International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 08 Issue: 12 | Dec 2021 www.irjet.net p-ISSN: 2395-0072

Seismic Performance Evaluation of Hollow Concrete Block Infilled Reinforced Concrete Buildings in Case of Ethiopia

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Abstract - *Masonry infills are usually treated as non-structural elements in buildings, and their interaction with the bounding frame is often ignored in analysis and design of reinforced concrete structures. The main aim of this study is to evaluate the seismic performance of HCB infilled reinforced concrete (RC) buildings by adopting probabilistic performance assessment approaches. For the purpose of this study, three distinct buildings namely, seven-story, eleven-story and sixteen-story, with typical floor plan were proposed as the case study. Each building cases are explicitly modeled as a bare frame and HCB in-filled model with varying percentage of infill configurations. Bare RC frame buildings are analyzed and designed based on the conventional design approach on ETABS 2016.2.1, while numerical modeling and analysis of HCB in-filled models are simulated on Seismo-Struct 2016. Static pushover analysis and nonlinear dynamic time history analysis were adopted for performance evaluation of the case study buildings with respect to local and global parameters. Results of the study showed that increase in initial stiffness, strength, and energy dissipation of the infilled frame is considerable, compared to the bare frame. Inclusion of infills has showed a significant decrease in fundamental vibration period and story displacements. Also it was found that infills have significant contribution in arresting large lateral deflections and results in lower and most tolerable story displacements under excited earthquake motion.*

Key Words: **Bare frame, infilled model, capacity curve, limit state capacities**

1. INTRODUCTION

In most modern buildings, the non-structural components account for 60 to 80 percent of the value of the building. HCBs are frequently used infill walls among the most commonly used masonry infills in Ethiopia. These infills participate in the lateral response of buildings and as a consequence alter the lateral stiffness of buildings. Hence, natural periods and modes of oscillation of the building are affected in the presence of masonry infills. The conventional design practice considers only the masses of the infill walls without an attempt to incorporate their lateral stiffness. As a result modeling the infill walls along with the frame elements is necessary to incorporate additional lateral stiffness offered by masonry infill walls.

Neglecting the significant interaction between the infill walls and building frames is the main reason why structural systems incorporating integrated infills panels react to strong earthquakes in a manner quite different from the expected one. There are many different techniques proposed in the literature for the simulation of the infilled frames, which can be basically divided in two groups, namely the micro models and the simplified macro-models. The micro-models considers a high level of discretization of the infill masonry panel, in which the panel is divided into numerous elements to take into account the local effects in detail, while the simplified macro-models are supported in simplifications with the objective of representing the global behavior of the infill panel with main structural elements.

Macro-modeling is used to present accurate and realistic response of infill walls and it uses equivalent diagonal struts to model the contribution of the infill walls to the response of the infilled frame. This method replaces the infill panel by two diagonal, compression-only struts. This approach is advantageous since the masonry is a very heterogeneous material and it is hard to predict the material properties of the constituent members accurately. For the nonlinear analysis of large and complex structures under severe loadings, as the induced by earthquakes, in many cases it is not suitable to adopt refined models. Thus, many authors have in the last decades proposed and used simplified nonlinear models for RC structures.

The main focus of this research is to study the effects of HCB infills on the seismic performance of RC buildings by implementing numerical models on the basis of finite element principles. Three distinct building model cases (i.e. G+6, G+10 and G+15) each as a bare frame and distinctly having defined percentages of infill configuration are proposed for numerical analysis purpose. Bare RC frame buildings are analyzed and designed on ETABS 2016.2.1 [1]. Analysis and design of the proposed building model cases followed the conventional design approach as prescribed on the new Ethiopian Buildings Code Standards [2], [3] and [4]. While numerical modeling and nonlinear time history analysis of designed building model cases with the proposed infill configurations are computationally done on Seismo-Struct [5] which is a fiber-based finite element software package capable of predicting the large displacement behavior of space frames.

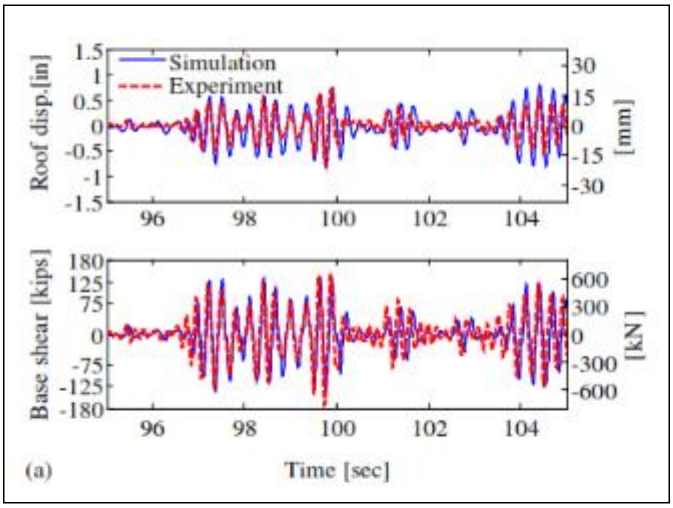
2. LITERATURE REVIEW

2.1. Behavior of Masonry Infilled Reinforced Concrete Frames

Unreinforced wall panels are typically used as infill walls in flexural framed buildings; structural frame is first built with the masonry walls constructed later leaving some gaps between the framed members and the wall. In these applications, masonry is regarded as mass with its stiffness disregarded in the analyses and neither the frame nor the wall is designed for their potential interaction. Where out-of-plane loads dominate on these infill walls, they fail prematurely, potentially leaving the framed structure (where designed properly for seismic action effects) with minimal damage. Due to the high stiffness, the wall will generate higher seismic forces for which the building would not have been designed, causing significant damage to framed structures with potential for collapse of the whole building. Several failures are reported in the literature as case studies and theoretical analyses [6].

