

Study on the Response of Strengthening Strategies for Masonry-infilled Open Ground Storey Framed Building

Aojoy Kumar Shuvo^{1,*}, Ashadul Islam²

Abstract

The strengthening of reinforced concrete (RC) frame buildings with masonry infill wall and with open ground storey is a very timely and significant topic because of the poor performance against seismic action. The absence of infill walls in the ground storey makes the ground storey less stiff and weaker than the all upper storeys which results in a poor performance against lateral loads. Soft storey mechanism prevails in these cases and causes premature failure. The objective of this paper is to oversee the response of different strengthening systems applied in ground storey of the building to improve the seismic behavior based on numerical analyzes. The strengthening options are chosen and provided in such a way that the options will not block the free space in the ground storey level which is kept open to serve different purposes. In addition, the study highlights the building performance by obtaining the capacity of different options and represents the variation of time period with the change of stiffness. The strengthening options investigated were design columns of ground storey for higher load, fixing diagonal bracing at the exterior sides, providing lateral buttresses and installing shear wall on exterior four corners. To find out the effective strengthening option without create any obstacle to the service for which the ground storey is kept open, the results from analyzes of strengthened buildings will be compared.

Keywords: Reinforced concrete frame, infill masonry, strengthening options, seismic effects, time period

INTRODUCTION

Due to expanding populace since the past few years car parking space for private lofts in populated cities may be a matter of major concern. Subsequently it becomes a trend to utilize the ground story of the building itself for parking. These sorts of buildings having no infill brick work dividers in ground story, but infilled in all upper story, are called Open Ground Story (OGS) buildings. As the ground storey keeps open, the strength and stiffness of this storey becomes lower than that of the upper storeys and responsible for discontinuities in lateral strength and stiffness along to the height of the building. The presence of masonry infill among the beams and columns makes the frame stiffer and causes rigid body movement when building subjected to lateral loading. The storey of the buildings

*Author for Correspondence

Aojoy Kumar Shuvo

^{1,2}Lecturer, Department of Building Engineering and Construction Management, Rajshahi University of Engineering and Technology, Rajshahi, Bangladesh

Received Date: June 18, 2021

Accepted Date: August 10, 2021

Published Date: August 30, 2021

Citation: Aojoy Kumar Shuvo, Ashadul Islam. Study on the Response of Strengthening Strategies for Masonry-infilled Open Ground Storey Framed Building. Journal of Structural Engineering and Management. 2021; 8(2): 22–37p.

will be called ‘soft story’ if the stiffness of that level is less than 70% as stiff as the floor instantly over it, or less than 80% as stiff as the normal firmness of the three floors over it. If buildings have no or little infill at ground level to facilitate car parking or such other functional needs, then due to the reduction of stiffness the floor becomes ‘soft’. As a result, the columns of the ground floor get damaged to collapse but the upper storeys remain in undamaged condition. This phenomenon indicates the effect of masonry infill on the seismic response of frame structure. So, it becomes necessary to count the effect of masonry infill

when the building is to be designed. But in conventional design practise and most of the design codes of different country do not consider the structural contribution of masonry wall. To guarantee a satisfactory structural conduct amid the seismic tremors it is essential to ensure the quality of the design prepare and the development. The recent seismic tremors have appeared that these two aspects, in especially the quality of development are exceedingly associated with the overall performance of the structure when submitted to seismic activities. It is common to accept that masonry infill (MI) dividers are continuously advantageous to the structural response, but the commitment of these components can be positive or negative, depending on the conditions and parameters. In considering the structural effect of infill in building design, two groups of national building code can be created—those that consider the role of MI wall while designing RC frames and those do not consider. A very few codes specifically recommend isolating the MI from the RC frames such that the stiffness of MI does not play any role on the overall stiffness of the frame. This paper presents the analytical investigation of several strengthening mechanisms to improve the seismic performance of open first story RC frames. The parking facilities or other facilities for which the ground story was kept open will not be hampered by those strengthening mechanisms. All the strengthening strategies are applied to the outer side of building to make the ground story usable. Equivalent static analysis, nonlinear static analysis and response spectrum analysis were carried out using ETABS 2016. Equivalent static analysis is normally used for low-rise regular structures. Buildings are assumed to be responded in its fundamental mode only and must not twist significantly when the ground moves due to earthquake motion. However, this method has been modified with many building codes by applying factors to make it applicable for higher buildings with some higher modes and for small scale of twisting. As nonlinear analysis, pushover analysis was carried out. Pushover analysis is a type of static analysis which uses simplified nonlinear technique to enumerate the deformation of structure under seismic loading. On the other hand, response spectrum analysis allows the multiple modes of response of a building rather than the fundamental one within the frequency domain. In this method, only maximum peak values of displacements and member forces in each mode of vibration are calculated with the help of smooth spectra curve obtained from the average of several earthquake motions. Response spectrum analysis is more scientific and accurate method than the equivalent static method [1–4].

Theoretical Background

Mashhadiali et al. [5] proposed a hybrid concentric braced frames system, to alleviate the soft storey effect and develop the structural response of the system. The recommended system is comprised of an energy dissipation device and a strong brace which was proved effective against soft storey mechanism and buckling. An inclusion of eccentric bracings in masonry infill reinforced concrete (RC) building was proved workable to strengthen the buildings [6]. Ruiz et al. [7] conducted an extensive study on their proposed three structural rehabilitation solutions to ameliorate the seismic performance of the building and among the three solutions, providing buckling restrained braces at the soft first storey level was more successful to reduce the structural fragility. In a new retrofitting technique called Thick Hybrid Wall Technique where steel plates were used for jacketing the RC columns, abled to considerably increase the lateral strength and stiffness and ductility [8]. Mashhadiali and Kheyroddin [9] proposed hexa-braced frame system for the enhancement of seismic resistivity of conventional steel-braced frames and this hexagonal bracing configuration was susceptible to distribute the lateral deformation along the height of the building which mitigate the soft storey collapse. Narkhede and Deshkukh [10] studied the performance of the RC building with shear wall at various positions by using various parameter and guidelines from as per IS 1893 (part-1): 2000. Their observation of results concluded that shear wall at middle core was more effective and greater in resisting the seismic force. Furtado et al. [11] studied an existing reinforced concrete building in which upper stories are masonry-infilled but not the ground floor to evaluate and analyze the effect of the masonry infill and the seismic response of the building. The investigation claimed that the safety assessment of the building can be achieved only by considering the introduction of infill masonry walls. Furthermore, they proposed four strengthening techniques (jacketing the RC columns, introducing RC shear walls, and addition of steel bracings with the presence and absence of

