Seismic Performance Evaluation of Existing Masonry Infilled Reinforced Concrete Framed Buildings in AEM

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Abstract

Present study focuses on the seismic performance evaluation of masonry infilled reinforced concrete (MIRC) buildings utilizing appropriate infill properties. Masonry infill properties were determined through analyses of an infilled RC test model in Applied Element Method (AEM) under in-plane cyclic load and were utilized for the time history dynamic analysis of an MIRC building considering different AEM models, i.e., soft story, retrofitted soft story, infills in all floors and RC frames neglecting stiffness contribution of infills. The analytical results revealed: 1) the unexpected soft story column failure compared to the similar RC frame, 2) the inability of infills to improve the seismic performance of the surrounding RC frames, 3) the effectiveness of steel plate jacketing for preventing soft story failure and, 4) the effect of overhead water tanks on the seismic behaviour of RC buildings.

1 Introduction

Multistoried masonry infilled reinforced concrete (MIRC) building with soft ground story is a popular construction practice in Bangladesh. Generally, in all framed structures in Bangladesh, bricks made from burned clay are used as infills in the RC frames. Lack of knowledge of masonry properties discourages local structural engineers from considering infills as structural components. As a consequence, it has become a common practice to exclude the stiffness and strength contributions of infills in structural analysis of MIRC buildings even under seismic loads. According to Asteris, P. G. et al.(2013), the presence of infills provides a local as well as global increase in strength and stiffness depending on their extent and their position in the frames, affecting the distribution and intensity of the inertia forces generated in seismic excitation. This may initiate stress concentrations in certain regions of structures, causing localized cracking or unexpected brittle failures detrimental to overall performance of MIRC frames. Hence, it is essential for professional structural engineers to understand the effect of local masonry infills on the seismic performance of MIRC buildings. In this context, the objective of the present study focused on the determination of the material properties of locally available masonry components, i.e. clay brick units and mortars in Applied Element Method (AEM) and evaluation of seismic performances of existing brick infilled RC framed structures in Bangladesh.

2 Literature Review

2.1 Seismic Performances of Masonry Infilled RC Frames

Over the last five decades, a large number of laboratory investigations (Dhanasekhar and Page 1986; Holmes 1963; Stafford Smith 1962, 1966) have been carried out to identify the effect of infill walls on the overall response of RC frames. Researches from 1950s to 1960s on masonry infills had revealed that the walls could be modelled as a strut formulation (Holmes 1961, 1963; Stafford Smith, 1962, 1966). The assumed ‘diagonal strut’ bears a part of applied seismic loads and transmit them to other regions of the structure providing relief to certain structural elements of the RC frames (Asteris 2003). Although this redistribution increases overall stiffness and load carrying capacity of the frame,
it may develop stress concentrations in specific areas of joints, beams and columns which may result in localized cracking even unpredictable failures (Asteris, et al.2013).

2.2 Composite Material Properties of Masonry Wall
Masonry is characterized as an anisotropic and inhomogeneous material composed of two materials of somewhat different properties: stiffer bricks and relatively soft mortar distributed at regular intervals. The masonry wall strength can be predicted from mortar and brick strength using the equation proposed by Hendry (1990):

\[
f_{mw} = 1.242 \cdot f_b^{0.531} \cdot f_m^{0.208}
\]

where,

\[
\begin{align*}
    f_{mw} & = \text{Wall high strength, N/mm}^2, \\
    f_b & = \text{Strength of masonry unit, N/mm}^2, \text{ and } \\
    f_m & = \text{Strength of mortar, N/mm}^2.
\end{align*}
\]

Moreover, Kaushik, et al. (2007) suggested simple relations for computation of the elastic modulus of bricks, \(E_b\), mortar, \(E_m\) and masonry, \(E_{mw}\) from their respective compressive strengths, \(f_b\), \(f_m\) and \(f_{mw}\) based on their experimental results and analyses, as follows:

\[
\begin{align*}
    E_b &= 300f_b \quad \text{Eq.2} \\
    E_m &= 200f_m \quad \text{Eq.3} \\
    E_{mw} &= 550f_{mw} \quad \text{Eq.4}
\end{align*}
\]

where all units are in MPa.

2.3 Applied Element Method for Modelling Masonry Infilled RC Frames
In the present study, a non-linear structural analysis software ‘Extreme Loading for Structure (ELS)’ based on Applied Element Method (AEM) (Applied Science International, 2010) has been chosen for modeling and analysis of MIRC specimen frames and MIRC full scale building structures. AEM was proposed by Meguro and Tagel-Din (2002) based on the concept of discrete cracking where structural components are separated into elements connected through non-linear normal and shear springs. Stresses, strains, deformations, and failure of structures are represented by each spring. In this way, AEM can analyze and visualize structural behaviors from linear elastic to non-linear small and large displacement along with geometric and material changes, element collision and element separation. Thus predicts structural behavior from initial loading stages, crack initiation, crack propagation to complete collapse in complex 3D structural model. Moreover, generation of brick springs and brick-mortar interaction springs are included in AEM where normal and shear stiffness of bricks and mortar springs are estimated from the element geometry incorporating corresponding elastic modulus and shear modulus of constituent materials. Additionally, equivalent stiffness of brick-mortar interaction springs are obtained both from stiffness moduli of bricks and mortars based on corresponding element geometry (Karbassi and Nollet 2013).