In many earthquake-prone countries, a concrete panel infill is reinforced with a masonry panel. Although the infill panel significantly increases the stiffness and strength of the frame, its contribution is often overlooked due to lack of knowledge in composite behavior of the frame and its infill panel [7].

Limited data exist on the dynamic properties of masonry wall infilled frames, since very few shake-table experiments are performed on masonry infilled structures. Fardis et al. [8] reported on the shake-table test performed on single-bay two-story RC frames with eccentric (asymmetric in plan) masonry infill walls subjected to bidirectional ground accelerations.



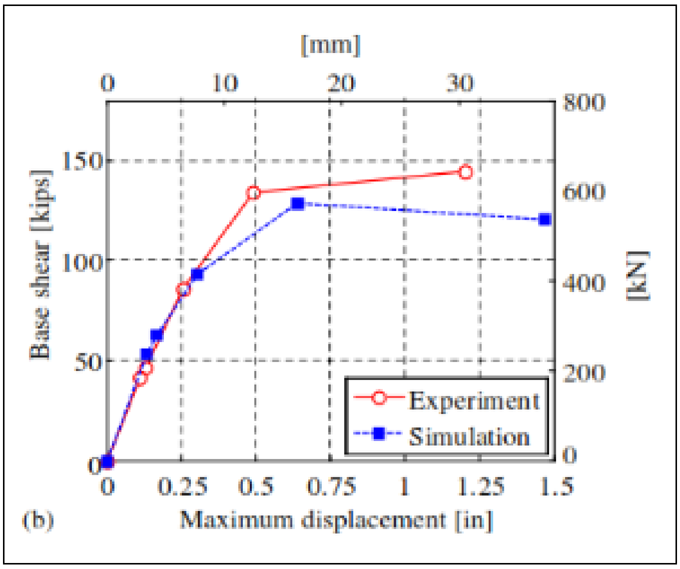


Fig-1: Comparisons between the experimental and simulated results [9]. (a) Partial time histories and (b) peak response

Considering the simple model used with a single strut for the URM infill wall, the OpenSees simulation results are in good agreement with the experimental results. From the above rigorous study the result showed that the URM infill wall had a significant role in the strength and ductility of the test structure and should be considered in both analysis and design.

2.2. Failure Modes of Infilled RC Frames

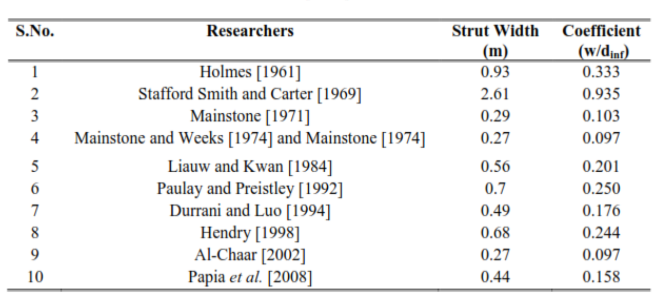
The failure mechanisms of the masonry infilled frames are complex because of the high number of parameters involved in the seismic response of the structure such as the material property, configuration, and relative stiffness of the frame to the infill, detailing, etc. Experimental results show that masonry infilled frames can experience a wide variety of the failure modes.

It is worth mentioning that only the first two modes, the Corner Crushing (CC) and the Sliding Shear (SS) modes, are of practical importance since the third mode Diagonal Compression (DC) occurs very rarely and requires a high slenderness ratio of the infill to result in out-of-plane buckling of the infill under in-plane loading. This is hardly the case when practical panel dimensions are used, and the panel thickness is designed to satisfy the acoustic isolation and fire protection requirements [10]. The fourth mode Diagonal Cracking (DK) should not be considered a failure mode, due to the fact that the infill can still carry more loads after it cracks. Although the fifth mode Frame Failure (FF) might be worth considering in the case of reinforced concrete (RC) frames, when it comes to steel frames infilled with unreinforced hollow concrete masonry blocks, this mode hardly occurs. The study conducted herein models the CC mode only, which is the most common mode of failure. In order to determine the governing failure mode, the capacity of the infill panels obtained by the proposed method should be compared to the capacity under the SS mode, which may be estimated using the method suggested by Paulay and Priestley [11].

2.3. Models for the Infill Panels

In modelling of infill panels the problem relies on identifying a reliable and simple model which could represent the masonry infill. Many difficulties were due to the intrinsic characteristics of masonry. As it is a non-homogeneous and anisotropic material, it is difficult to find a generally valid constitutive law. Furthermore the masonry shows significant degradation of stiffness and strength under cyclic loading. The result showed that the ratio of the estimated equivalent strut width to the diagonal length of infill (w/d_{inf}) are ranging between about 0.1 to 0.33 except the result calculated by using Stafford Smith and Carter [12] method equation which generate large value for the equivalent strut width.

