# Evaluation of Design Parameters on PBD of RC Buildings with Masonry Infills

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## ABSTRACT

*Masonry infills are provided in almost all residential buildings as enclosure. The building analysis and designs are carried out considering a representative empirical time period. The yield strength of URM infilled frames is much higher, and yield displacement is smaller for bare frames, providing higher ductility. The extent of damage to infill elements define the hazard level imposed and the corresponding risk associated with it. In this paper, the performance of RC building with infills is evaluated using pushover analysis for various seismic hazard levels and loading patterns as per ATC40 & FEMA356 in ETABS. A seven storey regular RC building is located in seismic zone-V (IS1893-0.36 g). The parameters of evaluation include time period formula, modelling technique of infill, masonry units used in practice, and location of openings in building. The code provisions for open ground storey buildings have been evaluated for performance assessment. Under 0.36 g hazard level, the building frame satisfied Life Safety performance objective under the three lateral loading patterns. It is found that AAC masonry blocks least affect the performance of frame elements and also the required failure mode for the structure.*

**Keywords:**
Performance based design; Pushover analysis; Masonry infill; Seismic resistant design; Nonlinear Static analysis; Failure mode control

## 1. Introduction

Design of building structures is in debate since decades. The design fallacies get exposed during an earthquake making the buildings vulnerable to seismic forces and the engineers humbled. The basic requirement for design of buildings is prescribed by each of the design codes of practice. With advancement in the knowledge of earthquake related phenomenon and the behaviour of building under seismic excitation, it is possible to reduce the damage caused by moderate - high level earthquakes using state of the art tools for estimation of seismic hazard, identification of fault locations, experimental studies and development of new design principles.

The damage to a structure generally propagates through the weakest part to the overall building leading to either severe damage or collapse. The buildings are provided with enclosure using masonry infills. Design of buildings with infill panels are carried out in general by adopting a representative empirical formula prescribed by code without actual modelling of the infills. Infill panels are the brittle elements of the system and can cause structural or non-structural damage if not considered in design stage.

The infill walls provide additional strength to the structure. The quality of the masonry work and material used for construction decide the extent to which infills will participate in seismic resistance. Much damage is caused by more frequent small - moderate level earthquakes apart from few high return period severe earthquakes. Many older buildings which are not designed for seismic forces and lack ductile detailing have survived moderate level earthquakes due to presence of infill panels that serve as a medium of damping and source of reserve strength in the structure.

An attempt has been made in this paper to evaluate the performance of a seven-storey building with infill. The building is designed as per the Indian standard code of practice for three-lateral loading patterns. The influence of masonry infill in terms of their strength and modelling procedure on performance of building structure are discussed in detail. Moreover, the performance of open ground storey (OGS) building frames has been studied and the code provision for design of buildings with OGS is checked for the acceptable performance under lateral loading. It is a mandatory step towards physical safety and planning purposes. After the 2001 Bhuj earthquake, the vulnerability of Gujarat state changed, and it now encompasses four hazard levels (0.1 g, 0.16 g, 0.24 g and 0.36 g) for which the structure is evaluated for the later three hazard levels.

This work is in extension to the work carried out by the author on performance based design of reinforced concrete structures [1-2]. The out of plane behaviour of infill is not considered for the present study.

## 2. Subject Review

Many studies have been carried out till date since 19th century for observations on behaviour, analysis and design of building with infill panels. The development of new masonry products leads to different capacity spectrum as per the material behaviour. The performance of infilled buildings has been studied in various sub-domains, and necessary provisions are suggested by code or guidelines for considering it. It is hence important to review the work carried out in independent domains to encompass the associative development.

### *2.1. Evaluation of Strut Models for Building Frames*

Polyakov [3] suggested the possibility of considering effect of infilling in each frame panel as equivalent to diagonal bracing. Holmes [4] and Smith [5] gave equivalent width of strut based on the experimental study. Smith & Carter [6] related the width of equivalent diagonal strut to the infill-frame contact lengths. This equation can be used for lateral load level up to 50% of ultimate capacity. Mainstone and Weeks [7] gave equivalent width of strut for infilled frames which was adopted by FEMA 306. Liauw and Kwan [8] proposed semi-empirical equation for strut model with 25-50° inclination. Paulay and Priestley [9] suggested the equivalent width of strut based on the experimental results and suggested 0.5% drift limit for DBD of infilled frames. Durrani and Luo [10] suggested the width of single strut based on the finite element results and comparison with other models. Thiruvengadam [11] proposed the use of multi-strut as the higher category of modelling infills with panel-frame interaction and openings. Chrysostomou [12] evaluated the performance of infilled frame with six compression inclined struts with three in each direction and the off-diagonal infills located at critical locations forming the contact length of masonry. This model takes into account the strength and stiffness degradation of infill in response evaluation (Figure 1).

Evaluation: A small example of a 2D single bay storey portal frame with and without infill panels based on the formulas suggested for modelling of strut widths will provide insight into the stiffness and time period of frames by eigen solution. The stiffness of infill is given by the expression $\{AE.\cos^2\theta/L\}$ [14]. The columns and beam are 0.3 m x 0.3 m in size. The width (b) and height (h) of the frame is 4 m and 3 m, respectively. The diagonal length of the frame is 5 m. The frame is not provided with any load other than lateral load. The thickness of infill considered is 0.23 m. Unit weight of masonry is 21 kN/m3 (Table 1).

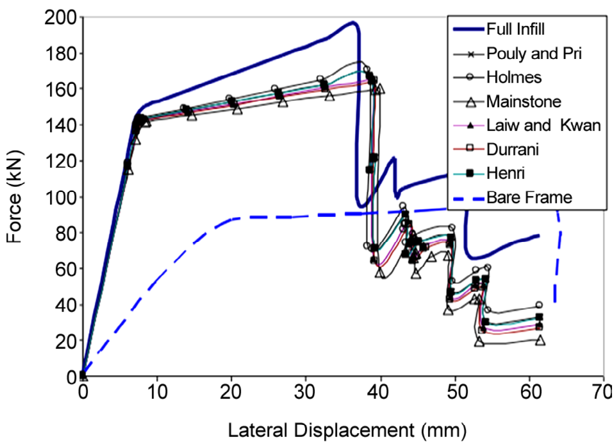


**Figure 1.** Comparison of Various Infill Model Types on Capacity Curves [13].

**Table 1.** Study of effect of strut model on stiffness and time period of portal frame.

| $E = 550f_m^{'} = 2200$ MPa | $A = w \times d = w \times 5$ ($m^2$) | *Mass* = 80.46 kN | $T = 2\pi/\omega$ |
|---|---|---|---|
| **Infill Model Type** | **Expression** | **Stiffness (k)** | **T (s)** |
| IS 1893 [15] | - | 174290 kN/m | 0.135 s |
| Holmes [4] | w = d/3 = 1.67m | 135304.4 kN/m | 0.153 s |
| Smith & Carter [6] | w = λ. h = 1.65m | 133618.6 kN/m | 0.154 s |
| Mainstone and Weeks [7] | $w = 0.175(\lambda h)^{-0.4}$ d = 0.66m | 53447.44 kN/m | 0.243 s |
| Paulay and Priestley [9] | w = d/4 = 1.25m | 101226.2 kN/m | 0.177 s |

## 2.2. Force Transfer Mechanism for Buildings with Infill Walls

In case of buildings with masonry infill, the frame sway mechanism gets restrained till the infill is in effective strength. The stiffness and weight of building is affected by the type of infill used for construction. When using the code time period formula for modelling of the effect of infill, then it provides correct estimate in regular configuration buildings without openings in walls. If the walls have shorter length about the periphery of frame, then the performance has to be evaluated in design stage so that corrective measures can be taken for moderate to high strength infill.

