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PERFORMANCE EVALUATION OF RC MOMENT RESISTING BUILDING USING MATERIAL STRAIN LIMIT APPROACH

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ABSTRACT

The recent push for performance-based approaches to be used in the design and evaluation of seismically vulnerable structures has greatly raised the need for trustworthy nonlinear inelastic static pushover analysis tools. As a result, in recent years, so-called adaptive pushover methods have been developed. These methods, unlike their conventional pushover counterparts, have the ability to take into account the distribution of seismic storey forces in relation to higher modes of vibration and progressive stiffness degradation. Because infill walls are an integral component of RC structures and increase the stiffness and strength of structures in seismically active areas, seismic evaluation and retrofit of reinforced concrete (RC) structures taking masonry infills into consideration is the suitable methodology. The SeismoStruct software was used to perform a nonlinear static adaptive pushover analysis on a three-dimensional, four-story building with masonry infills. In this study, three models have been taken into consideration: the full RC infilled frame, the open ground story RC-infilled frame, and the bare frame with no infills. A double strut nonlinear cyclic model has been used to simulate the infill walls. The "material strain limit technique" is employed in this work to evaluate the seismic performance of reinforced concrete buildings with masonry infills. This method, which determines the real damage possibilities for the structural members of RC constructions, is based on the threshold strain limits of concrete and steel. Therefore, the purpose of this work is to offer the material strain limit technique as the most efficient method for seismic evaluation and retrofit of any reinforced concrete structure.

Keywords: Nonlinear inelastic static pushover analysis, Adaptive pushover analysis, infill walls, material strain limit.

1. INTRODUCTION

Non-engineered buildings make up a sizable portion of the world's building stock; these structures violate building codes and are susceptible to ground motion, endangering the safety of occupants. Typically made of masonry, these structures are constructed using conventional methods and taking socioeconomic factors into account. However, they frequently fall short of accepted standards for workmanship, materials, and seismic resistance. Additionally, due to a lack of building norms and standards during the past century, construction has been done by trial and error and empirical guidelines, leaving buildings vulnerable to earthquakes. One of the most common and adaptable building materials is masonry infill. In many developing nations, using brick infill walls primarily in RC constructions is the standard method of construction. They are mostly elegant as an architectural point of view and cost-effective. Typically, a "response reduction factor" is used in seismic design algorithms to account for the structure's nonlinearity. The R factor transforms a structure's elastic reaction into an inelastic, or nonlinear, response. In different countries it is identified as “response modification coefficient”. The BIS code provides no detailed explanation of several concerns, such as the impact of taking into account infill walls, structural and geometric configuration, irregularities, etc. Determining the real response reduction factor of RC frame structures for various infill wall configurations as well as the opening in infill walls is the main goal of the current study.

When compared to other approaches now in use, material strains typically provide the best metric for identifying the performance state of a given structure. Because distributed inelasticity (i.e., realistic phenomena) is provided to each structural part in the SeismoStruct software, it is simple to detect the actual damaging phenomena based on the materials in a structure. To check the damage patterns of the structures, the performance criteria based on material strain used in the present numerical simulation are (1) yield strain limit for steel: 0.0025, (2) crushing strain limit for unconfined concrete: 0.0035, (3) crushing strain limit for confined concrete: 0.008, and (5) fracture strain limit for steel: 0.06.

2. LITERATURE REVIEW

M. Shendkar et. al. [1] suggested an approach for seismic evaluation of an RC structure by ‘material strain limit approach’ for the very first time. In order to determine the actual damage scenarios, this method is based on the threshold strain limit of steel and concrete. Also they considered masonry infills to increase the stiffness of the structure in seismically active areas. A double strut non-linear cyclic model has been used to simulate the infills. After the retrofit, a sizable rise in the response reduction factor and structural plan density was seen for open ground story RC infilled frames.

Alguhane et. al. [2] presented their study on the seismic evaluation of a 5-story RC structure with various infill configurations. Four model systems were provided: a bare frame, a frame with infill from a field test, a frame infilled in accordance with ASCE 41, and a frame infilled in conjunction with an open ground story in accordance with ASCE 41. The response modification factor (R) for the five-story RC building was evaluated using the capacity and demand spectra for each model. The authors arrived to the conclusion that while the bare frame does not satisfy the code's (SBC 301) condition, the presence of infill causes the R-factor to increase.