shear link) and made a comparison among the strengthened buildings and the original one. The result showed that the most efficient technique that effectively reduce the maximum value of the drift was the addition of steel braces and only able to remove the soft story mechanism of the ground floor. Sahoo and Rai [12] presented two strengthening methods that improve the seismic performance of existing non-ductile RC frames having soft story at the ground level. The techniques were: (i) column retrofitting by partial steel jacketing and (ii) using aluminum shear links positioned between the steel collector beams and the chevron braces act as the passive energy dissipation devices. The first technique uses four hot-rolled steel angle sections interconnected by the batten plates in regular intervals and the cages were attached externally to the existing reinforced concrete columns. The ultimate lateral strength, yield mechanism and damage state of the reinforced concrete and strengthened frames was measured by means of nonlinear static (pushover) analysis. Higher lateral strength and energy dissipation potential is exhibited in the first technique but due to limited energy dissipation through the plastic hinges such strengthened frames may not withstand all strong ground motions. The second method of strengthening behaves excellently under seismic action in terms of energy dissipation and increased lateral strength and the response of the story drift is much controlled. The shear links contributes on an average 76% of the total energy dissipation. Uva et al. [13] presented a case study for an existing framed reinforced concrete building by numerical and experimental approach that appraise the influence of infill masonry walls over the nonlinear structural response of reinforced concrete structures. They proposed a model for infilled frame structure where plastic hinges both for shear and flexure have been introduced at the ends of the element so as to model the nonlinear behavior of RC beams and columns. The research work investigated the effect of infill walls on the overall structural response for the case building. Amin et al. [14] investigated the effect of soft storey for multistorey RC building frame. They analyzed four building models having multiple story (3, 6, 9 and 12) with similar building plan. As suggested in FEMA-273, equivalent diagonal struts were provided in place of masonry to introduce the infill effect. The soft storey location was altered from ground level to top level of frame to investigate the effect of soft storey on the lateral displacement of frame. Inter-storey drift was found maximum at soft storey level. Kaushik et al. [15] studied the utility and effectiveness of various strengthening options to improve the performance of bare first story RC frame building. They created some models with different strengthening techniques and their performance was checked using pushover analyzes. The strengthening schemes were code specified method and improvement over code specified method, using extra column in ground storey level, providing diagonal braces in alternate bays and all bays in open first storey and providing lateral buttresses in outer sides. The strengthening schemes were found ineffective to improve the lateral deformability in some national codes. They observed that design of beams is not required for higher forces in the open first story rather provision of enough confining shear reinforcement could improve their ductility and shear strength. When extra columns and lateral buttresses were provided in the open first story both the lateral strength and ductility of the frame increased significantly. It was also noticed that a large increase in lateral strength and stiffness of the frame came up when diagonal braces were used but on the contrary the ductility of the frame decreases significantly than that of the frame which is strengthened by extra columns and lateral buttresses. The basic findings of their study were: code-oriented strengthening method and the design of the first-story members for higher forces cannot improve lateral load performance more specifically the ductility of the open first-story RC frame. Additional columns and lateral buttresses in the open first story could be an effective way in improving the performance of such frames. Erdema et al. [16] examined two strengthening techniques for reinforced concrete frame structure where the first one is strengthened by RC infill and the second method uses CFRP strengthened hollow clay blocks. In the study tests were carried out on two 1/3-scale, two-story, three-bay undamaged frames in which reversed cyclic quasi-static loading was applied on the test specimens and then a comparison was made among the test results. The RC infills were introduced only to the interior bay of the undamaged frames. In order to simulate the soft story formation at the ground floor the second story of the test frame was kept smaller in height than the first story. The existing frame and the infill were connected

by using steel dowels in RC infill and in case of hollow clay block infills CFRP anchor dowels was used with diagonally placed CFRP strips. The lateral displacement was measured by means of LVDT displacement transducers and two force transducers were used to measure the axial force, shear and moment. On the other hand, shear deformations of infills and the curvatures at the base of the exterior columns were measured by 12 electronic displacement gages kept mounted on the specimens. The behavior of the test specimens was compared based on stiffness, lateral strength and story drifts. The study revealed that a significant increase in stiffness and strength was achieved in case of both strengthening techniques. But beyond the peak the strength degradation in the frame strengthened with hollow clay block with diagonally placed CFRP strips was quick and more significant as compared RC infilled frame. It was also observed that infill carries the base shear not less than 90%.

Most of the previous researches have been carried out by adopting various techniques to make the frame more strengthened against seismic action. However, those techniques satisfactorily functioned against huge lateral force and displacement but have some installation complexity and are liable for creating the obstruction in the open spaces of ground floor. The present study focuses on the improvement of strength of frame structure and resistance against soft story mechanism selecting methods having no such complexity and easy to install as well as ensuring sufficient spaces at the ground floor of the building.

METHODOLOGY

Frame Considered in the Study

For beams and columns, common 3D frame element was used having 2 nodes with 6 degrees of freedom at each node. For slab, common shell element was used having 4 nodes with 6 degrees of freedom per node. For infills as diagonal struts, common 3D truss element was used having 2 nodes with 3 degrees of freedom per node. The diagonal struts were weightless. To account for the weight of the infill walls distributed load was applied to beam. A 3D view of the model is shown in Figure 1. For this study, 6-story building with twenty meters height, regular in plan was modeled. The building was fairly symmetric in plan and in elevation. The plan and elevation view of the building frame was studied as shown in Figure 1. In modeling plane frame, the following material properties and geometrical properties was used for beam, columns, masonry infill. Columns were assumed to be fixed at the base. M-20 grade concrete and Fe-415 grade of reinforcing steel were used for all the frame models used in the study. Modulus of elasticity of concrete and masonry was 22361 MPa and 700 MPa respectively. Poisson's ratio was 0.2 and 0.3 respectively for concrete and masonry. The unit weight of concrete and masonry was taken as 23.56 kN/m³ and 20 kN/m³. The floor finish and random wall on the floors were 1 kN/m². The live load on floor was taken as 2 kN/m². All beams and columns had cross-sectional area e.g. 45 cm × 30 cm and 45 cm × 45 cm respectively. Infill walls and slabs were modeled as 20 cm and 15 cm thick respectively.

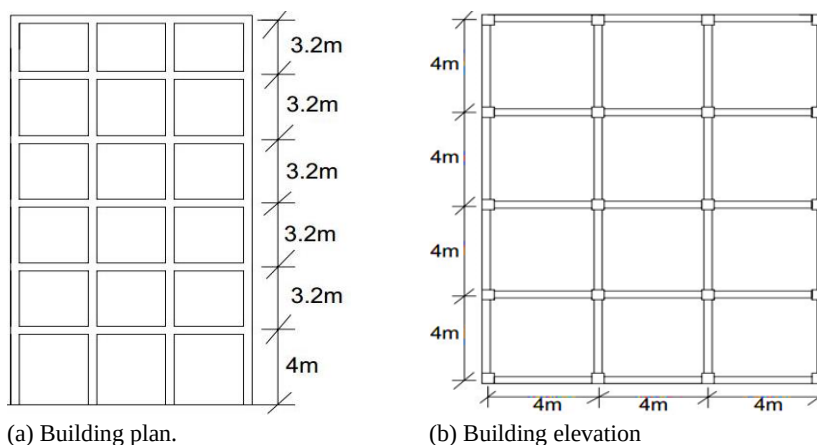


Figure 1. General view of the building under analyzes.