Table-1: Strut width and coefficient by various researchers [13]



S.No.	Researchers	Strut Width (m)	Coefficient (w/d_{inf})
1	Holmes [1961]	0.93	0.333
2	Stafford Smith and Carter [1969]	2.61	0.935
3	Mainstone [1971]	0.29	0.103
4	Mainstone and Weeks [1974] and Mainstone [1974]	0.27	0.097
5	Liauw and Kwan [1984]	0.56	0.201
6	Paulay and Preistley [1992]	0.7	0.250
7	Durrani and Luo [1994]	0.49	0.176
8	Hendry [1998]	0.68	0.244
9	Al-Chaar [2002]	0.27	0.097
10	Papia *et al.* [2008]	0.44	0.158

3. METHODOLOGY

3.1. Introduction

Reinforced Concrete frame structures are constructed initially due to ease of construction and rapid work in progress. Masonry infilled walls are most common building element found throughout the world. Infilled frame may be defined as combination of moment resisting plane frame and infill wall. Structural engineers, during the design process of a building, typically, ignore the effects of infill masonry walls in the structural analysis. The only contributions of masonry infill walls are their masses as non-structural elements. Consequently, analyses of the structures are based on the bare frames. In the last 4 decades, the effects of infill walls in frame structures have been extensively studied. Experimental and analytical study results show that infill walls have a significant effect on both the stiffness and the strength of structures.

3.2. Seismic Design of RC Buildings

Multi-story reinforced concrete buildings for apartment use (condominiums), and three building models having different number of story: seven-story (G+6), eleven-story (G+10), and sixteen-story (G+15) with similar floor plans and functions are used in this paper. The main purpose of having varying story as the case study is to investigate the effect of infills as the story height increases. As this paper is mainly focused on seismic performance evaluation of HCB infilled reinforced concrete buildings, it would give better understanding on how the infill effects alter the performance of the designed structures as the building get higher in story level.

All building models are proposed to be situated at Addis Ababa where the current building code classified as seismic zone III. After preparing general architectural plans for the proposed building models, analysis and seismic design of frame elements are performed according to new Ethiopian Buildings Code Standards (ES EN: 2015). The design process comprised preparing a basic structural analysis model of the building with the dimensions and details obtained from preliminary design strategies. Then apply design lateral forces, perform structural analysis, and then design structural elements based on stress resultants obtained from structural analysis. Seismic action is used as governing lateral force on the building structures and the analysis for the lateral action followed modal response spectrum method. The proposed building models are classified as regular both in plan and elevation that the parameters and results of the intended study could easily be interpreted in relation to infill walls.

3.3. Macro-Modelling of Infill Walls

Macro-modeling is used to present accurate and realistic response of infill walls and it uses equivalent diagonal struts to model the contribution of the infill walls to the response of the infilled frame. This method replaces the infill panel by two diagonal, compression-only struts. The adopted model assumes that the contribution of the masonry infill panel to the response of the infilled frame can be modeled by replacing the panel by a system of two diagonal masonry compression struts. The individual masonry struts are considered to be ineffective in tension.

Accordingly, infill panels are modeled by equivalent diagonal struts, which carry loads only in compression. The shear strut model, representing the infill panels shear capacity normal to the gravitational direction is implemented in an equivalent discrete shear-type model. In the proposed infill panel model, each masonry panel is structurally defined by considering four support strut-elements, with rigid behavior, and a central strut element, where the nonlinear hysteretic behavior is concentrated. The forces developed in the central element are purely of tensile or compressive nature. Besides it is possible to obtain mechanical properties of the infill walls from prism tests to model the equivalent struts, in this paper test machines used to determine the mechanical properties of the masonry prisms are not available that most prevalent values of compressive and shear strengths of HCB masonry prisms were browsed from relevant literatures and code conforming values are thus used as input data for numerical modeling of infilled RC frames on finite element software packages.

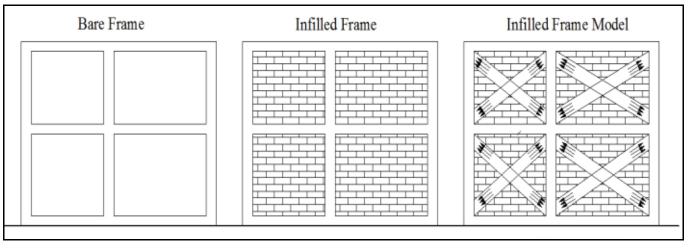


Fig-2: Structural layout of bare frame, infilled frame and infill frame models

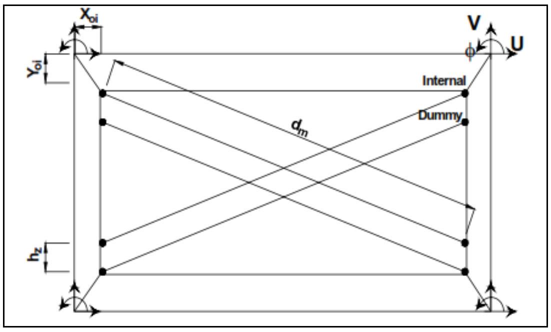


Fig-3: Equivalent diagonal strut model

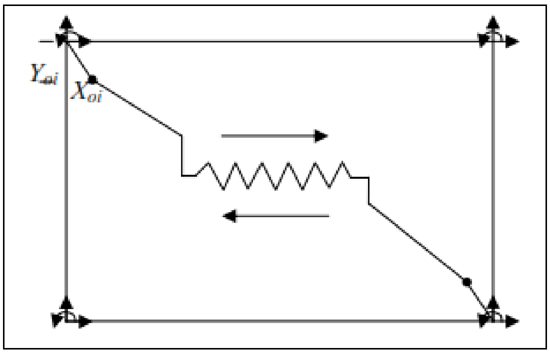


Fig-4: Equivalent shear spring model

The proposed building model cases with various infill configurations are thus numerically modelled on SeismoStruct 2016. This computer program is analytical software works on principles of finite element package for structural analysis, capable of predicting the large displacement behavior of space frames under static or dynamic loadings, taking in to account both geometric nonlinearities and material inelasticity. The software has inbuilt nonlinear and hysteretic material properties for concrete, steel, infills and other engineering materials. Five (5) infill configuration models are proposed for each designed buildings model cases to use in numerical modeling and assessment of seismic performances.