- The short column effect is the reason of damage in many cases as short height walls are built in the panels in contact with column faces [16].
- Buildings with infills modelled as single strut act as braces and lateral loads are transferred as axial forces. It stiffens and makes a tougher system than the relatively flexible frames. The columns experience higher compression and shear stresses [17].
- Buildings with infills modelled as multiple struts have more flexible action as compared to single strut. They affect the contact area, the distance between the struts, and may cause damage to beams, columns or joints. This occurs in case of infills with opening [18].
- In case of open ground storey buildings the moment and shears are transferred to columns at the ground storey level and then transferred to foundations (Figure 2).

## *2.3. Performance and Behaviour*

Following few relevant deductions are mentioned here pertaining to behaviour, testing, modelling, analysis and design of buildings with masonry infill:

- Tiedmann [20] carried out statistical evaluation of non-structural damage to buildings and mentioned that around 85% of loss to buildings with good engineering was due to the damage to non-structural components.
- Liauw et al [21] confirmed the superior characteristics of buildings with infill, if properly designed, to reduce the probability of collapse. The infill that can resist tension, compression and can be connected to bounding frame shall be provided.
- Asteris [22] provided valuable input regarding the failure modes of masonry infill to be considered while modelling the building for seismic performance evaluation. The various in-plane

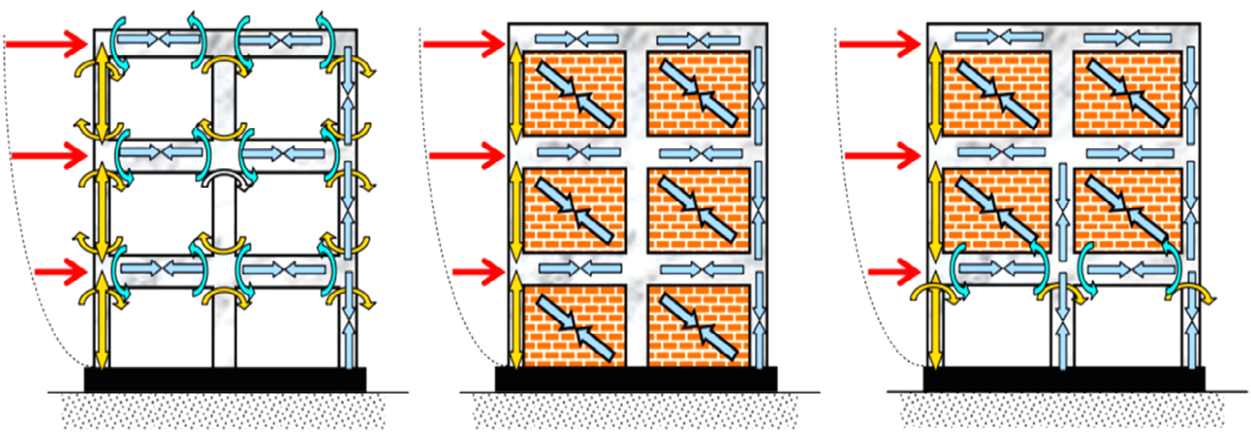

**Figure 2.** Lateral force transfer in RC frame buildings [19].

modes of failure include the compression failure, shear failure of bond and corner crushing. The minimum strength of the infill may be taken for modelling of the masonry strut.

- The building frame with URM infill has about 70% higher strength and has considerable higher ductility as compared to bare frame [23].
- The reason for the failure of many buildings in Bhuj earthquake of 2001 was due to open ground storey (OGS). This makes it imperative to understand and take proper measure in design of buildings with masonry infill [16].
- The equivalent diagonal strut model is a practical engineering tool for the design of infilled frames. The type of strut model adopted can alter significantly the results. Therefore, the strut model characteristics should be selected according to the objective of the analysis [24].
- Various methods of modelling of infills, viz. macro models and micro model with and without frame interaction, are available. It is found that macro models provide a reasonable estimate of the design forces in comparison to the more complex and time consuming micro-models [18, 25, 26].
- The test results show that the stiffness contribution of infill may be neglected if the opening area is 40% more than the area of the frame panel [26-27].
- FEM results showed that vertical load varies the length of beam-infill contact and hence equivalent strut approach shall consider the same [28].
- A three-storey frame was strengthened using infill and experimentally studied to find that the addition of infill walls increased the initial stiffness of structure by 500% and the base shear coefficient by 100%. Quick-crete mortar mix was used in infills (ASTM C 270 type -N mortar) [29].
- The extensive study showed that the fly-ash units are softer than brick units but has the same equivalent ultimate strength and higher deformation capacity [30].
- The strength of masonry infill is dependent on the quality of the masonry units and the mortar used for bonding. The interaction of the infill with frame can be modelled using gap element to simulate the real situation [31].
- The seismic evaluation of infilled building for different guidelines show that eccentric infill model gave satisfactory performance for design earthquake [32].
- An experimental study on damping characteristics of bare frame, masonry infilled, and CFRP retrofitted infills showed damping ratios were found to be 5%, 12% and 14%, respectively. The equivalent damping ratios were estimated based on the iterative energy balance formulation [33].
- Based on the study of 100 mainshock - after shock ground motions on buildings with and without infills, it was suggested that MS-AS sequence increases the seismic demand and shall be considered for risk consideration [34].
- Sucuoglu [35] carried out the comparative assessment of the provisions of EC8 and ASCE41 for frame elements and infills. He suggested for similar damage level at similar compatible performance level. If the building is undergoing 2.5%, 1.2% or 1% drift for different threshold limits, the infills considered as non-structural elements will undergo deformation beyond repair as their threshold limits are far less 0.6%, 0.5% or 0.4%. Hence, moderate level frequent earthquakes may impose threat to URM infills and should be considered by seismic standards to maintain IO performance level.

These deductions suggest the diversity of problems and associated solutions provided for seismic analysis and design of building structures with masonry infills.