Masonry Infill in RC Structure

Brick work infill dividers have a significant strength and stiffness and they have critical impact on the seismic reaction of the basic framework. Though the structural effect of the infill is not counted in conventional method, but it interacts with the surrounding frame and causes to vary the mechanism of resisting load and pattern of failure of the frame. Modeling the function of masonry wall under lateral loading condition is very complex because the structure shows extremely nonlinear behavior under such loading. There are several modes of failure associated with different failure loads. To understand the behavior of infilled frame many analytical and experimental works have been done previously. Several analytical models have been developed for featuring infill characteristics in RC frame. Those models are mainly two categories: macro-model and micro model. Macro-model is based on equivalent strut method and micro-model is related to the finite element method. Due to the computational simplicity and availability of structural mechanical properties from masonry test, macro-model is more convenient to use where the masonry wall is converted to a diagonal member Figure 2.

In equivalent strut method, some researchers proposed for single strut and some proposed for multiple strut, the thickness of which is equal to the thickness of masonry infills. Equivalent width is the basic parameter of the strut which affects the stiffness and strength. Extensive research has been carried out to find out the width of equivalent strut. In 1960, Polyakov first introduced the idea of diagonal bracing equivalent to the infill wall which can be used to count the effect of infilling. Holmes [17] then adopted the idea and converted the infill to an equivalent pin-jointed diagonal strut which has the same material and thickness as the infill panel. The width of the strut, $w = d_{inf}/3$, where, d_{inf} = diagonal length of the panel. Smith and Carter [18] did a large series of experiment and proposed an equation for the width of diagonal strut where he related the width with the stiffness of infill and frame.

$$w = 0.58 \left(\frac{1}{H} \right)^{-0.445} (\lambda_h H_{inf})^{0.335} d_{inf} \left(\frac{1}{H} \right)^{0.064}$$

$$\lambda_h = \left[\frac{E_{inf} t_{inf} \sin 2\theta}{4E_c I_c H_{inf}} \right]^{0.25}$$

H = Total frame height, t = Infill wall thickness, H_{inf} = infill height, E_c = Modulus of elasticity of the column, E_{inf} = Modulus of elasticity of the infill, I_c = Moment of inertia of the columns, θ = Angle between diagonal strut to the horizontal, λ_h = Dimensionless parameter.

Mainstone [19] performed several tests on model frame with brick infill and proposed an observational condition to decide the width of strut.

$$w = 0.16 d_{inf} (\lambda_h H_{inf})^{-0.3}$$

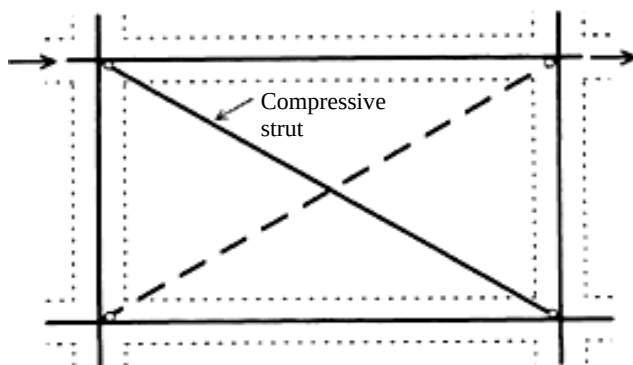


Figure 2. Diagonal strut model.

Mainstone and Weeks [20] and Mainstone [21], assist proposed an experimental condition to calculate strut width concurring to the exploratory and explanatory information.

$$w = 0.175d_{\text{inf}} (\lambda_h H_{\text{inf}})^{-0.4}$$

Depends on the finite element study for one-bay, one-story, infilled frames, Bazan and Meli [22] expressed an empirical equation to calculate the equivalent width,

$$w = (0.35 + 0.22\beta)h; \quad \beta = \frac{E_c A_c}{G_{\text{inf}} A_{\text{inf}}}$$

Here, β is a dimensionless parameter, A_c is the gross area of the column, $A_{\text{inf}} = (L_{\text{inf}}t)$ is the area of the infill panel in the horizontal plane and G_{inf} is the shear modulus of the infill. Figure 3 illustrates the ratio w/d_{inf} according to the above equation. It is additionally vital to note that it is troublesome to compare these comes about with past expressions since they are related to two distinctive parameters ($\theta = 50^\circ$ and $\theta = 25^\circ$).

Liau and Kwan [23] proposed a semi empirical expression for calculating the comparable width.

$$\frac{w}{d} = \frac{0.95 \sin 2\theta}{2\sqrt{\lambda_h}}$$

According to Paulay and Priestley [24], if the width is higher, it will cause the structure more stiff and higher seismic response. They proposed the value of width will be 25% of the diagonal length of panel. The proposed equation by Durrani and Luo [25], for the diagonal strut width is

$$w = \lambda d \sin 2\theta$$

$$\lambda = 0.32 \sqrt{\sin 2\theta} \left(\frac{h^4 E_w t_w}{m E_c I_c h_w} \right)^{-0.1}$$

$$m = 6 \left(1 + \frac{6h E_b I_b}{\pi E_c I_c L} \right)$$

Where, E_c and E_b represents the modulus of elasticity of the column and beam material respectively, and I_c and I_b indicate the moments of inertia of the cross section of column and beam respectively.

FEMA 306 [26] proposed equation for equivalent width, w , is given by

$$w = 0.175d_{\text{inf}} (\lambda_h H_{\text{inf}})^{-0.4}$$

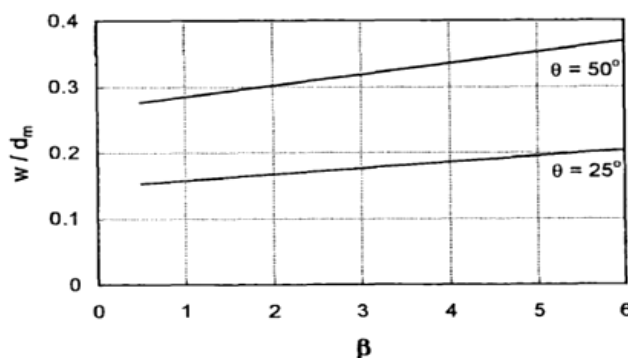


Figure 3. The variation of w/d with β ; according to Bazan and Meli [22].

Papia et al. [27] created an experimental condition for the compelling width of the inclining strut as

$$w = \frac{c}{z} \frac{1}{\lambda^*} d_{\text{inf}}$$

Here,

$$c = 0.249 - 0.0116\nu_{\text{inf}} + 0.567\nu_{\text{inf}}^2$$

$$\beta = 0.146 + 0.0073\nu_{\text{inf}} + 0.126\nu_{\text{inf}}^2$$

$$\lambda^* = \frac{E_{\text{inf}} t H_{\text{inf}}}{E_c A_c} \left(\frac{H_{\text{inf}}^2}{L_{\text{inf}}^2} + \frac{A_c L_{\text{inf}}}{4 A_b H_{\text{inf}}} \right)$$

$$z = 1 \text{ if } \frac{L_{\text{inf}}}{H_{\text{inf}}} = 1 \text{ and } z = 1.125 \text{ if } \frac{L_{\text{inf}}}{H_{\text{inf}}} \geq 1.5$$

Where, z = empirical constant, λ^* = stiffness parameter, E_c = the Young's modulus of the frame, ν_{inf} = poison ratio for the infill, A_c = cross-sectional area of the column and A_b = cross-sectional area of the beam.