All the proposed building models having infill panels are introduced with 20cm thick HCB as external wall and 15cm thick as internal walls. Also the effect of openings due to windows and doors has been considered through stiffness reduction factor. Static pushover and nonlinear time-history analysis are performed after complete numerical model of buildings in their three dimensional state.

3.4. Seismic Performance Evaluation

In this paper, pushover and nonlinear dynamic time history analyses are performed on SeismoStruct 2016 software to evaluate the seismic performance of the case study buildings. To predict the response of the selected structures during an earthquake, 30 artificial accelerograms using SeismoArtif 2016 are generated, scaled, and matched with Ethiopian response spectrum and loaded on all building model cases for nonlinear dynamic time history analysis.

4. ANALYSIS AND DESIGN OF REINFORCED CONCRETE BUILDINGS

The investigated buildings are a multi-story reinforced concrete buildings for apartment use (condominiums), and three building models having different number of story: seven-story (G+6), eleven-story (G+10), and sixteen-story (G+15) with similar floor plans and functions are used for the study. Seismic action is used as governing lateral force on the building structures and the analysis for the lateral action followed modal response spectrum method. The proposed building models are classified as regular both in plan and elevation that the parameters and results of the intended study could easily be interpreted in relation to HCB walls. All analyses and designs are performed on ETABS 2016 software (CSI 2016. ETABS. Integrated Building Design Software, Computers and Structures Inc. Berkeley). A three dimensional (spatial) structural model is used for all cases. The model cases are multistory reinforced concrete buildings composed of frame system and solid slab floors. Beams, supporting floors and columns are continuous and meet at nodes, often called “rigid” joints. Such frames can readily carry gravity loads while providing adequate resistance to horizontal forces, acting in any direction.

4.1. Analysis Approach

The structure is modeled, analyzed, and designed in computer software “ETABS 2016.2.1. Beams and columns are modeled with line or frame elements, shear walls are modeled with wall elements, and slabs and roof floors are modeled with area elements. Analysis and design of slabs entirely followed coefficient method where the approach depends upon whether it is a one – way or two - way slab, support conditions and the loadings. Accordingly, slabs are analyzed on spread sheets/excel sheets based on their support conditions and corresponding parameters as per EBCS. The calculated partition loads, floor finishes, and live loads are then assigned on the modeled area elements on ETABS 2016.2.1 so as to consider for their respective applied gravity loads.

5. NUMERICAL MODELING AND ANALYSIS

Non-linear dynamic time history analysis is considered as the most advanced and comprehensive analytical method for evaluating the seismic response and performance of multi-degree-of-freedom building structures subjected to seismic excitation.

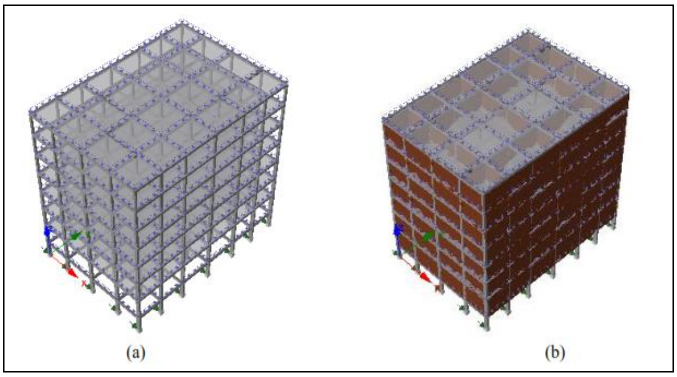


Fig 5: (a) 3D simulated G+6 bare frame building model, (b) 3D simulated G+6 infilled frame building model

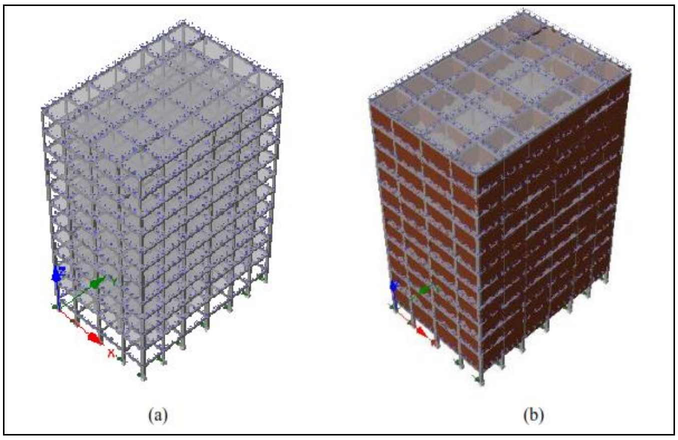


Fig 6: (a) 3D simulated G+10 bare frame building model, (b) 3D simulated G+10 infilled frame building model