Sadrmomtazi et al. [3] research was centred on seismic evaluation and retrofitting of Sarpole earthquake-damaged structures. The study evaluated a three-story RC building in Iran. They started by gathering background data on the sample construction before performing the NDT. In the end, they came to the conclusion that poor building practises such stirrup spacing, reinforcing bending, and coverings lead to more vulnerable structures. In order to eliminate the disaster impact, it is crucial to monitor the building's precise construction.

Dolˇsek and Fajfar et. al. [4] used the N2 approach to work on the seismic assessment of a four-story RC frame with masonry infills. For the study, three models—a naked frame, a partially infilled frame, and a fully infilled frame—were used. The study's findings suggest that infills can entirely alter the distribution of damage to the entire building, and it may also improve the structural integrity.

Uva et. al. [5] was involved in the seismic assessment of an old RC-framed structure in a high-risk area. Calabria has a seismic risk area. The structure has undergone a test trial to evaluate its quality and current state. Analysis of nonlinear static pushover has been carried out on the infilled frame and bare frame versions. The results of that study recommended that the failure mechanism of the infilled frame was less as compared with the bare frame due to the presence of infill walls.

Cavaleri et. al. [6] researched on how column shear failure will affect RC-infilled structures' seismic evaluation. By modelling infills and the degree of additional shear on the columns using concentric equivalent struts, the seismic performance of the RC structure was assessed. By using concentric struts for the infills, it may be possible to overestimate the structural capacity and the additional shear demand that infills alone for the base columns will provide.

P. T. Aswin, et. al. [7] studied the evaluation of a structure by the application of non- linear static pushover analysis. The structure will always fail when subjected to earthquake loads, according to research using the equivalent static method. All other beams were discovered to pass solely during hogging moments, with the exception of corridor beams which fail in both sagging and hogging situations. When it comes to columns, the ground floor columns in classrooms are strong enough to bend, but the ground floor column in the corridor bends too easily. It was discovered that most beams and columns passed in shear.

El-Betar et. al. [9] worked on two RC constructions in an earthquake-prone area of Egypt. The seismic examination employed case studies of both old and modern school buildings. The study's conclusions suggest that an old school structure would be more vulnerable to harm from a major earthquake. Since the majority of residential buildings were primarily intended to withstand gravity loads in high-earthquake regions, pushover analysis is always required to assess how well the structures perform during earthquakes.

R. Suwondo et. al. [10] Pushover analysis is usually needed to evaluate how well the structures perform during earthquakes because most residential buildings were primarily designed to withstand gravity loads in high-earthquake locations. Pushover analysis is a comparatively straightforward technique for assessing the nonlinear behaviour of the building during an earthquake. Pushover analysis takes into account both geometric and material nonlinearity. A rough method based on static loads, pushover analysis does not require time history information. If the structure is complex, it might not adequately depict a dynamic response. The goal displacement, which is the point where the capacity and demand curves intersect, as well as the hinges created in the beams and columns, determine the structure's performance level.

Arya and Agarwal et. al. [11] outlined the recommendations for seismic assessment and strengthening of existing reinforced concrete structures. It was made evident how the existing buildings were evaluated in depth and at length. According to the report's site visit, data collection, configuration-related checks, and strength-related checks are needed for preliminary evaluation purposes; if all of these tests show that the structure is structurally sound, further comprehensive evaluation is not necessary. For a thorough evaluation, a linear static or linear dynamic analysis is needed to determine the structural elements' demand to capacity ratio. The structural member is deemed a weak member and various retrofitting solutions are used (such as RC jacketing, the installation of infills, shear walls, etc.) if the demand to capacity ratio is more than 1.

Antoniou and Pinho et. al. [12] used an adaptive force-based pushover analysis, where each and every step of the eigenvalue analysis involves a constant change in the lateral load. The SRSS method was used to mix the responses from each mode. The sophisticated static analysis method's spectrum amplification step is essential for updating the load vectors. According to the literature, the record of earthquake ground motion and the amount of damping can be added for the adaptive pushover scenario.

3. METHODOLOGY

The research presented in this study attempts to: (a) study the comparison of conventional pushover analysis with adaptive pushover analysis. (b) investigate actual response reduction factor, ‘*R*’ for irregular RC buildings through nonlinear analysis using seismic parameters such as ductility factor and overstrength factor (c) compare the actual value of ‘*R*’ to that assumed in the design process (d) explore the impact of presence of infills on overall seismic performance of structure (e) analyse the damage pattern of materials based on the demand capacity curves generated and estimate the appropriate failure pattern of material as per given strain limits.

