Seismic performance analysis of multi-story RC frames strengthened with RC infill wall

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Abstract. Seismic performance of RC frame structures was investigated by creating 3-D models of the frame with additional solid RC infill wall along the height of Honolulu Building prescribed in FEMA design examples. Layered-shell element (LSE) was used to model the infill wall and gap element was introduced at the interface between the wall and the bounding frames. The modelling technique was validated against test results reported in the literature prior to its application on the 12 story building. The push over curves of all models were compared to obtain the most efficient model that conform to the strength and stiffness requirement of the seismic codes of Indonesia. The results showed that the non-linear behaviour of RC frame with RC infill wall can be modelled accurately using LSE and gap element. The RC wall addition improved the strength, stiffness and performance of the frame significantly. The most efficient model was that with infill wall up to the first 4 story levels in which, the performance of the structure improved from collapse prevention to immediate occupancy.

Keywords: RC frame; RC infill wall; seismic response; layered shell element; performance analysis.

1. Introduction
Safety against seismic hazard is one of the goal of design and construction of multi-story buildings in seismically active region. Retrofitting of an existing structure is one example of effort to achieve safety against higher seismic loading as the seismic codes are continuously updated based on more recent data of seismic records. There are many feasible and effective retrofitting techniques available to strengthen reinforced concrete (RC) frame structures. The use of RC walls as shear wall, infill wall or wing wall have been reported as effective to improve the overall capacity of RC frame structures including strength, stiffness and performance [1, 2]. A literature review on strengthening of RC frame using steel braces, RC infill wall and RC shear wall was reported by Tsionis et al. [3] and Tsionis et al. [4]. The results of these studies clearly showed that infilling an existing bay with RC wall resulted in the highest increase in strength and stiffness. The connection between the old concrete and the new one was reported as a critical issue. Guideline for the design and analysis of this type of retrofitted structure however, are not yet available. Accordingly, development of analytical models and their implementation in software is a necessary step towards the application of these strengthening techniques.
Experimental testing of non-ductile RC frame structure retrofitted by means of adding solid and partial RC wall for two-story structures was reported as being effective [5]. They also reported analytical results of ultimate strength that agreed well with the test results. For the initial stiffness of the frame however, the analysis results were much higher than those of test results. For the purpose of designing retrofitted structure, the initial stiffness is an important parameter rather than just the ultimate strength.

This paper is aimed at proposing simple modelling technique for RC frame retrofitted with RC infill wall. The bare frame was modeled with frame element and the RC wall was modeled using layered shell element to enable modelling of reinforcement on the wall. The modeling technique was validated against test results reported in [5] prior to its application to investigate performance of 12 story RC frame structure retrofitted with RC infill wall. The structure of Honolulu Building used in this paper was available in design example of FEMA P-1051 [6]. It was an open RC frame designed to resist moderate seismic loads. Addition of RC infill wall was applied starting from the lowest story until the retrofitted structure is safe to resist higher seismic load. To address the issue of connection between the old and the new concrete, gap element was introduced at the interface between the frames and the wall. Finally, the effect of adding RC wall using cracked sectional properties for the bare frames was also investigated using staged construction analysis available in SAP2000 [7].

2. Method

In the absence of guideline for the design and analysis of RC frame with RC infill wall, the proposed analytical model was validated against test results prior to the application of the modelling technique to design retrofitted structure. In this paper the issue of connection between the old frame concrete and the new wall concrete was addressed by introducing gap element. In masonry infilled frame, the interface between the frame and the wall can be modelled as gap element using gap stiffness proposed by Dorji and Thambiratnam [8]. In the absence of reference on the gap stiffness value for RC infill wall, trial value was used in validation model by modifying the value used for masonry infill.

2.1. Validation model

To validate the modelling technique, three out of 7 specimens of two-story RC frames with RC infill wall tested by Kara and Altin [5] were modelled in SAP2000. The single bay frame was modelled as frame element and the RC wall was modelled using 5 layers consist of 2 layers for decking, 2 layers for reinforcement and one layer for core concrete. The models were developed according to the tested specimens number 1, 2 and 5 which is the open frame (MOF), the bare frame with additional solid infill (MIFS) and the bare frame with partial infill (MIFP).