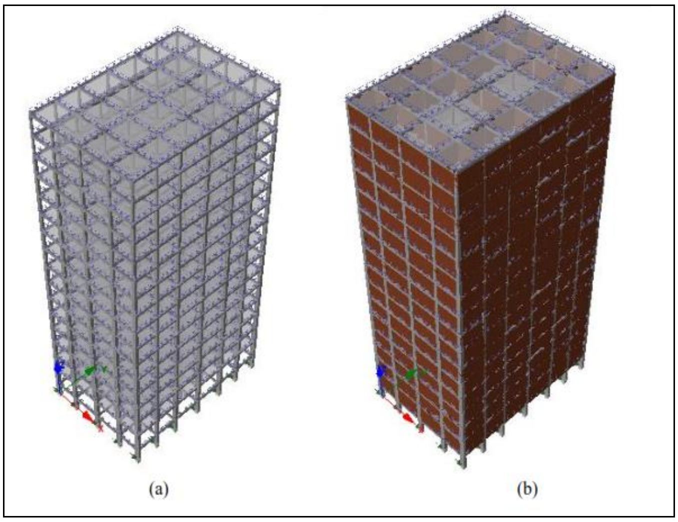


Fig 7: (a) 3D simulated G+15 bare frame building model, (b) 3D simulated G+15 infilled frame building model

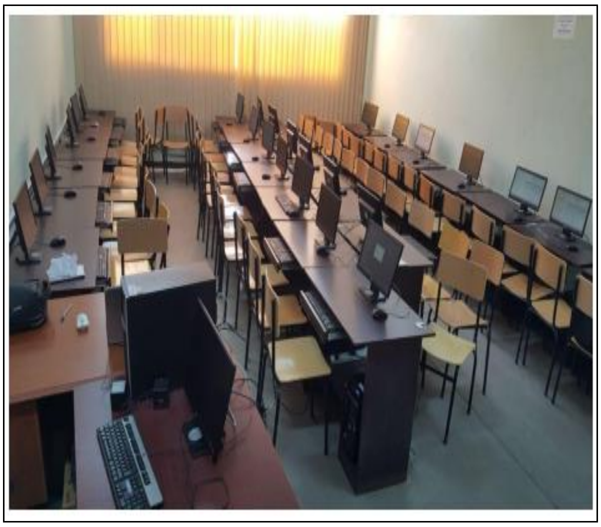


Fig 8: Computers used to run nonlinear dynamic time history analysis

6. RESULTS AND DISCUSSION

6.1. Base Shear

It was observed that seismic base shear for infilled building models are greater than bare frame building model. But the base shear of infilled models decreased abruptly to a value of about 1,000kN just after infill onset cracks where their stiffness contribution starts to degrade. Then the gradual application of incremental load calls upon frame elements resistance and thus the base shear would start to increase. The inclusion of infills has shown appreciable increase in seismic base shear at immediate occupancy (IO) performance level. 25% infill introduction in bare frame model has raised the seismic base shear to 6,117.80kN (39% increase), 7,488.30kN (65.9% increase) and 11,099.24 (132% increase) for G+6, G+10 and G+15 building models respectively. Accordingly, 100% infill introduction in bare frame model has raised the seismic base shear to 14,307.30kN (224% increase), 17,363.80kN (284.7% increase) and 23,519.43 (392% increase) for G+6, G+10 and G+15 building models respectively.

Generally it has been noticed that additions of infills have relatively larger effect as the number of story increases. As it has been seen the percentage deviations of seismic base shears for G+10 building models are greater than the corresponding values G+6 building model, and similarly that of G+15 building models are greater than the corresponding value G+10 building models.

Table-2: Seismic base shear at IO performance level for G+6 building models

Building Model Types	Case Designation	Base Shear at IO Performance Level (kN)	Deviation From Case-1 (%)
Bare Frame Model	Case-1	4,418.0	0
25% Infilled Model	Case-2	6,117.8	38.5
50% Infilled Model	Case-3	8,679.4	96.5
75% Infilled Model	Case-4	10,569.2	139.2
100% Infilled Model	Case-5	14,307.3	223.8

Table-3: Seismic base shear at IO performance level for G+10 building models

Building Model Types	Case Designation	Base Shear at IO Performance Level (kN)	Deviation From Case-1 (%)
Bare Frame Model	Case-1	4,513.6	0
25% Infilled Model	Case-2	7,488.3	65.9
50% Infilled Model	Case-3	10,816.4	139.6
75% Infilled Model	Case-4	13,234.5	193.2
100% Infilled Model	Case-5	17,363.8	284.7

Table-4: Seismic base shear at IO performance level for G+15 building models

Building Model Types	Case Designation	Base Shear at IO Performance Level (kN)	Deviation From Case-1 (%)
Bare Frame Model	Case-1	4,784.3	0
25% Infilled Model	Case-2	11,099.2	132.0
50% Infilled Model	Case-3	14,911.8	211.7
75% Infilled Model	Case-4	17,088.7	257.2
100% Infilled Model	Case-5	23,519.4	391.6

6.2. Story Displacements

Seismic performance evaluation is directly related to displacement or deformation and thus estimation of seismic deformation demand is a primary or fundamental concern in performance evaluation of reinforced concrete structures under seismic excitation. The basic analysis approach consists of performing nonlinear dynamic time history analysis for a given structure and ground motion, using three-dimensional nonlinear analysis on SeismoStruct software. The story displacement of the case study building models were studied under randomly selected individual ground motions. Accordingly out of employed 30 ground motions set in the dynamic analysis, 3 (three) ground motions were considered for evaluation of building performance with respect to story displacements.