## 3. Problem Statement

A seven-storey regular RC building is considered for performance evaluation. The plan of building is shown in Figure (3). The building is 16 m long in X direction (4m c/c) and 12 m wide in Y direction (3m c/c). The typical storey height is 2.8 m and the overall height of building is 19.6 m. The building is considered to be located in seismic zone V having EPGS of 0.36 g as per IS 1893 [15] with medium stiff soil conditions. The infill element is considered by modelling it as wall of thickness of various masonry units available for use in modern construction. The infill is modelled as single strut with equivalent width suggested by Holmes et al [4] and as three strut model suggested by Crisafulli et at [18]. The design of building is carried out using IS 456 [36], IS 1893 [15] and IS 13920 [37]. Seismic

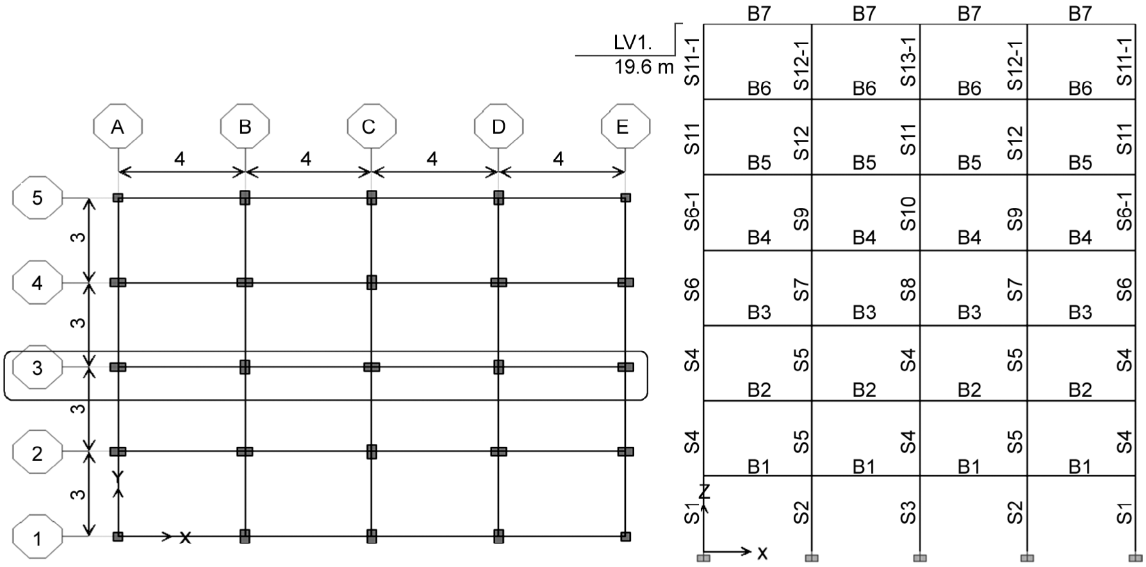


**Figure 3.** Building details - plan, elevation and member nomenclature of seven storey building.

hazard, lateral loading pattern, viz. parabolic, triangular and first mode as per ATC 40 - FEMA 356 [38-39], infill unit types and location are the major parameters for which the performance of building is evaluated using nonlinear static analysis in ETABS software. The linear and nonlinear behaviour of infill is modelled using single-strut and three-strut for performance evaluation of the building. For simplicity, the central representative frame is considered for the performance evaluation as marked in Figure (3), (Table 2).

## 4. Significance of Study

The present study showcases the influence of masonry infills on design and evaluation of building structures. It also presents the effect infill has on the parameters of evaluation. The various experimental and analytical studies carried out to standardize the infill element for design of building structures are used here for the building, viz. equivalent width, modulus of elasticity, masonry strength and failure modes. The effect of each type of masonry unit available for modern construction on performance of building has been shown in detail. The performance of open ground storey building has been evaluated for all the parameters of evaluation for all infill unit types. The strengthening procedure for OGS frames suggested by IS-code is evaluated. The results presented in this literature may be used by design engineers as a reference for in-plane lateral loading condition (Figure 4).

## 5. Compression Strength for Infill Model

The modelling of a building is an essential part of defining a real structure before its analysis can begin. Infills are an inherent part of the structure that contribute significantly in the earthquake response. To model any element of a structure, its size and properties shall be known for which different physical and chemical tests may be carried out on the material forming the element. For this study, the experimental data of the work carried out by eminent researchers in Indian context have been used to simulate the real model.

**Table 2.** Section dimensions of building elements.

| **Beams: 0.6 m × 0.25 m (all)** | | **Columns** | |
|---|---|---|---|
| B1: 0.6 m × 0.25 m | B2: 0.6 m ×0.25 m | S1: 0.6 m × 0.3 m | S2: 0.3 m × 0.6 m |
| B3: 0.6 m × 0.25 m | B4: 0.6 m × 0.25 m | S3: 0.6 m × 0.3 m | S4: 0.6 m × 0.3 m |
| B5: 0.6 m ×0.25 m | B6: 0.6 m × 0.25 m | S5: 0.3 m × 0.6 m | S6: 0.5 m × 0.3 m |
| B7: 0.6 m ×0.25 m | | S7: 0.3 m × 0.5 m | S8: 0.5 m × 0.3 m |
| **Strut Model** | | S9: 0.3 m × 0.5 m | S10: 0.5 m × 0.3 m |
| Diagonal length | 4.88 m | S11: 0.4 m × 0.3 m | S12: 0.3 m × 0.4 m |
| Strut thickness | 0.23 m, 0.15 m | S13: 0.4 m × 0.3 m | |

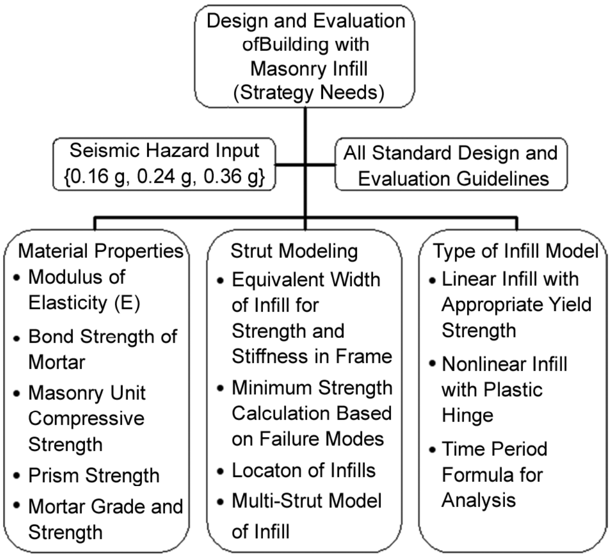


**Figure 4.** Methodology for the infill element in building frame.

Kaushik et al [40] carried out tests on 84 masonry prisms and provided the compressive strength for four masonry units and three mortar grades as shown in Figure (5a). Similar tests were carried out by Bose and Rai [41] to get the compression strength of AAC blocks with high strength bonding mortar as shown in Figure (5b). The results of these tests have been used for modelling of linear and non-linear infill.

## 6. Seismic Demand of Building with Time Period

The base shear of a building is estimated based on its time period. Time period of RC building is calculated for various codes of practice as shown in Table (3). The normalized spectral acceleration ($S_a/g$) is obtained from IS1893 [15] for all time period values. Some differences in the base shear ($V_b$) is observed in each case, which represents the seismic demand. The formula for time period may be referred from the literature of Kaushik et al [42].

The building is designed for the given base shears in ETABS and the capacity curves are obtained for each case as shown in Figure (6). It is seen that the difference in capacity curve is highest in case of building designed as per time period of Columbia code of practice. The capacity curves of the other are nearby each other. The infills are modelled as single strut in this case [4, 9]. The capacity of strut for each failure mode, i.e. diagonal compression and corner crushing, was considered and the lowest value was allotted to the strut to get the capacity curves.