Thiruvengadam [28] presented a model where the infill walls were converted to a number of pin-jointed inclining and vertical struts. Here, the shear and axial stiffness are represented by diagonal struts and vertical stiffness is counted by providing vertical struts. Hamburger and Chakradeo [29] also proposed a model consisted of multiple struts and appeared how those struts secures the beam column associations.

Chrysostomou [30] and Chrysostomou et al. [31] proposed a model in which the effect of infill wall was counted by six diagonal struts. Three parallel struts were utilized in each corner to corner heading (Figure 4).

Here, α is a parameter which represents a certain portion of length or height of panel and is associated with the position of the formation of a plastic hinge in a beam or a column.

Crisafulli and Carr [32] created a new demonstrate utilizing two parallel struts and a shear spring in each course. But there is a limitation that the model cannot legitimately anticipate the bending moment and shear forces within the encompassing frame (Figure 5).

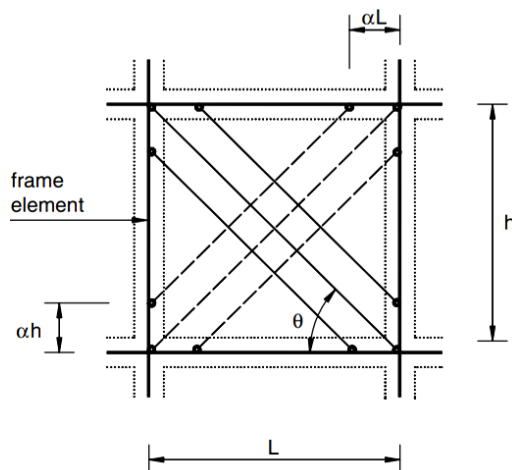


Figure 4. Model proposed by Chrysostomou [30].

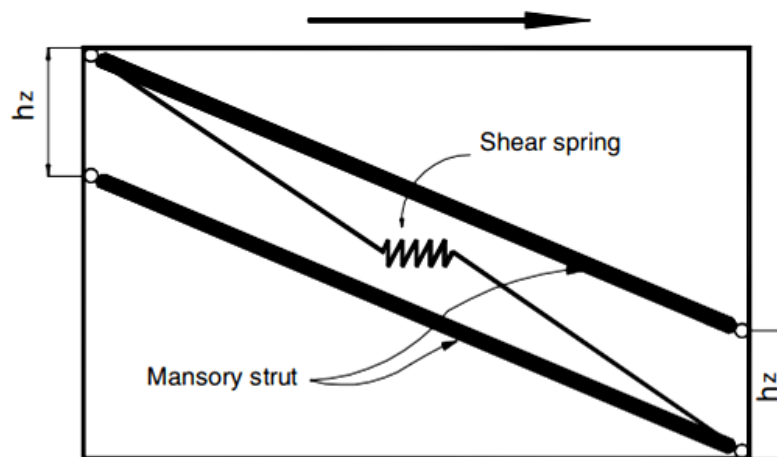


Figure 5. Model proposed by Crisafulli and Carr [32].

From the above discussion, it is clear that there are difference in opinion among the researchers regarding the width of strut and number of the strut. It is obvious that the multiple strut models are quite complex compare to single strut models. In this study, single strut model has been used for simplicity and width of the strut was calculated from the formula proposed by Paulay and Prestley [24], as the result obtained from the Paulay and Prestley [24] formula gave an average results among the single strut models [33].

Model Description (Figure 6)

Model 1

This frame represents the most currently used common practice of not including the strength and stiffness of masonry infill in the analysis and design procedure. Effects of infill were not considered in all stories.

Model 2

In this frame, the effects of infill were considered in the upper stories; however, the first story of the frame was kept open.

Model 3

In this frame, the effects of infill were considered in all stories.

Model 4

In this frame for strengthening ground story, sectional area of all column of ground story increased by 1.5 times.

Model 5

Diagonal bracings were provided in all external bays to improve lateral load performance of the frame. The sizes of section of the bracings were same as to beam and plastic hinge properties of bracings were kept identical to that of the already existing first-story columns.

Model 6

Lateral buttresses were provided in the open ground-story to ameliorate lateral strength. Inclination of buttresses with ground was 60° . Sectional property and plastic hinge properties of the buttresses were kept identical to that of the columns in the first story.

Model 7

In this frame, shear walls were provided in ground story only in external four corner and wall thickness were provided as 25 cm.