G+6 Building Model Cases

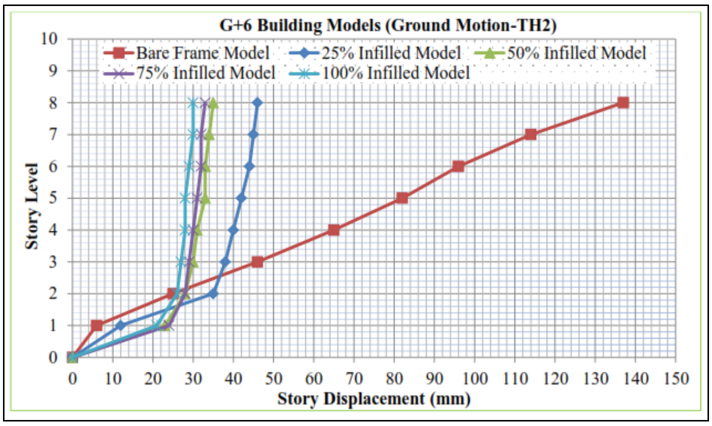


Fig 9: Story displacements of G+6 building model cases under TH-2 ground motion

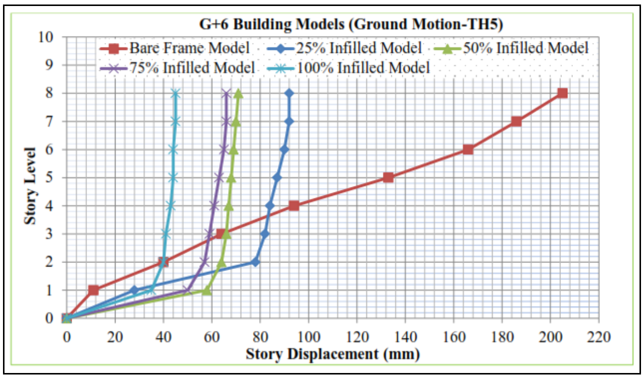


Fig 10: Story displacements of G+6 building model cases under TH-5 ground motion

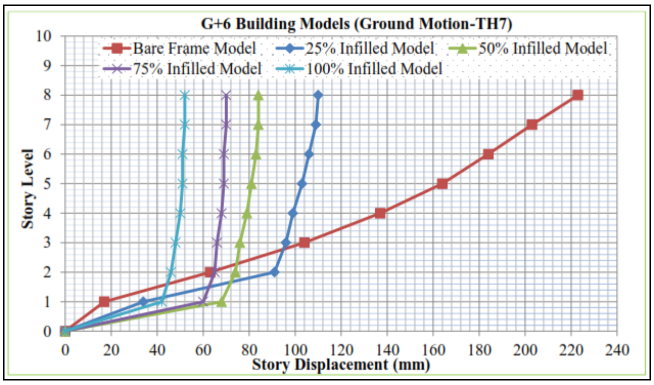


Fig 11: Story displacements of G+6 building model cases under TH-7 ground motion

Under simulated ground motions the bare frame model displaced in largely compared to the infilled models. It was found that the roof displacements of bare frame models are 137, 205, and 223 mm under TH-2, TH-5 and TH-7 ground motions respectively. On the other hand introduction of 25% infills into the bare frame model has considerably reduced the roof displacements to 46, 92, and 110 mm under TH-2, TH-5 and TH-7 ground motion respectively. Further inclusion of infills has reduced the roof displacements to appreciable value.

G+10 Building Model Cases

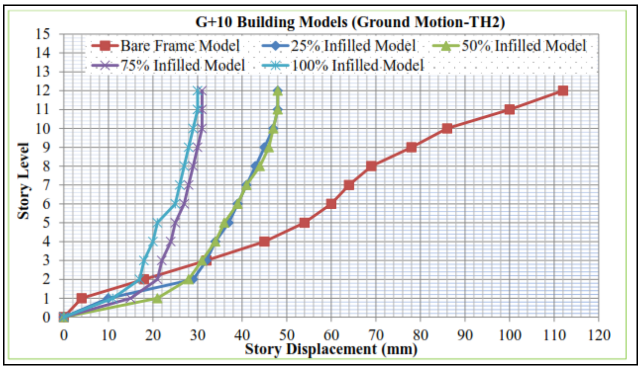


Fig 12: Story displacements of G+10 building model cases under TH-2 ground motion

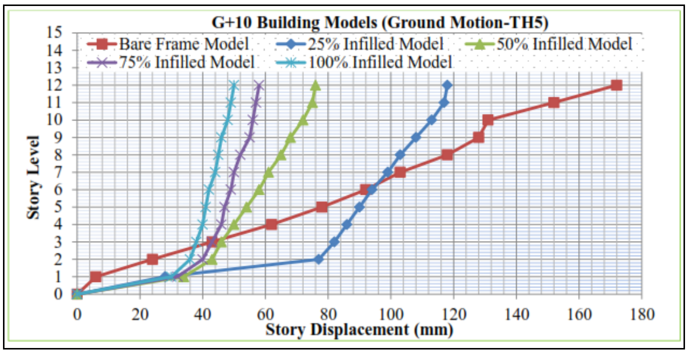


Fig 13: Story displacements of G+10 building model cases under TH-5 ground motion