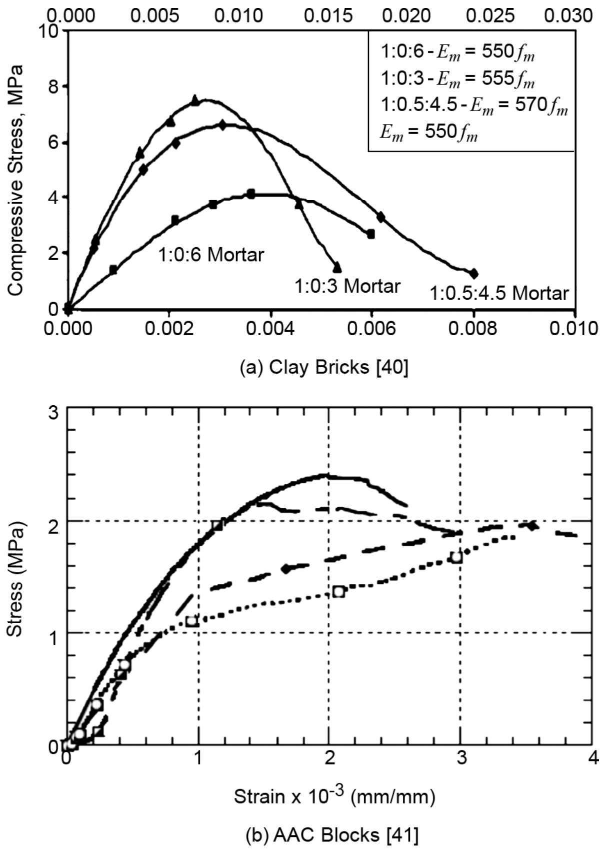


**Figure 5.** Stress-strain curve of AAC and Brick masonry units.

**Table 3.** Effect of code time period of building on base shear.

| Code | Time Period (s) | $S_a/g$ | $V_b$ (kN) = $A_h$ . $W$ |
|---|---|---|---|
| IS 1893, 2002 | 0.44 | 2.5 | 500.6 |
| AFPS, 1990 | 0.18 | 2.5 | 500.6 |
| Costa Rica, 1986 | 0.56 | 2.5 | 500.6 |
| SI 413, 1995 | 0.46 | 2.5 | 500.6 |
| Algeria Code, 1988 | 0.47 | 2.5 | 500.6 |
| Columbia Code, 1998 | 0.65 | 2.09 | 418.5 |
| USA | 0.64 | 2.12 | 424.51 |
| Iran Code | 0.52 | 2.5 | 500.6 |
| Euro Code 8 | OGS Not Recommended | - | - |
| Philippines, 1992 | OGS Not Recommended | - | - |

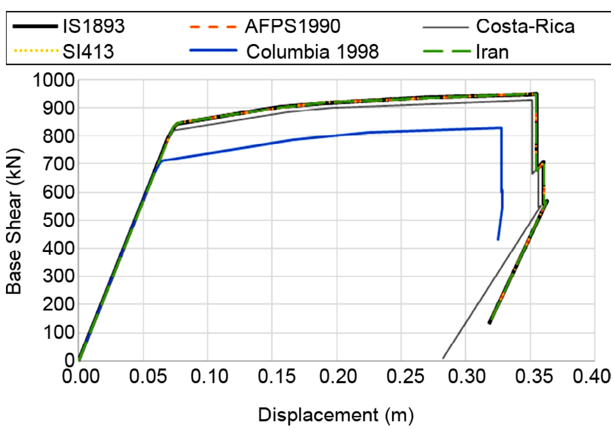


**Figure 6.** Capacity curve for buildings with different code time period formulas.

**Table 4.** Effect of different masonry units on design of G+6 frame [15, 43, 44].

| Type of Masonry | Seismic Weight (kN) | 1st Mode Period (s) | Base Shear (kN) | %Var. |
|---|---|---|---|---|
| Brick Masonry (230 mm) | 4288.15 | 0.793 | 643.2 | 0 |
| Hollow Block (150 mm) | 3195.33 | 0.722 | 479.3 | -25.48 |
| Hollow Light wt. Block (150 mm) | 3033.56 | 0.711 | 455.0 | -29.26 |
| Solid block (150 mm) | 3357.10 | 0.733 | 503.6 | -21.7 |
| AAC Block (150 mm) (With Three Density Values) | 2790.92 | 0.695 | 418.6 | -34.92 |
| | 2844.84 | 0.695 | 426.7 | -33.66 |
| | 2925.72 | 0.70 | 438.9 | -31.76 |

## 7. Seismic Demand on Building with Various Masonry Infills

Many new masonry units are being used to reduce the weight of structure and for thermal insulation. The design of the sample building was carried out for the parabolic loading pattern prescribed by IS 1893 [15] in combination with the gravity loads, i.e. dead load and live load. The seismic weight of the building frame was calculated using five masonry units with reference to the Indian standard as shown in Table (4).

The difference in base shear of buildings with different masonry units are mentioned in the last columns of the table as below. The brick masonry is considered to be the base unit with which other units are compared. The seismic weight of building is lowest in case of AAC masonry units of 150 mm thickness. The capacity curve of the building for various masonry units are shown below for reference to show the effect of masonry unit types on performance of building structures under design or evaluation. It was observed that the base shear in case of building with AAC blocks gets reduced by around 30% (Figure 7).

## 8. Evaluation of Building with Lateral Loading Patterns

In the above cases, the building was evaluated for only parabolic loading pattern and not for other loading patterns like triangular or 1st mode type. If the building is evaluated for the loading patterns suggested by ATC 40 [38] then the structure will be evaluated in shear mode. The building was designed for parabolic loading pattern and detailing of building frame was carried out as per IS 13920 [37]. From Figure (8), the capacity of building is found to be highest in case of parabolic loading pattern while the lowest in case of triangular loading pattern. The strength of building with infill model was found to be 100 kN more than the building with code empirical time period with bare model. From Table (5), it can be said that a building evaluated as per three loading patterns will give three different performance points, i.e. 2% difference. Moreover, it is seen that the difference in ultimate displacement value for building frame without strut model as per IS1893, i.e. 147 mm and the building with strut model i.e. 57 mm, 54 mm.