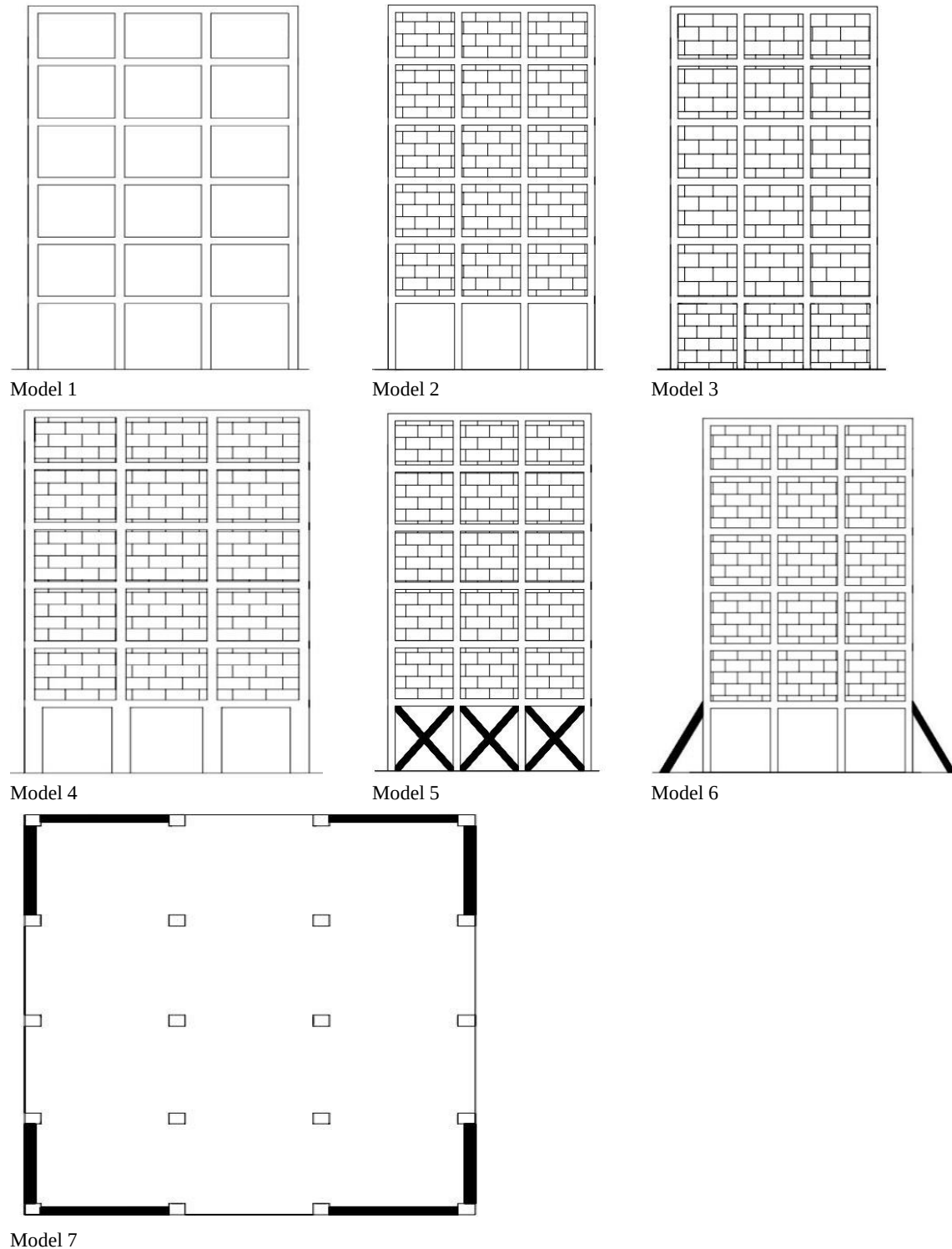


Figure 6. Model description.

Static Analysis

Linear elastic analysis of the building was carried out using the equivalent static method. In the present investigation, earthquake load was chosen as a source of lateral loading on the building frame as set forth by the provision of Bangladesh National Building Code (BNBC) at zone 2. The total share force due to the seismic load was applied in the centre of mass of all diaphragms. Earthquake load was applied at every story level of individual models.

Drift Analysis

Drift is defined as the lateral displacement of one level of a multi-storey structure relative to the level above or below. The lateral forces acting on the building mainly cause drift. Equation below defines the drift index (Figure 7).

$$\text{Drift index} = \text{Displacement/Height}$$

The total drift and interstory drift can be calculated from the later equations.

$$\text{Total drift index} = (\text{Total drift})/(\text{Building height})$$

$$\text{Interstory drift index} = (\text{Interstory drift})/(\text{Story height})$$

$$\text{Overall Drift} = \Delta_{\text{TOP}}$$

$$\text{Interstory drift} = \Delta_i - \Delta_{i-1}$$

$$\text{Overall drift index} = \Delta_{\text{TOP}}/H$$

$$\text{Interstory drift index} = \Delta_i - \Delta_{i-1}/h_i$$

These drift indices are kept limited to limit the non-structural damages.

According to BNBC code drift is limited to as follows:

- i $\Delta \leq 0.04 h/R \leq 0.005 h$ for $T < 0.70$ second.
- ii $\Delta \leq 0.03 h/R \leq 0.004 h$ for $T \geq 0.70$ second.
- iii $\Delta \leq 0.0025$ (for unreinforced masonry structure)

Where, h is the height of the building or structure

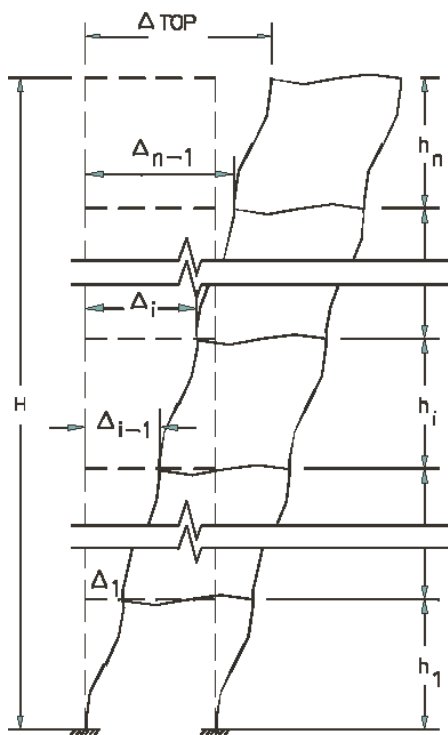


Figure 7. Building drift.

Response Spectrum Analysis

The response spectrum represents an interaction between ground acceleration and the spectral system, by an envelope of several different ground motion records. This method needs the collection of response function where the response might be spectral displacement, velocity, or acceleration. These seismic parameters are then reduced into a spectrum of seismic action versus time period. From the structural model detailed information are coupled with the corresponding spectral values for each specific mode of vibration. Then the independent results are combined by a suitable method to measure the response of the whole structure. Some combination methods are the absolute sum of squares (ABS), square root of the sum of the squares (SRSS), complete quadratic combination (CQC) method etc. From the maximum response the required response quantity of interest of the structure can be obtained in each mode of vibration. Normalized response spectrum for 5% damping ratio as per BNBC (2006) has been followed for response spectrum analysis (Figure 8).

RESULTS AND DISCUSSION

Static and dynamic analysis of different frames was carried out using ETABS software. The obtained results were represented graphically.

Story Drift and Displacements

Drift pattern at different story level for different model were shown in Figure 9 (a). More or less for all the models a general lateral drift pattern was generated. In bare frame where the effect of infill was not counted, maximum displacement occurred at first storey level and gradually decreasing to upper storeys. In the frame with bare ground storey maximum drift occurred at first storey level but sudden decrease of drift at second storey level due to increase of stiffness for the presence of infill wall and little change in drift pattern at the upper storeys. When masonry infill was in all storeys then all storeys became equal stiff and the drift pattern was almost same Model 2 from second storey level. When ground storey column sectional area were increased by 1.5 times of OGS frame then the first storey excessive displacement was reduced. Among the provision of diagonal bracings, lateral buttresses and shear wall to ground storey level to strengthen the frame, providing shear wall result maximum reduction of displacement of ground storey. The drift patterns of all models were almost same from storey 2 to storey level 6. This pattern directly indicated the physical deflection shape of a building frame due to earthquake loading.