3.1 Pushover Analysis:

The elastic analysis provides a good idea of the overall structure's elastic capacity and pinpoints the location of first yielding, but it is unable to foresee failure mechanisms or take into account the redistribution of pressures during progressive yielding. The elastic analysis is insufficient because they cannot predict the force and deformation distributions after the initiation of damage in the building. The response of the structure is taken into account beyond the elastic limit in performance-based design. By identifying failure modes and the possibility of gradual collapse, inelastic analysis processes aid in understanding how the building actually functions. The static non-linear analysis is one of the analysis techniques used for performance-based design. In recent years, the application of pushover analysis is generally used to check the nonlinear response of structures. It represents a significant alternative solution for nonlinear dynamic analysis of structures. However in the case of a multistoried structure, ignoring the effect of higher modes is one of the limitations of such approaches. Some researchers proposed considering higher mode effects depending on adaptive pushover procedures, which include the increasing variation in the dynamic properties like time period and frequency. For this, the applied load is revised at every incremental action depending on the current dynamical properties of the structure. At each stage of the eigenvalue analysis in force-based adaptive pushover analysis, the lateral load is continuously changed. The record of earthquake ground motion and the level of damping can be included in accordance with the literature for the adaptive pushover situation.

3.2 Elements for Inelastic Infill Panels

For low and medium rise reinforced concrete residential and office structures, a variety of brick infill walls are typically used. Even though brick infill panels change the seismic behaviour of structures, exterior and interior partitioning walls are typically classed as non-structural features. The impact of infill panels may dramatically increase stresses created in various structural sections of the building under earthquake loadings. A particularly dangerous pattern develops in residential and office buildings with ground-floor retail or parking areas, where soft story mechanisms may cause early breakdowns.

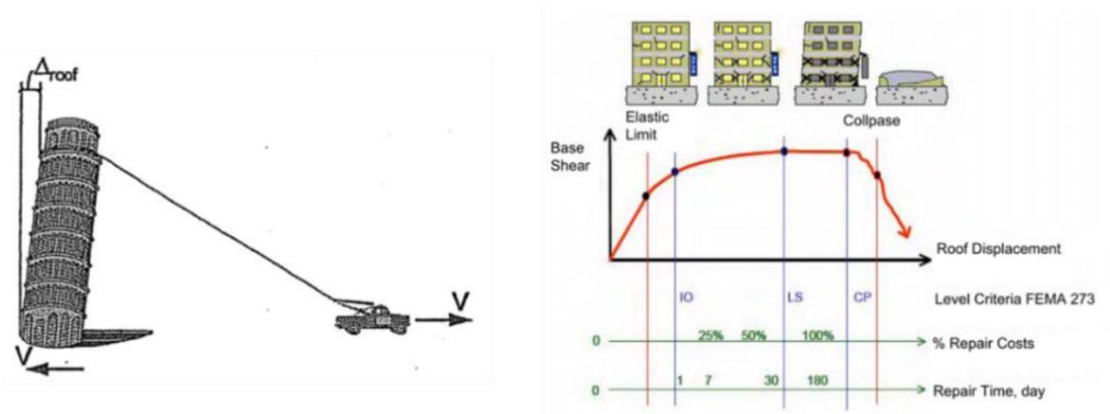

Figure 1: Pushover analysis illustration and pushover curve[7,8]

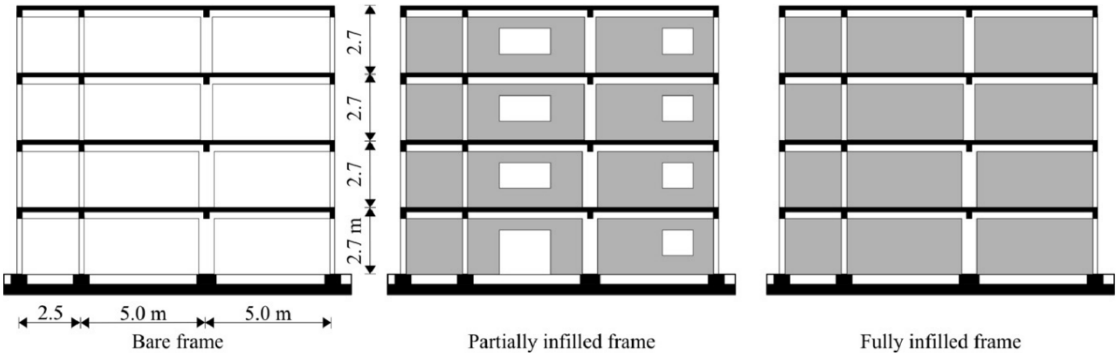

Fig. 2. The elevation view of the studied structures.