From above procedure, it was found that the

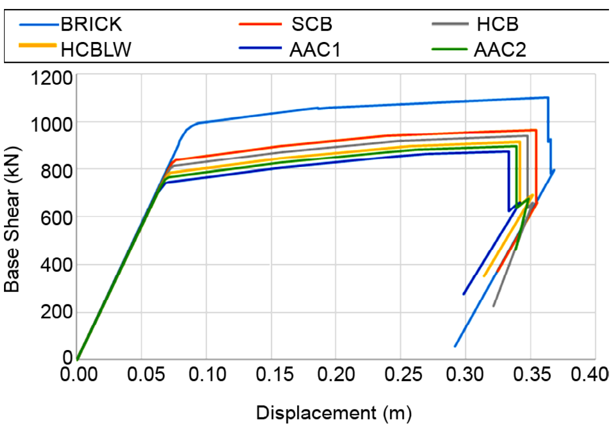


**Figure 7.** Capacity curves for building with five masonry units.

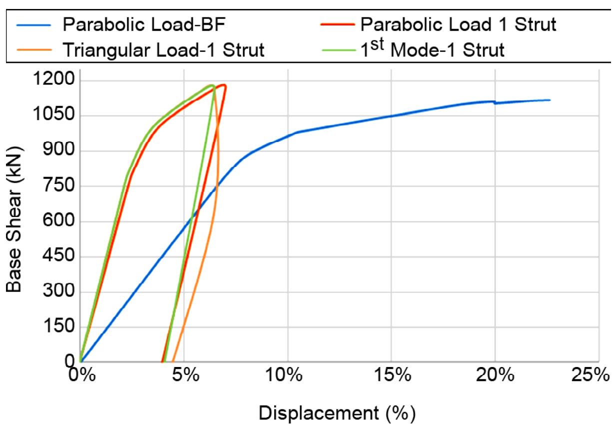


**Figure 8.** Capacity curves of the building with and without infill (linear model).

**Table 5.** Performance of building with three-lateral loading pattern and without infill.

| | Loading Pattern | Hazard Level | Performance Point (V) | Performance Point (D) | Building Class | Rank |
|---|---|---|---|---|---|---|
| | Parabolic (Bare Frame) | (0.16 g)<br>(0.24 g)<br>(0.36 g) | 827.02 kN<br>962.28 kN<br>1045.0 kN | 0.074 m = 74 mm<br>0.100 m = 100 mm<br>0.147 m = 147 mm | IO<br>IO - LS<br>LS | Not Proper Figures |
| 1 Strut Model | Parabolic | (0.16 g)<br>(0.24 g)<br>(0.36 g) | 898.37 kN<br>1032.61 kN<br>1118.97 kN | 0.031 m = 31 mm<br>0.043 m = 43 mm<br>0.057 m = 57 mm | IO - LS<br>LS<br>LS - CP | 1<br>1<br>1 |
| 1 Strut Model | Triangular | (0.16 g)<br>(0.24 g)<br>(0.36 g) | 913.23<br>1043.35 kN<br>1132.50 kN | 0.030 m = 30 mm<br>0.041 m = 41 mm<br>0.054 m = 54 mm | IO - LS<br>LS<br>LS - CP | 3<br>3<br>3 |
| 1 Strut Model | 1st mode | (0.16 g)<br>(0.24 g)<br>(0.36 g) | 912.21 kN<br>1042.48 kN<br>1128.22 kN | 0.030 m = 30 mm<br>0.041 m = 41 mm<br>0.054 m = 54 mm | IO - LS<br>LS<br>LS - CP | 2<br>2<br>2 |

modeling of building for design and evaluation should be carried out based on the flexure behavior for buildings greater than or equal to seven storey from ground level as the larger column length makes it more flexible to undergo deformation as compared to shorter buildings goverened by shear mode. Moreover, if the damping in the structure considering infill as a energy dissipator is increased then the inherent damping in combination with additional damping would be around 10% if moderate infills are used for design [33]. It was also found that the performance point for the extreme event harzard level was obtained for effective damping of greater than 20%, which can happen in few cases and hence damage to infill will take place in linear infill model used for evaluation of the building.

## 9. Modelling of Infills as Multi-Struts

Infills can be modelled using macro-models or micro-models based on the necessity of evaluation. Micro-models provide the complete analysis strategy for infills but requires more time and efforts. Macro-models have been evaluated and compared with FEM results to suggest that the three-strut model can be used for seismic evaluation of buildings with URM infills [25]. The masonry building was modelled using single strut and three strut macro-models for performance evaluation under lateral loading. The performance of buildings was carried out for three lateral loading patterns, i.e. parabolic, triangular and 1st mode shape. The specialist literature may be referred for getting the equivalent width of the strut in each case.

ASCE 41 provides the guidelines for modelling of infills with and without openings. In Figures (9) and (10), the comparison of the capacity curves can be seen and the effect can be visualized in each case. The dynamic analysis of the frame with URM panels provided the time period of the structure to be 0.50 s for single strut infill and 0.52 s for three strut infill model in comparison to 0.44 s as per IS1893.

## 10. Seismic Performance of OGS Frame with Masonry Units

The building was modelled with bricks masonry, AAC masonry and fly-ash masonry blocks for

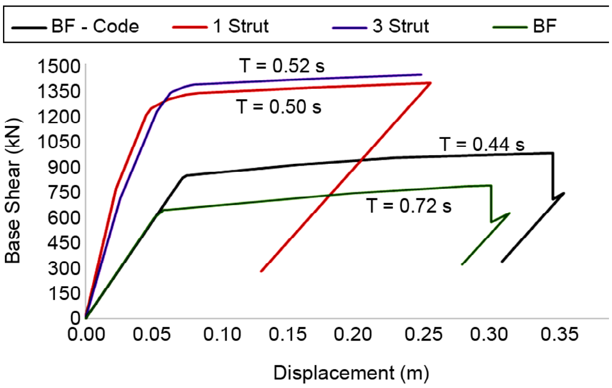


**Figure 9.** Design of buildings with and without linear infill panels.

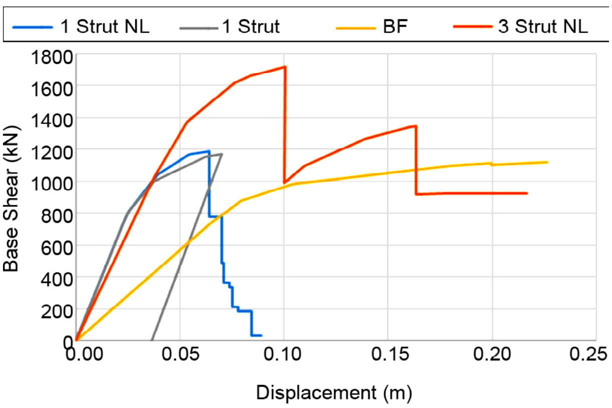


**Figure 10.** Capacity of building with and without non-linear infill panels.

seismic evaluation under zone V hazard level. It can be seen from the capacity curves in Figure (11) that the strength of frames with brick infill is highest and the strength of building with AAC or fly-ash blocks is near about similar. From Figure (12) it can be seen that the building with AAC blocks have the highest ductility as compared to the building with brick infill. If the infill is not modelled, then the ductility of building with brick units is highest. The

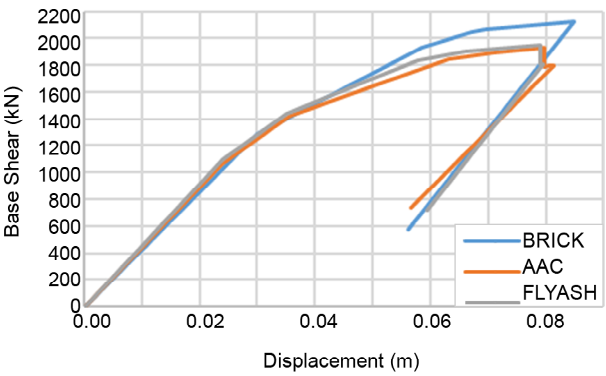


**Figure 11.** Capacity curve for buildings with different masonry units.

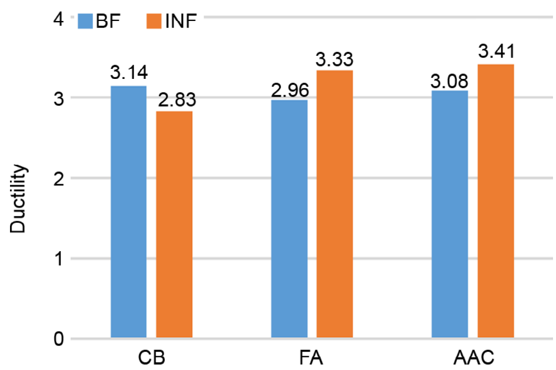


**Figure 12.** Effect of masonry units on ductility of the frame structure.

results shown here are for single strut masonry infill and the similar results can be obtained for multi-strut model. For the three different masonry units, it can be seen that the demand on lowest columns get increased in case of brick and fly ash units as compared to the building with AAC blocks (Figure 13). The performance of building with AAC blocks was found to be in Life Safety objective level under lateral loading action. Thus, it can be said that the buildings with AAC units have a better performance and their effect on structural elements was found to be the least.