The value of gap stiffness equation proposed by Dorji and Thambiratnam [8] for masonry infill was modified for RC infill by trial using two directions of gap stiffness, instead of one, to account for the shear stiffness. After many trials, the value of gap stiffness given by the equations below was used in the proposed models.

\[ K_g = 0.04 K_i \]  
\[ K_i^1 = E_i t \]  
\[ K_i^3 = G_i t \]

\( K_g \) is the gap stiffness (N/mm), \( K_i \) is the infill stiffness (N/mm) in direction-1 (in plane of wall) and 3 (perpendicular to wall plane). \( E_i \) is elastic modulus of infill (N/mm²), \( G_i \) is shear modulus of infill (N/mm²) and \( t \) is the wall thickness (mm).

The dimensions and properties of materials are those reported by Kara and Altin [5]. The 1/3 scale specimens consist of 100/150 mm columns and 150/150 mm beams of 13 MPa concrete with 50 mm RC infill wall of 26 and 27.7 MPa concrete. Table 1 shows the properties used in the models. In the test program the frame was laterally loaded using cyclic load until failure. Of the 400 kN load, 1/3 of the load was applied on the first floor and 2/3 of the load was applied on the top floor. No vertical load was applied on the frame.
Static push over analysis was performed for the three models and the base shear-deformation curve were plotted together with the test results. The stress contour on the wall were also compared to the crack pattern of the tested specimens.

Table 1. Property of materials and gap stiffness used in validation models.

| Model | Elastic Modulus (MPa) | Shear Modulus (MPa) | Stiffness Kg1 (N/mm) | Stiffness Kg3 (N/mm) |
|-------|-----------------------|---------------------|---------------------|---------------------|
| MOF   | 16,416                | -                   | 6,840               | 0                   |
| MIFS  | 17,205                | 23,965              | 7,168               | 9,985               |
| MIFP  | 17,333                | 24,736              | 7,222               | 10,307              |

2.2. Multi-story model of Honolulu building

After validation of the modelling technique, it is applied to modelling high-rise structure of Honolulu building [6] as shown in figure 1. The building was designed for moderate level of seismicity and the lateral load-resisting system consist of a series of intermediate moment-resisting frames in both the E-W and N-S directions. The beams and columns dimensions are slightly smaller than those used for Berkeley building, reflecting the lower seismicity. The plan on the left figure shows addition of infill wall on the mid span of the frame. According to the analysis results in the design example of FEMA, the structure in Y-direction is significantly stiffer than that in X-direction. Accordingly, the infill walls were added in the X-direction as shown on the left of figure 1. On the right is elevation of the frame showing placement of the infill wall along the height of the building. The 12 story RC frame structure that initially designed as intermediate moment frame was strengthened using RC infill wall on the middle bays to satisfy the requirement of special moment frame. The number of stories to which infill wall addition were required was determined by trialling starting from the wall on basement only (IFB). The next trial was the wall in basement and 1st story level (IF1) and so on until the structure is capable of sustaining higher lateral load safely in accordance with the ACI codes [9]. As reference, the original open frame model (OF) was also created.

The frames consist of 711x711 mm columns and 500x762 mm beams of 34.47 MPa concrete along the height of the building. The floor system used 152x508 mm ribs with 100 mm slab. The infill wall thickness was 400 mm at the basement and 355 mm at the 1st story level and above using the same concrete strength as that for the frame. The reinforcement yield stress was 413 MPa. Table 2 shows the properties of materials and gap stiffness used in the models.

The load applied to the building consist of dead load and life load of 2.45 kN/m² and 0.98 kN/m² for the floor and the roof according to [10], respectively. The seismic load parameter used were Ss of 0.578 and S1 of 0.169 to calculate equivalent lateral force (ELF). Linear as well as non-liner static push over analysis was performed to obtain the behaviour and performance of each 3-D models available in SAP 2000 software [7].