3 Methodology and Verification Process
The methodology of the current analytical research followed three steps:

Step-1: Determination and verification of the masonry constituent properties considering fine masonry mesh for infills
Masonry constituents (brick and mortar) properties for fine masonry mesh (1 brick=16 elements) model in AEM were previously determined by Zerin, et al (2015) where material level verification of the proposed constituent properties was successfully performed through corresponding test results of masonry prism under uniaxial compression. Moreover, member level verification was also performed by analyzing a single story single bay half scaled brick infilled RC frame under cyclic load. Hysteretic behavior, failure load, initiation and propagation of cracks through the analytical model showed substantially good agreement with the test results (Fig.s 1(a), 2(a) and 2(b)) (Zerin and Amanat, 2015 and Zerin et al, 2015). The dimensions along with the reinforcement details incorporated in test and analytical models are illustrated in Fig.1(b). In the analytical model each brick unit was divided into 16 elements to produce fine masonry mesh to ensure the propagation of cracks through bricks along with mortar joints. The established constituent (bricks and mortars) properties for fine masonry mesh are illustrated in Table 1.
Step-2: Determination and verification of composite masonry properties for masonry and coarse masonry meshes

Since fine masonry mesh produces too large number of elements, composite masonry properties for masonry mesh model have been proposed to keep the element numbers into the allowable analysis limit. In the masonry mesh, brick units were undivided and considered as single elements, thus the cracks were allowed to propagate only through the brick-mortar interfaces. The composite masonry properties were applied at the brick-mortar interfaces instead of mortar properties to obtain the masonry composite behaviour. The compressive strength of the composite masonry was calculated according to the Hendry (1990) equation (Eq.1, Section 2.2) from compressive strengths of bricks and mortars determined for fine masonry mesh. The elastic modulus of the masonry has been derived from Eq.4 in section 2.2. The tensile strength of the masonry composite (0.97 MPa) was determined from extensive parametric study. The proposed composite masonry properties for masonry mesh in Table 1 were compared with the same experimental results of brick infilled RC frame (Zerin and Amanat 2015). Crack propagation, maximum shear capacity and hysteresis curves obtained from the AEM model illustrated in Fig.3(a)(b) proved to have good agreement with the test results, thus verified to be applied in masonry mesh models.

Table 1 Determined masonry properties for three types of masonry mesh models

<table>
<thead>
<tr>
<th>Properties (unit:MPa)</th>
<th>Fine masonry mesh 1 brick = 16 elements bricksize:115x70x45mm</th>
<th>Masonry mesh 1 brick = 1 elements brick size:115x70x45mm</th>
<th>Coarse masonry mesh 1 brick=1 elements brick size:380x250x120mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brick</td>
<td>Mortar</td>
<td>Composite masonry properties for brick-mortar interface</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>17</td>
<td>11</td>
<td>9.3</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>1.6</td>
<td>1.9</td>
<td>0.97</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>5170</td>
<td>2207</td>
<td>5106</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>2414</td>
<td>883</td>
<td>2042</td>
</tr>
</tbody>
</table>

Table 2 Average material properties for RC frame obtained from the laboratory experiment

<table>
<thead>
<tr>
<th>Properties (unit:MPa)</th>
<th>Concrete</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>1.9</td>
<td>-</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>26897</td>
<td>200000</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>11034</td>
<td>80000</td>
</tr>
<tr>
<td>Tensile yield strength</td>
<td>-</td>
<td>388</td>
</tr>
<tr>
<td>Ultimate strength</td>
<td>-</td>
<td>537</td>
</tr>
</tbody>
</table>

Fig. 1  (a) Crack propagation in infilled RC frame test model at +178 kN lateral load, (b) Geometric and reinforcement details of RC frame model (Zerin and Amanat, 2015)
Further, coarse masonry mesh (element size: 380mmx250mmx120mm) has also been proposed for analyzing full scale MIRC buildings to keep the element numbers into analysis limit. In coarse masonry mesh model tensile strength of composite masonry has been determined from parametric studies while other properties were kept constant as masonry mesh model (Table 1). The maximum shear strength and displacement of the analytical model was also verified with the test results of the same infilled RC test frame (Fig.4(a) and 4(b)).