## 11. Seismic Performance Regulation of Building with OGS Frame

Open ground storey (OGS) frames are provided in almost whole of India for variety of reasons (mostly parking). Due to the presence of OGS, the lowest storey becomes a soft storey in which the displacement of storey is about 80% of the dispalcement of above three storeys. Earthquakes cause damage to them and the whole structure falls like a person having weak knees. This had been identified in the Bhuj earthquake in many buildings of Ahmedabad city along with other reasons. IS 1893 [15] gives a modification factor (*m.f*) 2.5 to be mutiplied with the bending moments and shear forces of beams and columns of the lowest storey. Kaushik and Jain et al [42] have studied the behavior of buildings with open ground storey and suggested that the above factor may be used for buildings with brick infills but should be relaxed for other masonry units as the seismic demand gets reduced. In this section, the multiplication factor for lowest storey

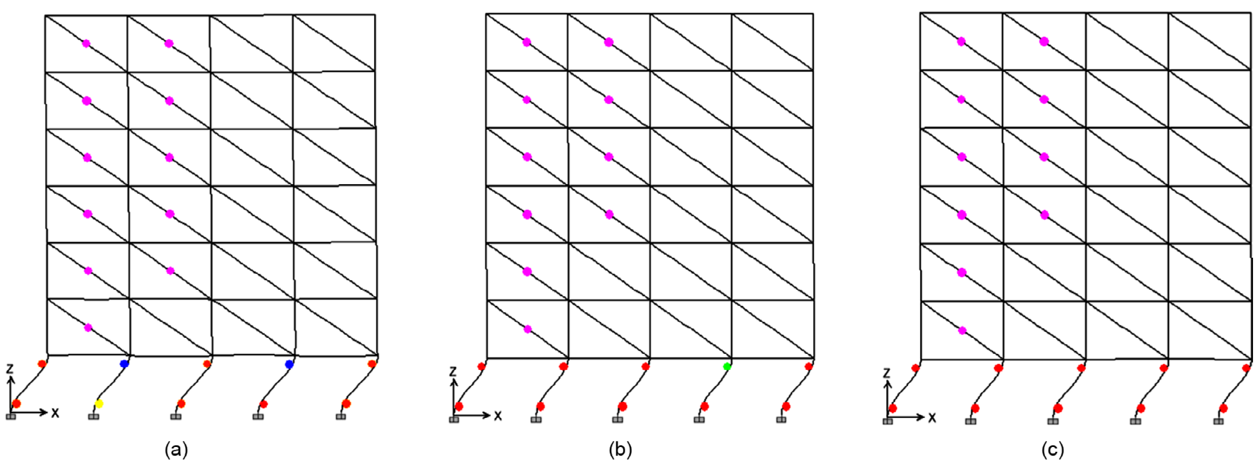


**Figure 13.** Failure mode of building with: (a) Brick units (b) Fly ash units and (c) AAC units.

columns of OGS with brick units, AAC blocks and fly ash blocks have been calculated using Equation (1) in Table (6) [45].

$$\eta = \frac{H_s + \sum V_{col}}{\sum V_{col}} \tag{1}$$

$H_s$ = lateral resistance offered by masonry infill in first storey

$\sum V_{col}$ = summation of shear strength of all columns in first storey

On designing the columns of open ground storey for additional multiplication factor, the reinforcement requirement increased from 2.72% to 4.11% for the frame with AAC blocks. The failure was found to be in ground storey columns, but the performance is enhanced through this procedure. Increasing the size of columns of ground storey further improve the performance of the structure.

**Table 6.** Multiplication factor for OGS columns.

| Masonry Unit | AAC | Clay Brick | Fly Ash |
|---|---|---|---|
| η | 1.50 | 2.21 | 2.88 |

## 12. Seismic Performance of Building with Panel Openings

Various cases of buildings are provided in reality that makes it difficult to model each infill as strut in building structure. The spaces where strut may not be provided will lead to reduction in the overall performance of structure. Considering the location effect, nine cases have been evaluated to understand the effect of opening in performance of structure. The hinge state of building frame can be referred from the figures with the nomenclature FI for fully infilled and PI for partially infilled frames. The capacity of each of the nine cases of infill configuration was obtained, and comparison was made with respect to bare frame profile (Figure 14).