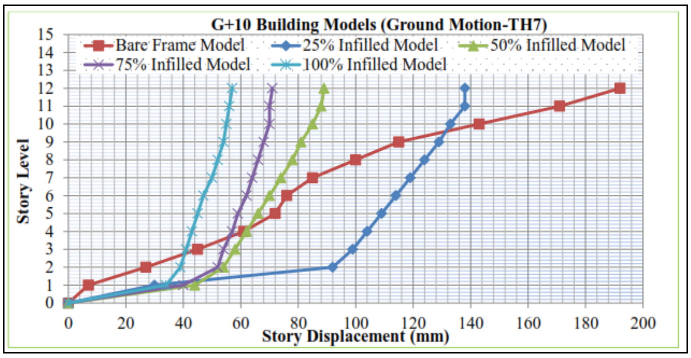


Fig 14: Story displacements of G+10 building model cases under TH-7 ground motion

Under simulated ground motions the bare frame model displaced in largely compared to the infilled models. It was found that the roof displacements of bare frame models are 112, 172, and 192 mm under TH-2, TH-5 and TH-7 ground motions respectively. On the other hand introduction of 25% infills into the bare frame model has considerably reduced the roof displacements to 45, 118, and 138 mm under TH-2, TH-5 and TH-7ground motion respectively. Further inclusion of infills has reduced the roof displacements to appreciable value.

G+15 Building Model Cases

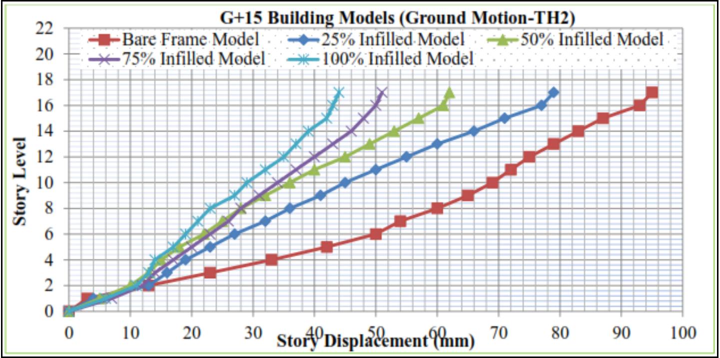


Fig 15: Story displacements of G+10 building model cases under TH-2 ground motion

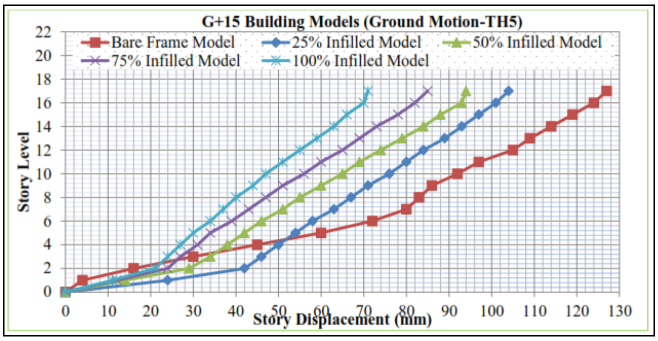


Fig 16: Story displacements of G+10 building model cases under TH-5 ground motion

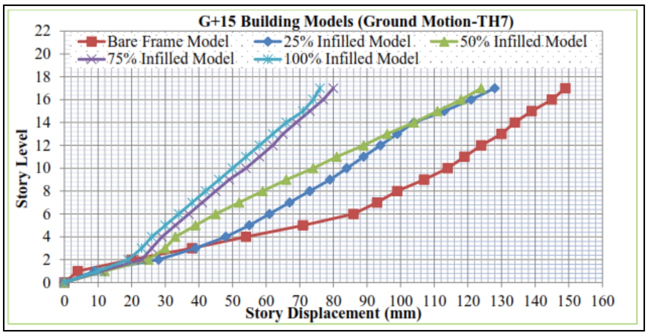


Fig 17: Story displacements of G+10 building model cases under TH-7 ground motion

Under simulated ground motions the bare frame model displaced in largely compared to the infilled models. It was found that the roof displacements of bare frame models are 95, 127, and 149 mm under TH-2, TH-5 and TH-7 ground motions respectively. On the other hand introduction of 25% infills into the bare frame model has considerably reduced the roof displacements to 79, 105, and 128 mm under ground motion respectively. Further inclusion of infills has reduced the roof displacements to appreciable value.

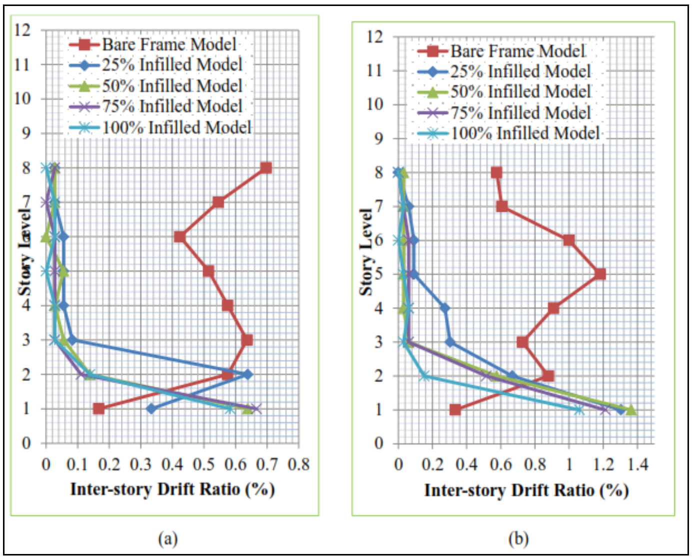
From the investigation of story displacements under the simulated ground motions it was noted that the effect of infills in reducing the story displacements is considerable. Building models with large infills have lesser story displacements and perform well under seismic excitations.