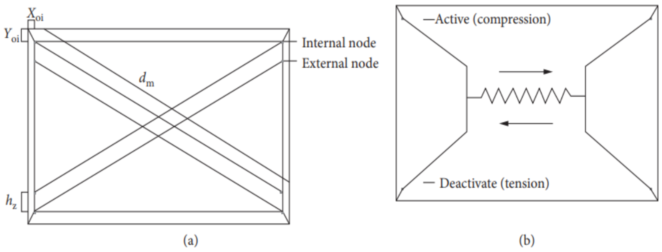

Fig. 3 Inelastic infill panel element

3.3 Response Reduction Factor

Response Reduction Factor is based on the idea that intricate seismic frame systems might withstand significant inelastic deformations without collapsing (ductile behaviour) and acquire lateral strength over their design strength. The *R* factor was first introduced in 1978, and was used to reduce the elastic shear force (V_e) obtained by elastic analysis using a 5% damped acceleration response spectrum for the purpose of calculating a design base shear (V_d). The major static analysis routines are the equivalent lateral force method and response spectrum method; in both procedures, *R* factors are utilized to calculate the design base shear. A review of the literature indicates that the response reduction factor depends on overstrength, ductility and redundancy factors

There are differences in the value of the behavior factors specified in various codes for the same types of structures (ATC-19, 1995; IS 1893, 2016; ASCE, 2005; Eurocode-8, 2004). The parameters indicated in Fig. 3 can be mathematically expressed as:

$$R = \Omega \times R_D \times R_R \qquad (2)$$

where Ω, R_D and R_R stand for overstrength factor, ductility reduction factor and redundancy factor, respectively. By rearranging Eq. (2) and the Indian seismic code provisions, the response reduction factor can be presented as:

$$(2R) = \frac{\text{Elastic strength demand}}{\text{Design strength}} = R_D \times \Omega$$

3.3.1. Overstrength factor

The overstrength factor is used to quantify the difference between the required and the actual strength of material, a component or a structural system. The overstrength factor (Ω) can be defined as the ratio of the actual to design level strength. Mathematically, it can be expressed as:

$$\text{Overstrength factor } (\Omega) = \frac{\text{apparent strength}}{\text{design strength}}$$

$$\Omega = \frac{Vu}{Vd} \qquad (4)$$

3.3.2 Ductility Factor:

It is common knowledge that ductile constructions perform significantly better than brittle structures. A structure with high ductility can experience significant deformations before collapsing. Large structural ductility enables the structure to move as a mechanism while operating at its greatest potential strength, dissipating a substantial amount of energy in the process.

The extent of inelastic deformation experienced by the structural system subjected to a given ground motion or a lateral loading is given by the displacement ductility ratio 'μ' (FEMA-451, 1999). The inelastic behaviour of a structure can be idealized as:

$$\mu = \frac{\Delta max}{\Delta y} \qquad (5)$$

where μ is the displacement ductility, Δ_{max} is the maximum displacement and Δ_y is the yield displacement. Yield displacement and yield base shear are judged through an idealization of the capacity curve