![Crack propagation in fine masonry mesh model](image1)

(a) Crack propagation in fine masonry mesh model, (b) Comparison of hysteresis behavior for AEM fine masonry mesh model and the corresponding infilled RC frame test model (Zerin, et. al. 2015).

![Crack propagation in masonry mesh model](image2)

(a) Crack propagation in masonry mesh model, (b) Comparison of hysteresis behavior for AEM masonry mesh model and the corresponding infilled RC frame test model

![Crack propagation in coarse masonry mesh model](image3)

(a) Crack propagation in coarse masonry mesh model, (b) Comparison of hysteresis behavior for AEM coarse masonry mesh model and the corresponding infilled RC frame test model

**Step-3: Seismic performance evaluation of MIRC building models**

Determined and verified all the material properties in Table 1 and Table 2 have been utilized for time history dynamic analysis of full scale MIRC frame models to evaluate their seismic performances.
4 Seismic Performance Evaluation of MIRC Building Models

4.1 Structural Model

The 8-storied structural models analyzed are illustrated in Fig 5 and demonstrated in Table 3.

Table 3 AEM Models and Input Ground Motions

<table>
<thead>
<tr>
<th>Models</th>
<th>Applied PGA (g)</th>
<th>Model Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. RC frame (WT*)</td>
<td>0.20; 0.28; 0.36; 0.50</td>
<td>RC framed building with overhead water tank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wall load is considered in unit weight of beam concrete</td>
</tr>
<tr>
<td>b. RC frame (no WT)</td>
<td>0.20; 0.30; 0.36;</td>
<td>RC framed building without overhead water tank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wall load is considered along unit weight of beam concrete</td>
</tr>
<tr>
<td>c. Soft story</td>
<td>0.20; 0.25; 0.28</td>
<td>MIRC framed building with open ground floor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(with overhead water tank)</td>
</tr>
<tr>
<td>d. Infilled</td>
<td>0.20; 0.3; 0.36;</td>
<td>MIRC framed building infilled with brick walls in all</td>
</tr>
<tr>
<td></td>
<td></td>
<td>floors (Overhead water tank is omitted)</td>
</tr>
<tr>
<td>e. Retrofitted</td>
<td>0.3; 0.36;</td>
<td>open ground floor of MIRC framed building is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>retrofitted with steel plate (9.5 mm thick) jacketing</td>
</tr>
</tbody>
</table>

Water Tank

Table 4 Steel ratio ($\rho$) and mesh discretization for structural and building components

<table>
<thead>
<tr>
<th>Structural/building components</th>
<th>Element number</th>
<th>Spring Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns ($\rho_{\text{longitudinal}}$=3-4%, $\rho_{\text{transverse}}$=0.3-0.6%)</td>
<td>6x3x4 per meter</td>
<td>Concrete and Steel</td>
</tr>
<tr>
<td>Beams ($\rho_{\text{longitudinal}}$=1.5%, $\rho_{\text{transverse}}$=0.4-0.8%)</td>
<td>7x1x5 per meter</td>
<td>Concrete and Steel</td>
</tr>
<tr>
<td>Slabs ($\rho$=0.6%)</td>
<td>1x1x1 per m$^2$</td>
<td>Concrete and Steel</td>
</tr>
<tr>
<td>Masonry Fine Brick Mesh (ground-1$^{\text{st}}$ floor)</td>
<td>1 brick = 16 elements (brick size: 240x120x70 mm)</td>
<td>Bricks and mortar</td>
</tr>
<tr>
<td>Masonry Mesh (2$^{\text{nd}}$-3$^{\text{rd}}$ floor)</td>
<td>1 brick = 1 elements (brick size: 240x120x70 mm)</td>
<td>Brick-Mortar interface spring (composite masonry properties)</td>
</tr>
<tr>
<td>Coarse Masonry Mesh (4$^{\text{th}}$-7$^{\text{th}}$ floor, WT)</td>
<td>1 brick = 1 elements (brick size: 380x240x120 mm)</td>
<td>Brick-Mortar interface spring (composite masonry properties)</td>
</tr>
</tbody>
</table>

All of the five models possessed the same building geometry in plan, structural design and reinforcement details according to the existing building under study. In all cases, the foundation is assumed fixed to the ground. The normalized PGAs as depicted in Table 3 were applied from 6 to 18 seconds duration of Kobe earthquake ground motion to optimize the analyses time. Table 4 summarizes the mesh discretization along different stories and in different building components and tentative steel ratio of the structural members of the models.
4.2 Analytical Results and Discussions

Table 5 summarizes the overall seismic performances of the models. Moreover, failure mechanisms as well as seismic performances of different models in different PGA have been illustrated in Fig.6.