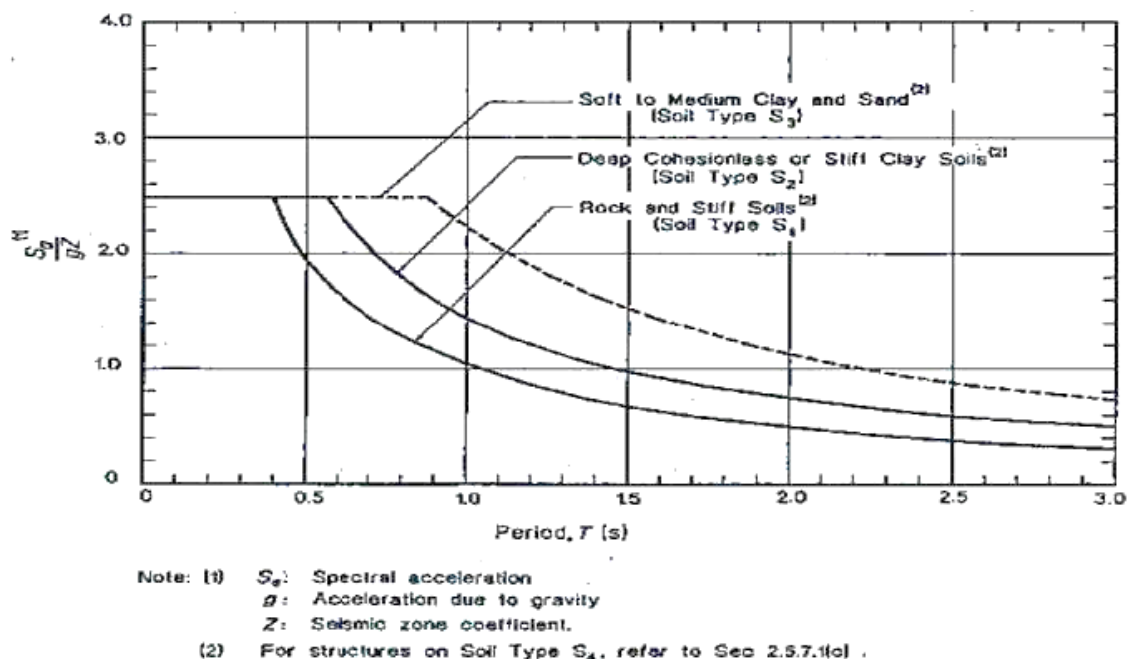


Figure 8. Normalized response spectra for 5% damping ratio BNBC [34].

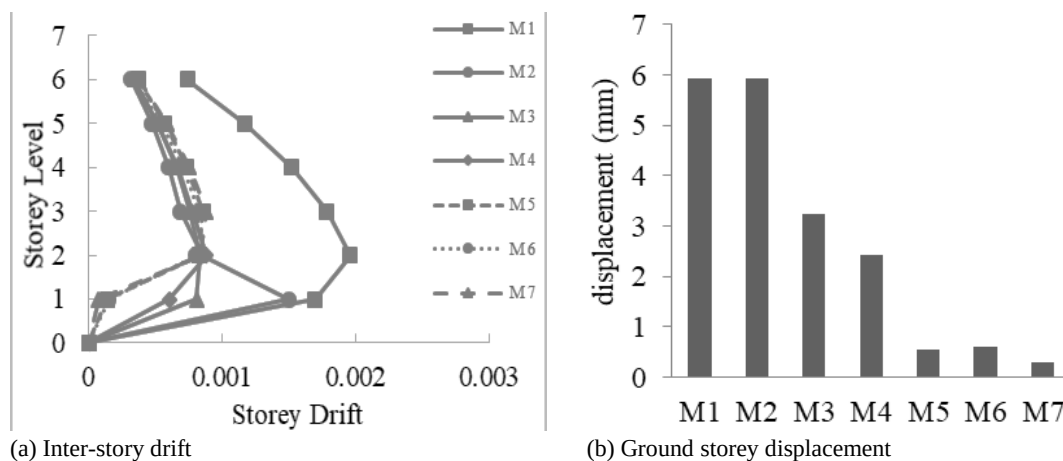


Figure 9. Linear analysis result.

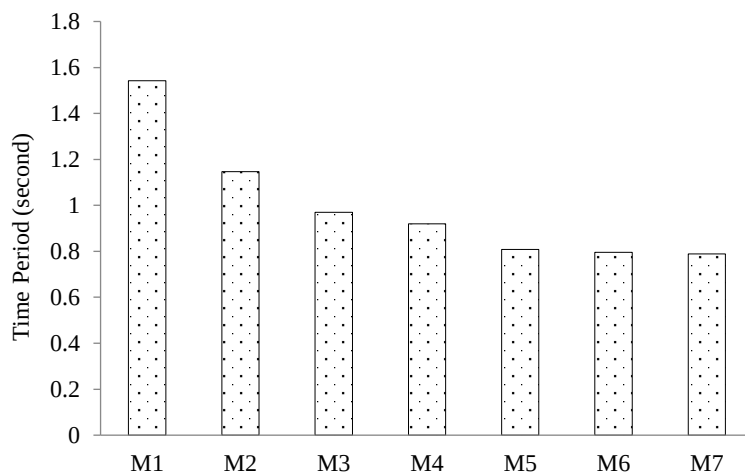


Figure 10. Variation of time period with Model.

Natural Frequencies

The dynamic characteristics, such in terms of mass or stiffness affect directly the response of the structures. The study of the influence of infill masonry walls presence was initially made by comparing the natural frequencies of the model with infill masonry model (IMM) and without these elements bare frame model (BFM). It was observed that the model with masonry infill have higher frequencies than the BFM. As the strengthening techniques were introduced to the OGS frame, the stiffness of open ground storey increased. This attracts higher forces due to the increase of stiffness, which results in a reduction in the natural period of the structures. From the modal analysis of the first vibration shape mode, illustrated in Figure 10 it was observed that minimum time period obtained by providing shear wall into ground storey.

Story Responses

Analysis result graphically represented in Figure 11. All storey of bare frame had equal stiffness so storey stiffness plot was almost straight line and base shear was minimum. In Model 2, stiffness at storey level 2 was 402 MN/m and at ground storey level was 196 MN/m which was less than 70% of its upper storey. Except Model 1, all the models had equal stiffness from storey level 2 to storey level 6 due to same configuration. With the introduction of strengthening techniques, the stiffness of ground storey level increased to a large limit. Provision of shear wall increased the stiffness of OGS about 27 times and exhibits maximum stiffness among all. With the improvement of stiffness, the models attracted more load and base shear increased. Provision of diagonal bracings and lateral buttresses to ground storey represented about same stiffness and base shear.

