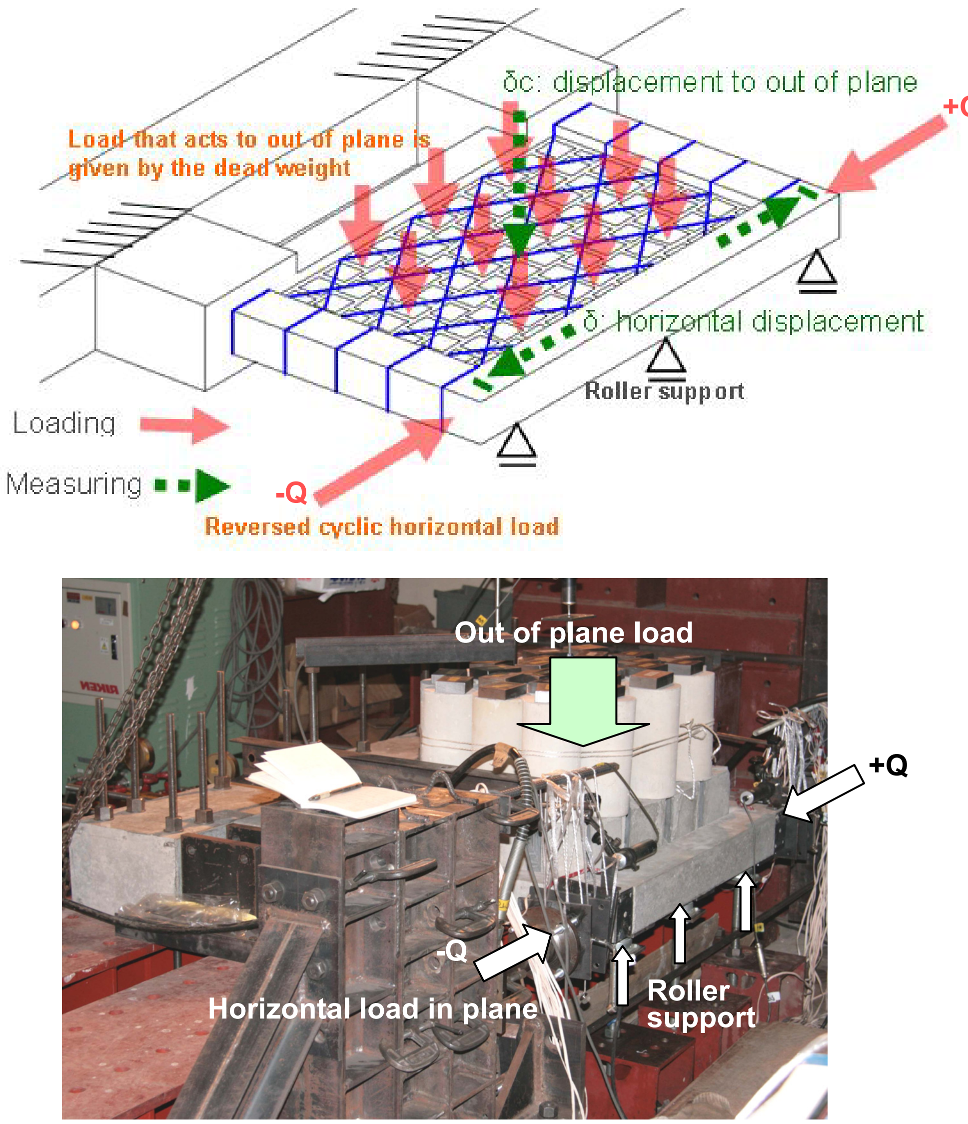


Figure 9. Test Setup

6. TEST RESULTS

The horizontal load (Q)-displacement (δ) relations of four specimens are shown in Fig.10 (a) to (d). No.2 and No.3 specimens with sewing bands showed horizontal load carrying capacity gain in comparison with No.1 specimen without sewing bands. The relations between the horizontal drift (δ) and the displacement capacity of the walls in the out of plane direction (δ_c) are shown in also Fig.10 (a) to (d). δ_c decreases from No.3 specimen to No.1 specimen as the number of strands in a sewing band increases. When the story drift angle was γ=1/40 (δ=15.75mm) and the displacement of wall panel to out of plane reached 20mm, the joint mortal of No.1 specimen started to fall down and the collapse occurred during this loading cycle. The specimens with sewing bands still kept the form of wall panel and didn't collapsed even after γ=1/40 (δ=15.75mm). The infill-wall continued to carry some horizontal load even though the displacement of wall to out of plane (δ_c) became large. The number of strands in a sewing band of No.4 specimen is determined by the required minimum volume of strands in Table 1. However it showed almost same response as that of No.2 specimen if not better.