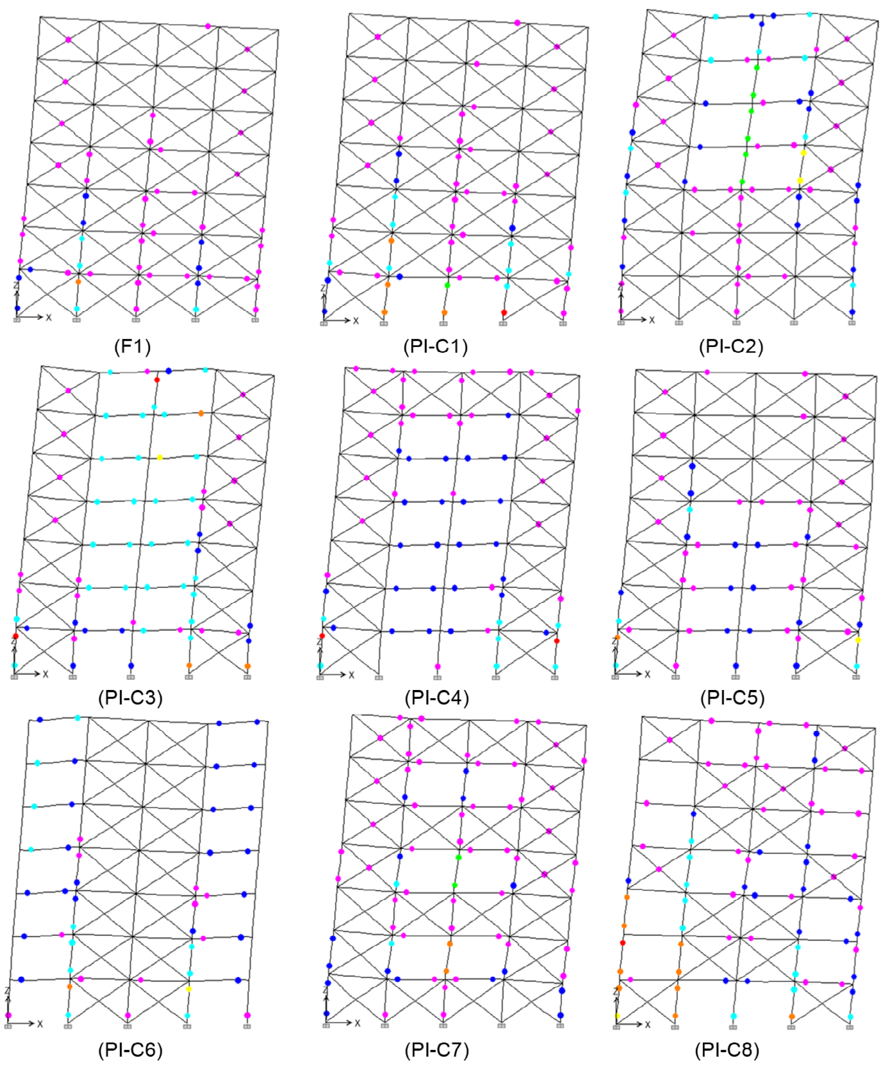


**Figure 14.** Capacity curve for various masonry infill units with openings.

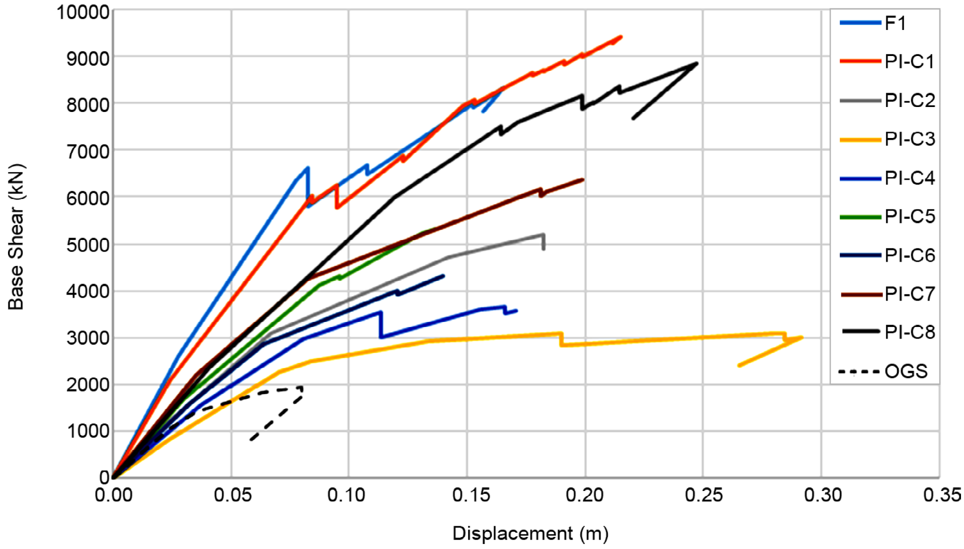


**Figure 14.** Continue

## 13. Performance of Building Elements with URM Infills & OGS

Performance of building elements like columns and beams may be evaluated to understand the significance of infills on them. The bending and shear capacity of columns is mainly evaluated here for display of the effect of various infills on OGS frame. The performance of building frame with brick masonry infill under three lateral loading patterns, viz. 0.16 g, 0.24 g and 0.36 g are shown in Figure (15a, b, c). In bare frame, the moment on the corner columns showed major difference for DBE-0.36g seismic hazard level i.e. 350 kN.m as compared to 450 kN.m for OGS with 1-strut infill. The effect of three lateral loading patterns on the value of moment in corner columns is not significant to be considered separately; however, the shearing force at the base level needs further consideration. The different hazard levels considering foreshock or mainshock may impose different hazard levels to building elements at different height locations and in that case the design of buildings with parabolic loading pattern imposes lesser threat at higher building level. The moment and curvature capacity of corner column S1 is evaluated for the hazard levels as shown in Figure (15e). Three-strut model shows higher capacity than code time period BF model and 1-strut model in Figure (15d). In case of column S1, the design shear reinforcement required for BF model was 95 mm c/c and for 1-strut infill it was 80 mm c/c showing the effect of infill on frame elements.

## 14. Observation and Discussion

Many observations were encountered based on the category of mechanism considered by performance based design and evaluation of seven storey building. The following are the observed points:

- Performance evaluation of building with masonry infill has progressed step by step to include mostly all parameters that are required for modelling of infill element, i.e. modulus of elasticity ($E = 550f_m'$), mortar grades (1:4, 1:5, 1:6), prism strength (bricks, fly ash block, AAC blocks, concrete blocks). The result of grade of infill element will change the results to greater extent (3MPa, 4MPa, 5MPa).
- The performance of buildings with code based procedure without infill model shows high displacement capability while the building model with 1-strut masonry infill shows the increased strength but reduced displacement.
- In the case of building with 3-strut infill model, the strength gets increased along with higher displacement capability than 1-strut infill mode (linear infill).
- In the case of building with infills modelled as nonlinear infill, the significant difference in building performance is visible as the infills get step by step eliminated in pushover analysis.
- For open ground storey buildings, it was found that the infills do not get beyond yield limit as the deformations are mostly taken by the ground storey.