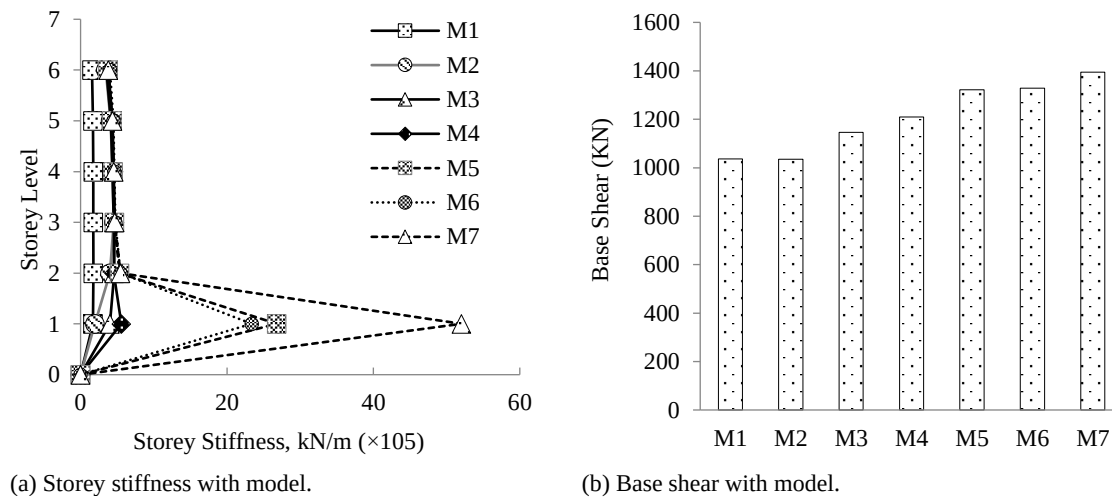


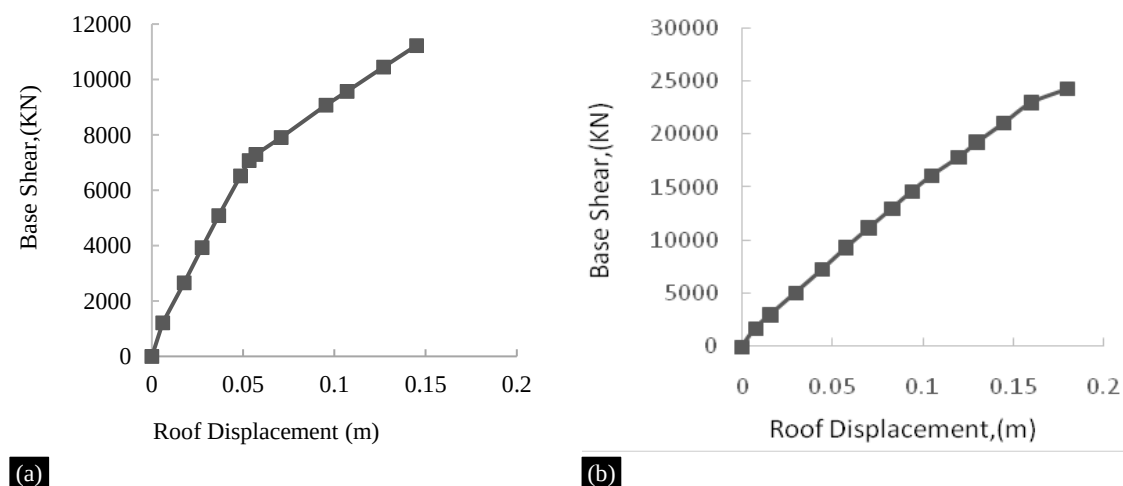
Figure 11. Variation of storey stiffness and base shear.

Performance Analysis

As observed before the structural responses clearly indicate the soft storey mechanism. The behavior of the frame leading to the massive inter-storey drift demand at first storey level for the open ground storey frame where little deformation takes place on the upper storey levels. Pushover analysis can simulate the yielding phenomenon of frame by applying load until the weak link in the structure is found. To estimate the seismic capacity of the strengthened frame pushover analysis for all the frame were carried out. After gravity pushover lateral pushover was done till formation of collapse mechanism. Results of the pushover analysis are presented in capacity curve which indicate the resistance of the structure at the time of deforming into the inelastic range. The capacity curve presents the base shear vs. top displacement variation. To create a collapse mechanism the frame was pushed up to 4% of the height of the building. The strengthened frame with shear wall withstood higher base shear with controlled lateral displacement. The performance of Model 5 and Model 6 was quite the same and capable to carry higher shear force. But the performance of Model 4 was not at a satisfactory level (Figure 12).

CONCLUSION

It was observed that a correct assessment of the building safety can only be achieved by considering the presence of infill masonry walls. The absence of the infills on the ground floor introduced a soft-store mechanism on the structure when subjected to seismic actions. The response of upper storeys when subjected to static or dynamic loading much depended on the ground storey condition



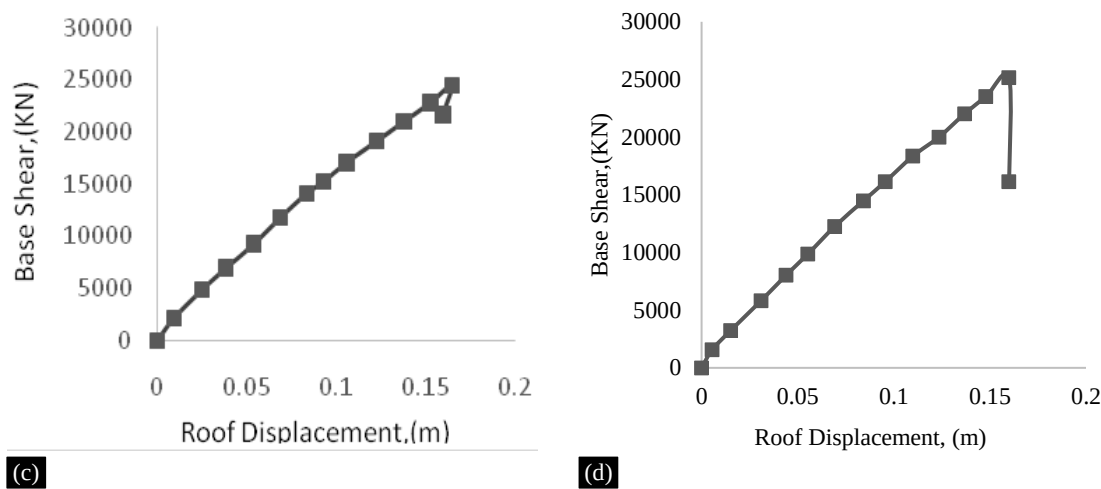


Figure 12. Capacity curves: (a) Model 4 (increased column sectional area); (b) Model 5 (strengthened by X bracing); (c) Model 6 (strengthened by lateral buttresses); (d) Model 7 (strengthened by shear wall).

From above dialogue the following conclusions can be drawn:

- If the ground storey column is designed for higher load or increased the cross-sectional area (Model 4), its behavior is almost same to the model with masonry infill in all storey (Model 3). But it cannot resist satisfactorily the formation of soft storey for higher loading condition. The stiffness provided by this option is near to the value provided by infill in ground level.
- Providing X bracing (Model 5) and lateral buttresses (Model 6) in the ground level is very efficient in increasing the stiffness and strength significantly. The stiffness of the strengthened frames was at least twelve times that of the bare frame. The responses of the both techniques are about similar and displacement reduction capacity is quite satisfactory.
- Among all the models the model with shear wall (Model 7) in the four exterior corners showed the higher responses. This option increased the stiffness of ground level about 26 times compare to open ground storey and a sudden drop of storey stiffness at second storey level was observed. It is very much efficient in reducing the displacement and time period of vibration.
- From performance check by pushover analysis, it was clear that strengthened by x bracing, lateral buttresses and shear wall exhibited better contribution under seismic action. The ground storey column designed for higher load showed very lower resistance and cannot become a better strengthening solution.
- The greatest advantage of those strengthening options is all the options were applied at exterior sides of building that is why those will not create disturbances in the free spaces in ground storey level. All the options can be adopted with the frame at the time of construction of building and there will no further complexity regarding the installation and material.