Staged construction analysis was conducted to consider the effect of crack on existing frame prior to addition of infill wall, assuming 3 different crack condition of moment inertia, Icr relative to the gross moment of inertia, Ig. The first analysis use no crack condition followed by slight crack (0.7 for beams and 0.9 for columns named Staged Con. 2) and severe crack condition (0.35 for beam and 0.7 for column named Staged Con. 3) as specified in the building code [9]. The results were compared to the conventional analysis as if the wall and frame were built at the same time.
Figure 1. Typical plan of the building with infill wall (left) and frame elevation (right).

Table 2. Property of materials and gap stiffness for Honolulu Building.

| Model       | IF (Base) | IF (1)  | IF(2)  | IF(3)  | IF(4)  |
|-------------|-----------|---------|--------|--------|--------|
| Wall thickness (mm) | 457.20    | 355.60  | 355.60 | 355.60 | 355.60 |
| Concrete f’c (MPa)    | 34.47     | 34.47   | 34.47  | 34.47  | 34.47  |
| Gap stiffness (Kg₁) N/mm a,b | 9.42E+12  | 7.73E+12 | 6.28E+12 | 6.28E+12 | 6.28E+12 |
| Gap stiffness (Kg₃) N/mm a,b | 4.75E+12  | 3.70E+12 | 3.70E+12 | 3.70E+12 | 3.70E+12 |

a = 2,759E+04 MPa, b = 1,158E+04 MPa

3. Results and discussion

3.1. Validation models
The finite element models of MIFS and MIFP are shown in figure 2 showing the mesh, gap and stress contour at ultimate loads. The location of maximum stresses follows the compressive diagonal strut of the infilled frame with masonry wall. Even when the wall is separated by an opening the diagonal compressive stress was still visible from the stress contour. The test results reported by Kara and Altin [5] showed that, failure of the wall form an X-shape because of the cyclic loading, instead of monotonic loading applied in the model.

Figure 3 shows the shear force-displacement curve of the models and the test results obtained from static pushover analysis. It can be seen that the finite element model mimics the load-displacement curve of the test results well, especially its initial stiffness. The ultimate load of the tested specimens, however, were higher than those of the models except those for the open frames. For the purpose of designing retrofitted structure, the load-displacement curve is more important than the ultimate load. Accordingly, the modelling technique used in the validation model can be applied for the analysis and design of RC frame with RC infill wall. In addition, the retrofitting method of adding RC infill wall is justified by the significant increase in strength and stiffness and reduction in ductility.

3.2. Honolulu building
The effect of adding RC wall was evaluated firstly on the column interaction ratio under combined vertical and lateral loads. Without strengthening (OF) some columns on the ground level up to the fourth
floor level underwent interaction ratio of more than one. This means that the existing structure were not strong enough to resist the increased seismic loading. The over stress problem remains until after RC walls were added up to the second floor level. When the wall on the third floor was added, the maximum interaction ratio in the columns was 0.96, very close to one. When another walls were added at the fourth floor level the column stress ratio reduced to 0.87 which is an acceptable number for design purposes. Accordingly, the trial was stopped and all 6 models were further evaluated for its force-displacement relationships as shown in figure 4.

![Model of MIFS (left) and MIFP (right) with stress contour at ultimate load.](image)

**Figure 2.** Model of MIFS (left) and MIFP (right) with stress contour at ultimate load.

![Base shear-displacement graph of test result (dash line) and analytical models.](image)

**Figure 3.** Base shear-displacement graph of test result (dash line) and analytical models.

From figure 4 (a) it is apparent that the strength and stiffness of IF models were proportional to the number of additional walls. The more walls added the stronger the structure and hence, the stiffer the structure become. By adding infill wall up to the fourth floor level the top displacement reduced by more than 25%. Displacement at the 4th floor level reduced by more than 50%. Addition of walls in X-direction however, did not meaningfully change the stiffness of structure in the Y-direction as shown in figure 4 (b). When addition of infill wall was continued until the top story level, similar pattern of curve was obtained and the structure become very stiff [11]. The data was not complete and accordingly, not included in this paper.
As in the case of linear analysis, the static pushover analysis was performed on the 3-D structure to include the contribution of all frame members in X and Y-directions. The results from non-linear analysis were shown in figure 5 and table 3. Figure 5(a) shows the hinge development in open frame model and figure 5(b) shows the hinges in infilled frame. The corresponding pushover curve in X-direction was shown in figure 5(c).