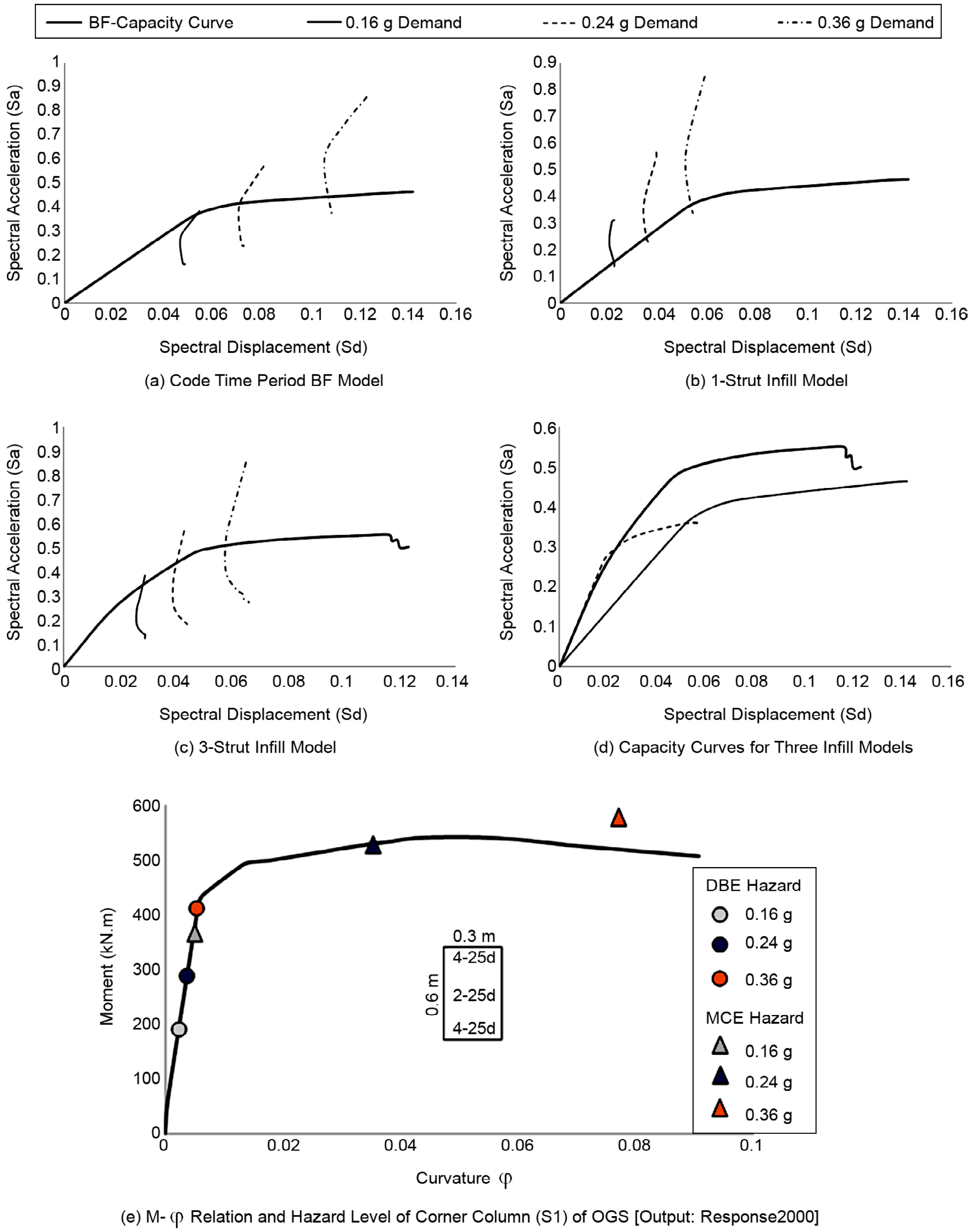


**Figure 15.** Capacity curves of the building and section properties of column S1.

- As seen in the case partial infill (PI) - C8, the systematic orientation of infill mostly covers the strength requirements of buildings. Thus if possible, these infills must be identified as structural element and may not be altered during the building life.
- The modelling of infill element must be done based on the nature of behaviour expected during a seismic event in design stage (linear infill) or in seismic evaluation stage (non-linear infill).
- Capacity-based design concept was applied in this study to make sure that the OGS frames with various infill types satisfy the Life Safety performance objective decided for the building for the design event of 0.36 g.
- When reviewing the concept of contact points for modelling of infills and the gap scenario in infill to frame, one can say that if the theory of contact

points is considered for modelling of infills with openings (3-strut) then region of contact will experience the forces defined in design load combinations.

- Moreover, if the sliding failure of infill is considered as the significant failure mode (1-strut), then the contact region shifts and affects the column shear due to lateral loads.
- In multiple hazard scenario conditions, the infill and frame interaction decides the final state of building for which an accurate model may be put up for design or evaluation.
- The damping obtained from the performance evaluation was found to be 20% or more for the structure which is high as compared to the physical testing carried on frames with infills (10-14%). Hence, proper modelling of masonry infill in correspondence to the test scheme would provide accurate results.

## 15. Conclusion

In this paper, the performance of a seven-storey building was carried out for life safety performance objective under various parameters of evaluation. The outcomes of the study of eminent researchers was put up for infill modelling, i.e. strength and stiffness calculations. The building was evaluated considering state of art test results on masonry units in Indian context. Performance of a structure gets affected by a variety of reasons associated with the infill panels used in construction. The load versus deformation characteristic using pushover analysis gives the indication of overall performance of building under various stages of loading. However, the study of local effects may be carried out to reduce seismic risk. If the mode of infill gets added to the frame for seismic evaluation, then a variety of infill panels utilized till date make the main structural components vulnerable to shearing, as seen from the analysis. Nevertheless, the increased initial stiffness and ductility provide better building performance. The analysis showed that the three-strut model is more flexible than one-strut model frame. The three-strut model induces more demand on OGS level as compared to single-strut model requiring for more strengthening. The performance of a building designed for 0.36 g seismic demand, showed that the building gets shifted from medium to low seismic performance under different hazard levels. It was found that the building with AAC masonry units perform better than buildings with other masonry units in terms of strength, deformation and OGS force increment ($m.f$ = 1.5). The performance of buildings with masonry infills designed as per Indian code was found to be under reliable category if all precautions are duly employed.

The realistic behaviour of old buildings and new buildings with infills require different strategy scheme for seismic evaluation. The performance matrix would make it simple for an engineer to display the effects and take necessary decision under single or multiple seismic excitations. The performance evaluation of a building with out-of-plane action of infill and near-fault effect on infill may be carried out to extend the scope of performance estimation.

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## Appendix A: List of Equations

1. Base shear: $V_b = A_h.W$; seismic weight = $W = DL + 0.25\ LL$; $\frac{z}{2}\frac{1}{R}\frac{S_a}{g}$

2. Lateral load patterns: $Q_i = \frac{w_i h_i^2}{\sum w_i h_i^2} V_b$; $Q_i = \frac{w_i h_i}{\sum w_i h_i} V_b$; $Q_i = \frac{w_i \phi}{\sum w_i \phi_i} V_b$

3. Time period formula IS1893: $T = \frac{0.09h}{\sqrt{d}}$

4. Equivalent strut width (Smith and Stafford): $\lambda = h\sqrt[4]{\frac{E_i t_i \sin 2\theta}{4 E_c I_c h_m}}$

5. Equivalent strut width (Mainstone): $a = 0.175(\lambda h)^{-0.4}$
6. Contact length of infill: $\alpha_m = \dfrac{\pi}{2} h \sqrt[4]{\dfrac{4E_c I_c h_m}{E_m t \sin 2\theta}}$
7. Crushing strength of infill: $R_c = \alpha_c t f'_m \sec\theta$ (kN)
8. Shear strength of infill: $R_s = 0.65\left(\dfrac{L}{h}\right)^{0.6} \times (\lambda h)^{\left(-0.05\left(\frac{L}{h}\right)*0.5\right)} f_{bs} h t$ (kN)
9. Bending strength of columns: $M_{u,\lim} = C_1 f_{ck} bD \times \left(\dfrac{D}{2} - C_2 D\right) + \sum_1^n \dfrac{p_{ibD}}{100}\left(f_{si} - f_{ci}\right) y_i$
10. Bending strength of beams: $M_{u,\lim} = 0.36 f_{ck} b x_u \times (d - 0.42 x_u)$
11. Design shear strength of RC columns IS13920:

$$V_u = 1.4\left[\frac{M_{u,\lim}^{bL} + M_{u,\lim}^{bR}}{h_{st}}\right]$$

12. Design shear strength of RC beams IS13920:

$$V_u = V^{D+L} \pm 1.4\left[\frac{M_{u,\lim}^{A} + M_{u,\lim}^{B}}{L}\right]$$

## Appendix B: Abbreviations

$f'_m$ = compressive strength of masonry prism (MPa)
$E_m$ = modulus of elasticity of masonry (550 $f'_m$ (MPa))
$E_c$ = modulus of elasticity of concrete ($5000\sqrt{f_{ck}}$ (MPa))
$L$ = length of masonry walls in frame void (m)
$h$ = height of masonry walls (m)
$Z$ = zone factor or representative EPGA {0.10;0.16; 0.24;0.36}
$I$ = importance factor of building {1, 1.5}
$R$ = response reduction factor {3,5}
$Sa$ = spectral acceleration
$\theta$ = angle of infill strut w.r.t frame base ($\tan^{-1}(h/L)$)
*URM* = unreinforced masonry
*DBE* = design basis earthquake
*MCE* = maximum considered earthquake
*m.f* = force multiplication factor for OGS columns