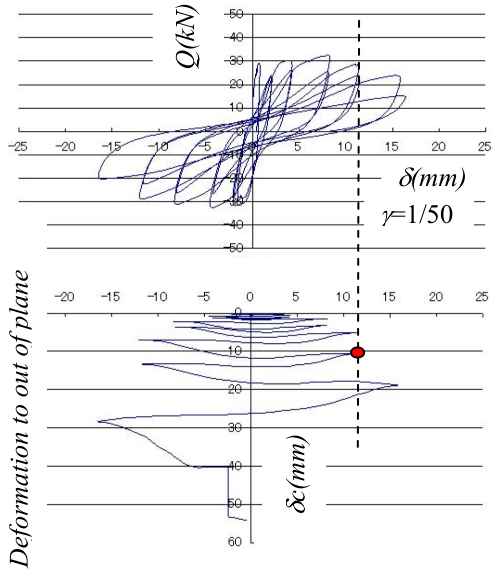


Figure 10 (a) No.1 specimen (N00)

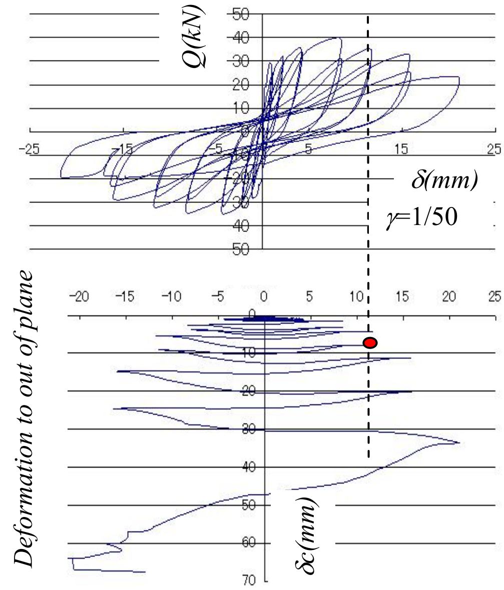


Figure 10 (b) No.2 specimen (N16)

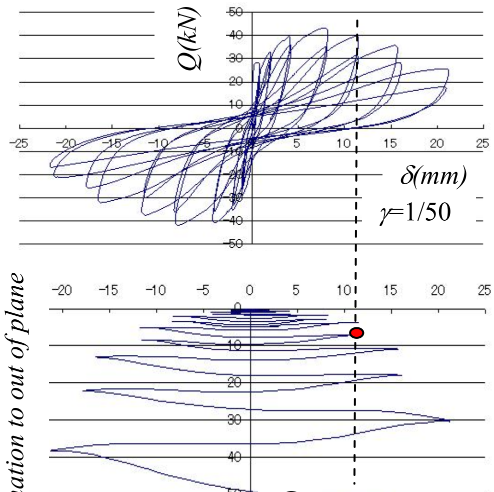


Fig.10 (c) No.3 specimen (N35)

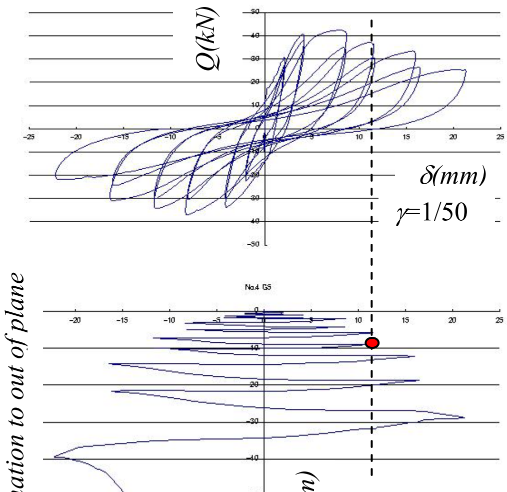


Fig.10 (d) No.4 specimen (G05)

In all specimens, the stiffness started to decrease with audible cracks around Q=30kN. All specimens reached the maximum load at δ=8mm of horizontal displacement (Story drift angle: γ=8/577=1/72). At γ=1/50 (δ=11.5mm), the damage of joint mortal became visible. The picture of infill-brick walls after final loading is shown in Fig.11 and Fig.12. The infill-wall of No.1 specimen without sewing bands (Fig.13) completely collapsed after γ=1/40 (δ=15.75mm). The bricks deflected down to the reaction frame. The infill-wall of No.2 specimen with sewing bands took the form of the wall panel. The displacement to out of plane became large and the bricks came in contact with the reaction frame. However the infill-brick wall didn't collapse. In this condition, the infill-brick wall could still carry some horizontal force and it was able to resist the gravity loads.