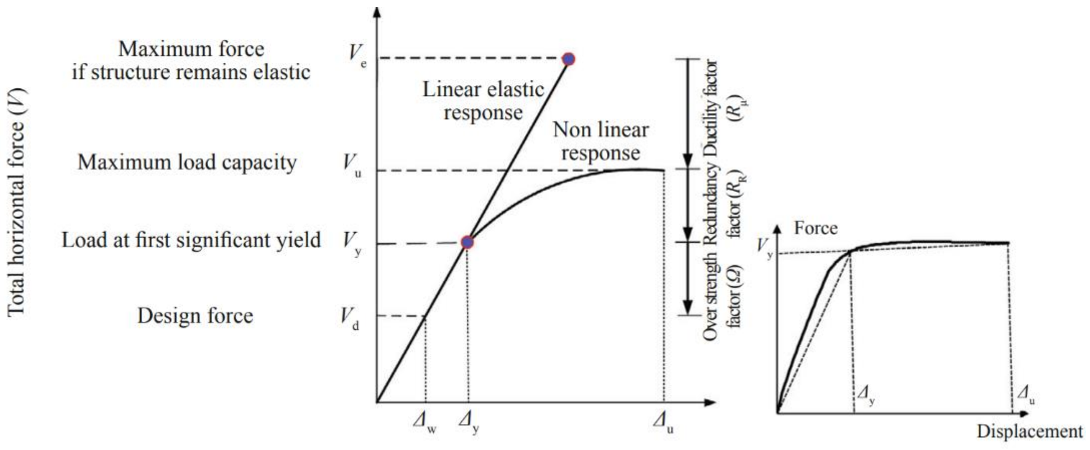

Fig. 4. Interrelation between response reduction factor, overstrength factor, and ductility reduction factor

The R-μ-T relationships developed by Newmark and Hall [22] were used to evaluate R_D as follows:

If time period < 0.2 seconds, $R\mu = 1$

If 0.2 seconds < time period < 0.5 seconds, $R\mu = \sqrt{2\mu - 1}$

If time period > 0.5 seconds, $R\mu = \mu$

3.4 Damage Patterns:

The failure pattern of a reinforced concrete structure is an important aspect to be assessed. Pushover analysis is a static method for calculating seismic structure deformations using a streamlined nonlinear method. When there is an earthquake, buildings remodel themselves. The dynamic forces on a structure are transferred to other components as individual ones give way or fail. By applying loads up until the structure's weak point is identified and then updating the model to account for the changes the weak link has brought to the structure, a pushover analysis replicates this occurrence. The redistribution of the loads is shown in a subsequent iteration. To find the second weak link, the structure is "pushed" once more. This procedure is repeated until a yield pattern is found for the entire structure when subjected to seismic loads.

Many researchers have worked on the failure pattern of the RC frames in several ways. The “material strain limit approach” is the newly developed and most realistic method to identify the damage of the reinforced concrete structures. Based on this approach, it will help to get information regarding the actual damage in the materials of RC structures.

Identification of the performance state of a given structure when compared with other existing methods is possible in the SeismoStruct program because, in this software, the distributed inelasticity (i.e., realistic phenomena) is given to each structural member, so it is easy to identify the actual damage phenomena based on the materials in a structure.

To check the damage patterns of the structures, the performance criteria based on material strain used in the present numerical simulation are (1) yield strain limit for steel: 0.0025, (2) crushing strain limit for unconfined concrete: 0.0035, (3) crushing strain limit for confined concrete: 0.008, and (5) fracture strain limit for steel: 0.06. The different damage states have been described in detail for the different models.

4.MODEL DESCRIPTION

For this study, a three-dimensional four-storey building with different masonry infill conditions has been analyzed with nonlinear static adaptive pushover analysis by using the SeismoStruct software. The building is designed for gravity and lateral earthquake load. Three models have been considered in this study: the first model is a full RC infilled frame, the second model is an open ground storey RC-infilled frame and the third model is a bare frame with no infills. The infill walls have been modeled as a double strut nonlinear cyclic model. Figure 5. shows the building plan, while Figure 6. shows the models of the building. Table 1 provides the structural details of the building.

In the present study, for spectral amplification, we considered the accelerogram time history of the Chi-Chi earthquake (magnitude: 7.6, location: 23.78° N and 121.09° E, and recording station: TCU045) in Taiwan (date: 20 September 1999) taken from PEER database [21] as shown in Figure 7 and its response spectrum is shown in Figure 8. In the present study, adaptive and conventional pushover analyses have been used for comparison purposes, and finally, all the seismic design parameters have been evaluated based only on the adaptive pushover analysis due to its more realistic nature as compared with the conventional pushover analysis.