**Figure 4.** Force-displacement curve of open frame and infill frames.

**Figure 5.** Hinge development and pushover curve for model OF and IF(4) in X-direction.
It is apparent from the push over curve that the infilled frame model was about 33% stronger than the open frame model. The bare frame failed at maximum drift ratio of 1.32% while the infilled frame failed at 0.95% drift ratio which showed slight reduction of ductility. The performance level according to criteria of FEMA 356 [12] for each models shown in table 4 indicates that addition of infill wall up to fourth floor level improved the performance from collapse prevention for the bare frame to immediate occupancy for the infilled frame.

It is interesting to note that, at performance point, the stress in the concrete and reinforcement of the wall were within its elastic limit. This is in agreement to the reported test results that the amount of wall reinforcement did not play important role on strength and stiffness of retrofitted structure as much as that of the detail connection between the wall and the bounding frames [4].

| Model  | Performance Point | Base Shear (kN) | Performance Level |
|--------|-------------------|----------------|-------------------|
|        | V (kN) | d (mm) | Design | First Yield |                      |
| OF     | 12,137 | 582   | 3,895 | 3,600 | LS-CP               |
| IF(B)  | 12,137 | 582   | 3,895 | 3,600 | LS-CP               |
| IF(1)  | 12,394 | 420   | 3,895 | 4,225 | IO-LS               |
| IF(2)  | 12,547 | 344   | 3,895 | 4,542 | IO-LS               |
| IF(3)  | 13,580 | 331   | 3,895 | 6,712 | IO-LS               |
| IF(4)  | 14,801 | 323   | 3,895 | 7,099 | IO-LS               |

3.3. Staged construction analysis
The results obtained from staged construction analysis in figure 6 showed that, without considering cracked section (staged con. 1), the difference in roof displacement was 1% larger than that of conventional analysis. Assuming crack moment of inertia, I_cr equal to 0.7 of the gross moment of inertia, I_g for beams and 0.9 for columns (staged con. 2) the displacement increase was 25% in X-direction and 28% in Y-direction. To the extreme, if I_cr equal to 0.35 I_g for beam and 0.7 for column (staged con. 3) the displacement increase was 97% in X-direction and 111% in Y-direction. These results agree with previous results obtain for RC frames retrofitted with steel braces but in smaller percentage of difference [13]. Similar results were also reported by Pathan et al. [14] for RC open frame.

Figure 6. Force-displacement curve of infill frames using staged construction analysis.
4. Conclusion

From the available literature and the analysis of RC frame retrofitted with RC infill wall can be concluded that addition of RC infill walls to existing RC frames significantly improves the strength and stiffness of the structure to resist seismic load, and hence, the retrofitting method is reliable and justified.

The non-linear behaviour of RC frame with RC infill wall can be modelled accurately using Layered Shell Elements for the wall and gap element for the interface between the frame and the wall. The static pushover curve of the model mimics the curve of test results well and the stress contour of the models simulate the crack pattern developed in the tested specimens.

The model for retrofitted 12-story Honolulu Building showed that addition of RC infill walls up to the fourth floor increases the strength and stiffness of the bare frame to the intended level, in which there is no member of the frames was overly stressed and the retrofitted structure conforms to the specified maximum drift without significant reduction in ductility. The performance of the structure improved from collapse prevention for the open frames to immediate occupancy for the infilled frame.

Staged construction analysis performed for the retrofitted Honolulu Building showed significant effect only if the cracked sections were used in the analysis. The difference could be as much as 100% according to the extent of crack developed on the frame section prior to strengthening.

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