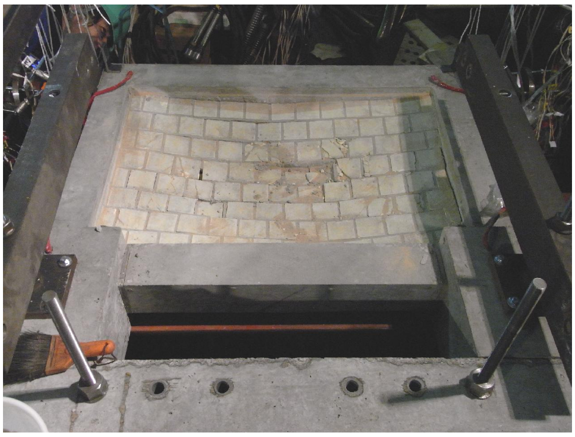


Figure 11. Failure aspect of Specimen No.1

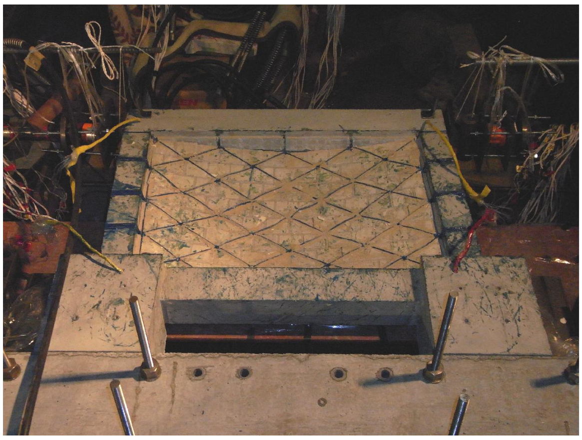


Figure 12. Failure aspect of Specimen No.2

7. VERIFICATION OF THE SIMPLE LOAD DEFLECTION MODEL

The verification studies were conducted using the experimental results of frame specimens described above. The cyclic horizontal force deformation response of test specimens along with estimated monotonic capacity curves obtained using the proposed model in Fig.4 and Fig.5 are shown in Fig.13 and Fig.14. It should be noted that the curve describing the horizontal capacity values, Q_{cr}, K, ΔQ are computed using Eqn.3.1 to Eqn.3.3 and displacement values, γ_{cr}, γ_u, and γ_r are determined from the model in Fig.5. It can be observed that use of sewing bands contribute to lateral load carrying capacity and enhance the deformability of the system, even if the horizontal load is acting to direction outside of the frame. Furthermore, estimations obtained by using the proposed model are reasonably accurate until γ=1/50 of story drift angle. After γ=1/40, the horizontal carrying load decreases and separates from the model because the displacement of wall to direction outside of plane was extremely large. The seismic strengthening design may possibly be done for a target drift angle of γ=1/50. If the infill-wall collapse is eliminated at such drift angles, and the infills could stay inside the frame, they may partially contribute to axial load carrying capacity in addition to their contribution to lateral building strength.

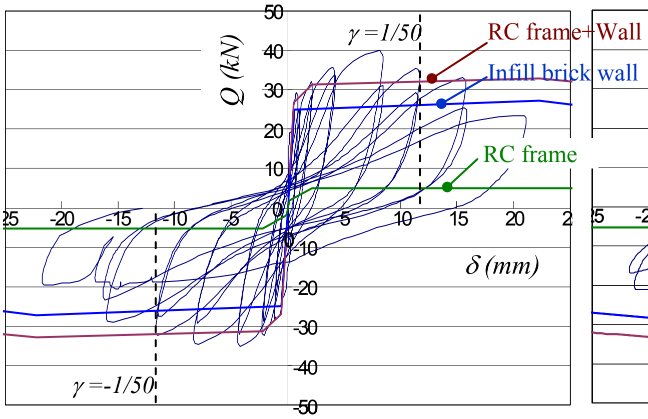


Figure 13. No.2 specimen (N16)

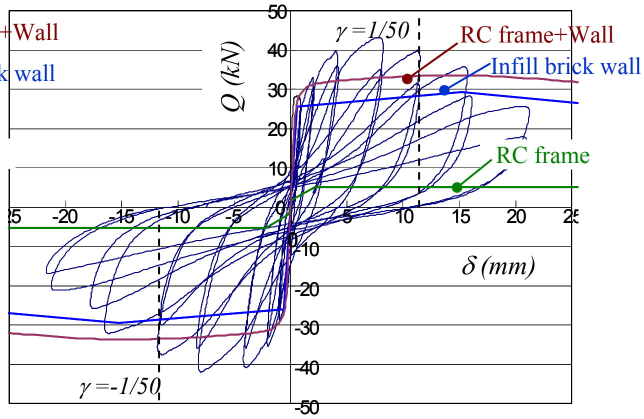


Figure 14. No.3 specimen (N35)

8. CONCLUSIONS

The scaled one-story, one-bay brick infilled RC frames that were retrofitted with “sewing bands” were tested by imposing combined in and out of plane loads. The infill-brick walls deformed to the direction outside the frame significantly, but did not exhibit out of plane collapse even at large lateral in plane displacement excursions. “Sewing bands” successfully trapped the infill bricks into a net made of FRP bundles, and the horizontal load carrying capacity in the plane of the frames was maintained. The horizontal drift angle up to 2% was sustained without any collapse. The proposed analytical model was validated by using the results of frame tests conducted under in and out of plane loadings. Our preliminary test results show that out of plane wall failure risk could be reduced and lateral deformability of the system can be enhanced by employing sewing bands in the infill walls of RC frames. Obviously, additional full scale testing is needed prior to the site application of our proposal for collapse prevention using FRP sewing bands.

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