In this method, different seismic parameters, like zone factor, importance factor, *R*-factor, spectral

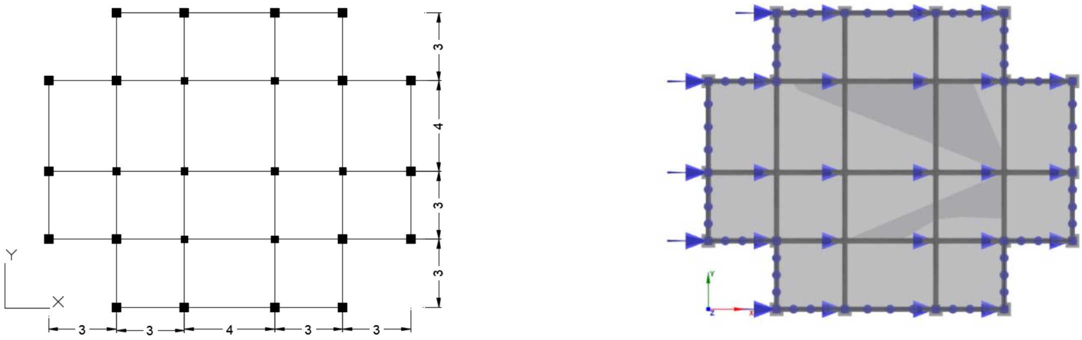

Fig. 5. Plan of the building

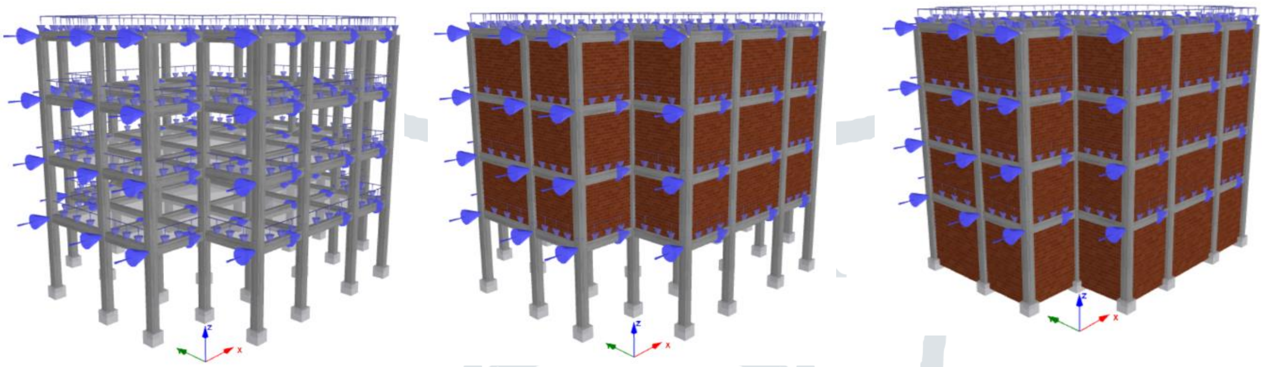

Fig. 6. 3D models (a) bare frame (b) open ground storey (c) full infill frame

Table 1. Structural detailing of building

No. of storeys	4
Seismic zone	III
Floor height	GF- 4m, others - 3m
Infill wall thickness	External – 230mm Internal – 115mm
Compressive strength of masonry	5 MPa
Young's modulus	2750 MPa
Type of soil	Medium stiff soil
Column size	Interior – 300X300
Beam size	Exterior – 380X380
Slab depth	200mm
Live load	4 kN/mm^2
Material	M-25 concrete Fe-415 reinforcement
Damping	5%
Importance factor	1.2

acceleration coefficient, and seismic weight are used to calculate base shear. After the calculation of the base shear, it is distributed at each floor as per IS codal provisions. Subsequently, based on different deformations criteria, e.g., check of the demand (D) to capacity (C) ratio (D/C) a check is done of the deficient members of structures. The following steps are to be followed:

(1) Calculate the design base shear value based on the seismic weight of the structure as per IS 1893 (Part1) : 2016

(2) Distribute the design base shear value at each floor

(3) Perform an adaptive pushover analysis of the structure

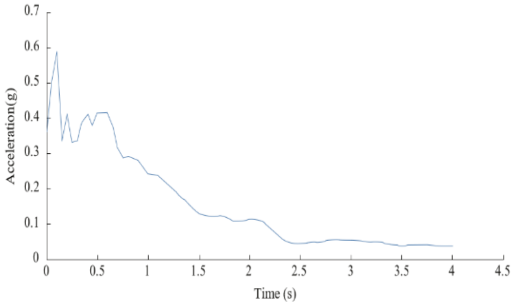

Fig. 7. Acceleration time history of the Chi-Chi earthquake

and the seismic parameters of the structure are calculated

(4) Based on the material strain limits approach (i.e., performance criteria), the deficient members present in the structure can be identified.