![Image of structural models](image1)

Fig. 6 Seismic Performances different of AEM models at different peak ground acceleration

<table>
<thead>
<tr>
<th>Models</th>
<th>Applied Scaled Down Kobe Earthquake PGA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2g</td>
</tr>
<tr>
<td>a. RC frame(WT)</td>
<td>Sustained</td>
</tr>
<tr>
<td>b. RC frame(no WT)</td>
<td>Sustained</td>
</tr>
<tr>
<td>c. Soft story</td>
<td>Sustained</td>
</tr>
<tr>
<td>d. Infilled</td>
<td>Sustained</td>
</tr>
<tr>
<td>e. Retrofitted</td>
<td>Sustained</td>
</tr>
</tbody>
</table>

4.1.1 Seismic Performances of Soft Story Model in Comparison to RC Frame Model

![Image of seismic performance graphs](image2)

Fig. 7 Seismic performance of Soft Story and RC frame (WT) model

The analytical results revealed that soft story model sustain up to 0.25g PGA ground motion, whereas, it initiated failure at ground floor columns under 0.28g PGA due to huge shear and moment development caused by vertical stiffness irregularity between ground and upper floors having differential infill distributions and consequent total collapse was observed at 0.36g PGA. The soft story model experienced maximum base shear (2200 kN in Y axis) at 0.28g and maximum acceleration (1000 gal in Y axis) at 0.25g PGA. Fig.7 illustrates that soft story model experiences 170% higher base shear than the RC frame with overhead water tank model (same RC frame system as soft story model) which experiences partial damages in two columns at 0.36g in which stiffness contribution of infills was neglected according to conventional design practice.
4.1.3 Seismic Performances of Infilled, RC Frame (WT) and RC Frame (no WT) Model

Both the Infilled and RC frame (no WT) models collapsed at 0.36g PGA. The infilled model experienced maximum base shear (4200 kN in Y axis) which is 300% larger than that of RC frame. In the failure PGA, Infilled model exhibits maximum top acceleration as 600 gal (aprox.) while corresponding RC frame model showed nearly 6000 gal maximum acceleration (Fig.s 8(a) and 8(b)). Moreover, Fig.s 8(c) and 8(d) exhibit that RC frame with overhead water tank sustained 0.36g PGA due to its increased time period induced by the water mass at the top. On the other hand, RC frame without water tank collapsed due to its altered time period and natural frequency compared to RC frame with overhead water tank.

![Comparison of base shear between Infilled and RC frame (no WT) model](image1)

![Comparison of top acceleration between Infilled and RC frame (no WT) model](image2)

![Comparison of top displacement between RC frame (no WT) and RC frame (WT) model](image3)

![Comparison of top acceleration between RC frame (no WT) and RC frame (WT) model](image4)

*(Fig. 8) Seismic performance of Infilled, RC frame (no WT) and RC frame (WT) models*

4.1.3 Seismic Performances of Retrofitted Model

Brick infilled RC framed soft story building model retrofitted with steel plate (9.5 mm thick) jacketing in ground floor columns sustained the 0.3g. While it exhibited failure in first floor columns at 0.36g PGA due to the inherent weakness of the RC frames. The Retrofitted model exhibited maximum base shear as 4400 kN (Fig.9) which is 180% of that of un-retrofitted Soft story model.

![Base shear comparison Retrofitted model and Soft story model](image5)

*(Fig. 9) Base shear comparison Retrofitted model and Soft story model*

5 Conclusions

The conclusions of the present study are depicted as follows.

i. Determined masonry constituent and composite properties to utilize in AEM infill model have been verified with the corresponding experimental results and successfully applied in the full scale MIRC building models.

ii. Time history dynamic analysis confirmed the unexpected column failure of soft story MIRC model at 0.28g PGA. Whereas, the similar RC frame model sustained 0.36g PGA with partial
damages revealing that conventional design method ignoring stress concentration induced by infills in RC frames overestimates the seismic performance of soft story buildings.

iii. Existence of brick infills in all floors sustained 0.3g PGA while failed at 0.36g confirming that infills cannot improve the overall seismic performance of surrounding RC frames.

iv. Steel plate jacketing of ground floor columns can enhance the seismic performance of the soft story model up to 0.30g PGA.

v. RC frame with overhead water tank sustained 0.36g PGA due to its increased time period induced by the water mass at the top while RC frame without water tank collapsed due to alteration in time period and natural frequency of the frame affecting its dynamic behavior.

6. Future Scopes of the Present Study

The future scopes of the present study as follows.

i. Different ground motions other than Kobe earthquake can be applied to generalize the overall seismic performances of the models.

ii. Seismic evaluation of AEM models with column-flat plate type RC frames with brick infills or column-flat plate-shear wall system with infills (other common structural systems except column-beam RC frame structure in Bangladesh) can be performed.

iii. Different retrofitting techniques can be evaluated under different seismic excitations to determine the appropriate cost effective measures against soft story mechanism.

References