REFERENCES

- Saneinejad A, Hobbs B. Inelastic design of infilled frames. *J Struct Eng.* 1995;121(4):634–50. doi: 10.1061/(ASCE)0733-9445(1995)121:4(634).
- Abdelkareem KH, Abdel Sayed FK, Ahmed MH, et al. Equivalent strut width for modelling R.C. infilled frames. *J Eng Sci.* 2013; 41(3):851–66p.
- Asteris PG, Antoniou ST, Sophianopoulos DS, Chrysostomou CZ. Mathematical macro modeling of infilled frames: State of the Art. *J Struct Eng.* 2011;137(12):1508–17. doi: 10.1061/(ASCE)ST.1943-541X.0000384.
- Furtado A, Rodrigues H, Varum H, et al. Assessment and strengthening strategies of existing RC buildings with potential soft-storey response. 9th International Masonry Conference. Portugal: Guimaraes; 2014. p. 1–9p.

5. Mashhadiali N, Saadati S, Mohajerani SAM, Ebadi P. Hybrid braced frame with buckling-restrained and strong braces to mitigate soft story. *J Constr Steel Res.* 2021;181. doi: 10.1016/j.jcsr.2021.106610, PMID 106610.
6. Khan D, Rawat A. Nonlinear seismic analysis of masonry infill RC buildings with eccentric bracings at soft storey level. *Procedia Eng.* 2016;161:9–17. doi: 10.1016/j.proeng.2016.08.490.
7. Ruiz SE, Santos-Santiago MA, Bojórquez E, Orellana MA, Valenzuela-Beltrán F, Bojórquez J, Barraza M. BRB Retrofit of mid-rise soft-first-story RC moment-frame buildings with masonry infill in upper stories. *J Build Eng.* 2021;38. doi: 10.1016/j.job.2020.101783.
8. Javadi P, Yamakawa T. Strength and ductility type retrofit of soft-first-story RC frames through the steel-jacketed non-reinforced thick hybrid wall. *Eng Struct.* 2019;186:255–69. doi: 10.1016/j.engstruct.2019.02.013.
9. Mashhadiali N, Kheyroddin A. Seismic performance of concentrically braced frame with hexagonal pattern of braces to mitigate soft story behavior. *Eng Struct.* 2018;175:27–40. doi: 10.1016/j.engstruct.2018.08.036.
10. Narkhede DV, Deshkukh GP. Performance of shear wall building at various positions by using pushover analysis. *Int J Res Advent Technol.* National Conference Convergence 2016. April 06–07, 2016 [Special Issue].
11. Furtado A, Rodrigues H, Varum H, Costa A. Evaluation of different strengthening techniques efficiency for a soft storey building. *Eur J Environ Civ Eng.* 2017;21(4):371–88. doi: 10.1080/19648189.2015.1119064.
12. Sahoo DR, Rai DC. Design and evaluation of seismic strengthening techniques for reinforced concrete frames with soft ground story. *Eng Struct.* 2013;56(11):1933–44. doi: 10.1016/j.engstruct.2013.08.018.
13. Uva G, Porco F, Fiore A. Appraisal of masonry infill walls effect in the seismic response of RC framed buildings: A case study. *Eng Struct.* 2012;34(1):514–26. doi: 10.1016/j.engstruct.2011.08.043.
14. Amin MR, Hasan P, Islam BKMA. Effect of soft storey on multi storied reinforced concrete building frame. 4th Annual Paper Meet and 1st. Dhaka, Bangladesh: Civil Engineering Congress; 2011. p. 267–72p.
15. Kaushik HB, Rai DC, Jain SK. Effectiveness of some strengthening options for masonry-infilled RC frames with open first story. *J Struct Eng.* 2009;135(8):925–37. doi: 10.1061/(ASCE)0733–9445(2009)135:8(925).
16. Erdem I, Akyuz U, Ersoy U, Ozcebe G. An experimental study on two different strengthening techniques for RC frames. *Eng Struct.* 2006;28(13):1843–51. doi: 10.1016/j.engstruct.2006.03.010.
17. Holmes M. Steel frames with brick and concrete infilling. *Proceedings of the Institution of Civil Engineers.* 1961;19(4):473–8. doi: 10.1680/iicep.1961.11305.
18. Smith BS, Carter C. A method of analysis for infill frames. *Proceedings of the Institution of Civil Engineers.* 1969;44:31–48.
19. Mainstone RJ. On the stiffness and strength of infilled frames. *Proceeding Inst Civ Eng.* 1971;57–90p; Supplement IV.
20. Mainstone RJ, Weeks GA. The influence of bounding frame on the racking stiffness and strength of brick walls. *Proceedings of the 2nd interface brick masonry conference.* Watford, England: Building Research Establishment; 1970. p. 165–71p.
21. Mainstone RJ. Supplementary notes on the stiffness and strength of infilled frames. *Current. Vols. 13/74.* Garston, Watford, U.K.: Building Research Station; 1974:Paper CP.
22. Bazan E, Meli R. Seismic analysis of structures with masonry walls. 7th World conference on Earthquake Engineering. Vol. 5. Tokyo: International Association of Earthquake Engineering (IAEE); 1980. p. 633–40p.
23. Te-Chang L, Kwok-Hung K. Nonlinear behaviour of non-integral infilled frames. *Comput Struct.* 1984;18(3):551–60. doi: 10.1016/0045–7949(84)90070–1.

-
24. Paulay T, Priestley M. Seismic design of reinforced concrete and masonry buildings. Jhon. New York: Wiley & Sons Inc; 1992.
 25. Durrani AJ, Luo YH. Seismic retrofit of flat-slab buildings with masonry infills. Proceedings of the from NCEER workshop on seismic response of masonry infills, Buffalo, NY. National Center for Earthquake Engineering Research; 1994. p. 1–8p.
 26. FEMA 306. Evaluation of earthquake damaged concrete and masonry wall buildings: basic procedures manual; 1998. Available from: <https://mitigation.eeri.org/files/fema-306.pdf>.
 27. Papia M, Amato G, Cavaleri L, et al. Infilled frames: influence of vertical load on the equivalent diagonal strut model. The 14th World Conference on Earthquake Engineering. Beijing, China. 2008, October 12–17.
 28. Thiruvengadam V. On the natural frequencies of infilled frames. Earthquake Engng Struct Dyn. 1985;13(3):401–19. doi: 10.1002/eqe.4290130310.
 29. Hamburger RO, Chakradeo AS. Methodology for seismic-capacity evaluation of steel-frame buildings with infill unreinforced masonry. Proceedings of the of the National earthquake conference central U.S. Vol. 2. Memphis, TN: Earthquake Consortium; 1993. p. 173–91p.
 30. Chrysostomou CZ. Effects of degrading infill walls on the nonlinear seismic response of two-dimensional steel frames [Ph.D. thesis]. Ithaca, NY: Cornell University; 1991.
 31. Chrysostomou CZ, Gergely P, Abel JF. A six-strut model for nonlinear dynamic analysis of steel infilled frames. Int J Struct Stab Dyn. 2002;2(3):335–53.
 32. Crisafulli FJ, Carr AJ. Proposed macro-model for the analysis of infilled frame structures. Bull N Z Soc Earthquake Eng. 2007;40(2):69–77. doi: 10.5459/bnzsee.40.2.69–77.
 33. Hendry AW. Structural masonry. 2nd ed. London: Macmillan Press; 1998.
 34. BNBC. Bangladesh National Building Code. Housing and Building Research Institute and Bangladesh Standards and Testing Institution. 2006.