The contributions of infills increase as the number of stories increase and the monitored story displacements would be thus lesser compared with low rise buildings. Thus infills have a significant contribution in arresting large lateral story displacements since their stiffness are participating in lateral load resisting system for externally applied lateral loads.

6.3. Inter-Story Drift

Lateral deflection is the predicted movement of a structure under lateral loads; and story drift is defined as the difference in lateral deflection between two adjacent stories. During an earthquake, large lateral forces can be imposed on structures and it requires that the designer assess the effects of this deformation on both structural and nonstructural elements. It has been recognized that the inter-story drift performance of a multistory building is an important measure of structural and non-structural damage of the building under various levels of earthquake motion.

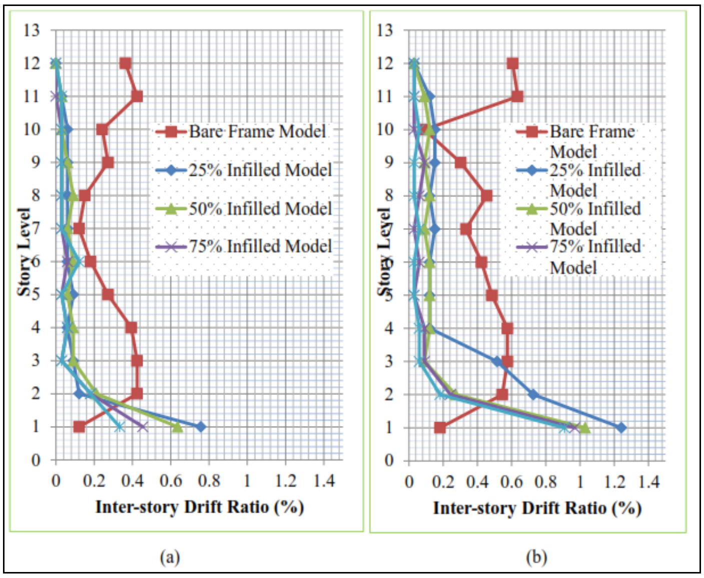
G+6 Building Model Cases



(a) (b)

Fig 18: Inter-story drift ratio of G+6 building model cases (a) under TH-2 ground motion and (b) under TH-5 ground motion

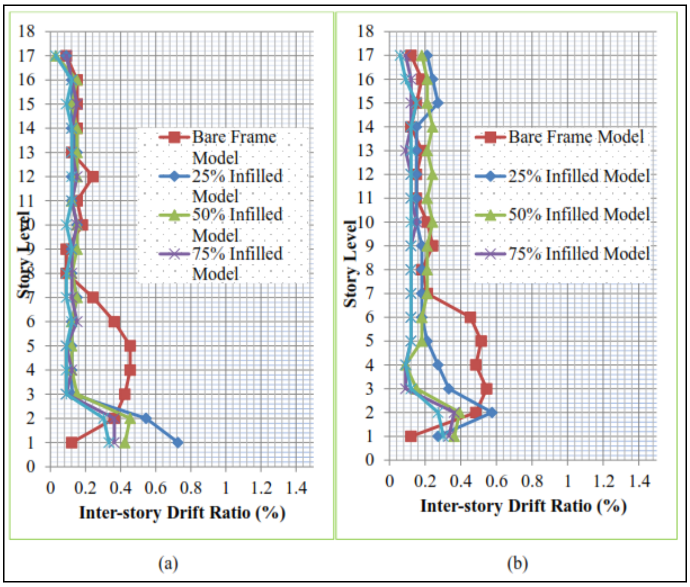
G+10 Building Model Cases



(a) (b)

Fig 19: Inter-story drift ratio of G+10 building model cases (a) under TH-2 ground motion and (b) under TH-5 ground motion

G+15 Building Model Cases



(a) (b)

Fig 20: Inter-story drift ratio of G+15 building model cases (a) under TH-2 ground motion and (b) under TH-5 ground motion

Inter-story drift for the building model cases under randomly selected ground motions were studied and the results showed that building models with infill walls have smaller inter-story drift and this value decreased appreciably above second story. Since the ground and first floors have larger floor displacement as compared to other floors their story drift is somehow grater that the floors above. Bare frame building models have a higher story drift and inclusion of infills into them has substantially reduced the story drifts to appreciable value. The effect of infills is thus considerable in limiting the story drifts experienced in the building structures subjected to seismic excitation.

7. CONCLUSIONS

- The inclusion of infills has shown appreciable increase in seismic base shear at immediate occupancy performance level. 25% infill introduction in bare frame model has raised the seismic base shear to 6,117.80kN (39% increase), 7,488.30kN (65.9% increase) and 11,099.24 (132% increase) for G+6, G+10 and G+15 building models respectively.

- Inclusion of infills has reduced the roof displacements to appreciable value. It was found that the roof displacements of bare frame models are 137, 205, and 223 mm under TH-2, TH-5 and TH-7 ground motions respectively. On the other hand introduction of 25% infills into the bare frame model has considerably reduced the roof displacements to 46, 92, and 110 mm under TH-2, TH-5 and TH-7 ground motions respectively.
- Bare frame building models have a higher story drift varying in between (0.167-0.697) % under TH-2 ground motion and in between (0.333-1.12) % under TH-5 ground motion. But the inclusion of infills into the frame elements has substantially reduced the story drifts to oscillate in the range (0-0.13) % above second floors and about 0.63% up to second floors. The effect of infills is thus considerable in limiting the story drift experienced in the building structures subjected to seismic excitation.

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