The results from the numerical analysis are discussed in this section. In this study, the adaptive pushover and conventional pushover analysis have been used for the simulation of different models. For comparison purposes, we have conducted the two analyses for different models, but the calculation of several parameters like strength, ductility, overstrength factor, and *R*-factor is evaluated only from the adaptive pushover analysis due to the more realistic seismic analysis as compared with conventional pushover analysis. The significance of infills which play an important role in the reinforced concrete frame has been quantified.

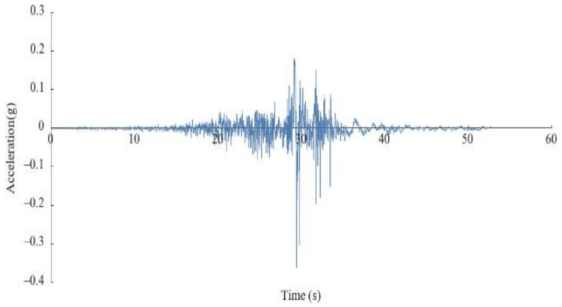

Fig. 8: Acceleration response spectrum of the Chi-Chi earthquake

5. Analysis and interpretation of results

Findings based on Comparison between adaptive and conventional pushover analysis are shown in Fig. 9, Fig.10 and Fig. 11. Estimation of Seismic parameters – ductility, overstrength and response reduction factors and comparison with design response reduction factor is given in detail in Table 3. Analysis of damage pattern based on material strain limits:

To check the damage patterns of the structures, the performance criteria based on material strain used in the present numerical simulation were (1) yield strain limit for steel: 0.0025, (2) crushing strain limit for unconfined concrete: 0.0035, (3) crushing strain limit for confined concrete: 0.008, and (5) fracture strain limit for steel: 0.06. The different damage states have been described in detail for the different models as in Table 4.

Table 2. R values allocated in codes and guideline

Structural system	R- value		
	IS 1893	Eurocode-8	ASCE7
Ordinary moment resisting frame (OMRF)	3.0	-	-
Special moment resisting frame	5.0	-	-
Medium ductility class (DCM)	-	3.0 $V_u/V_y = 3.90$	-
High ductility class (DCH)	-	4.5 $V_u/V_y = 5.85$	-
Ordinary moment frame	-	-	3.0
Intermediate moment frame	-	-	5.0
Special moment frame	-	-	8.0

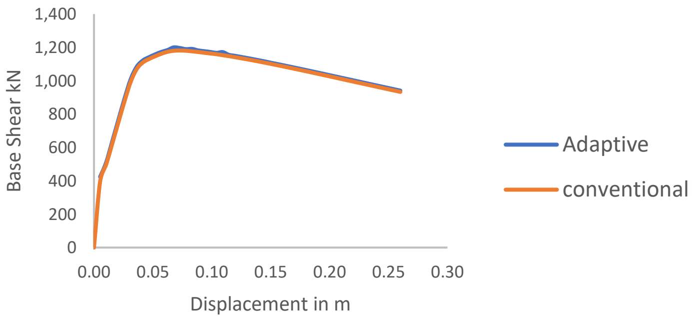

Fig. 9: Conventional and Adaptive Pushover curves obtained for bare frame

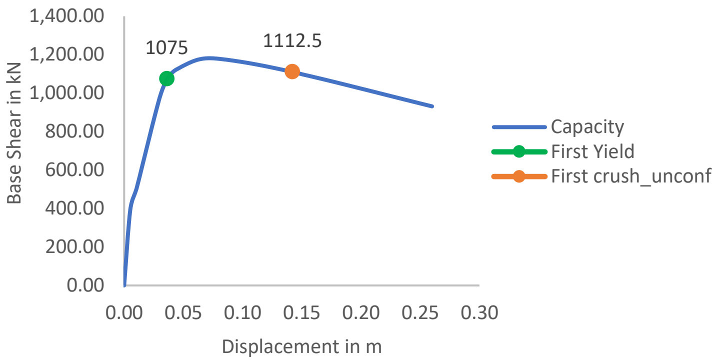

Fig.12: Yield of steel and crushing of unconfined concrete in bare frame

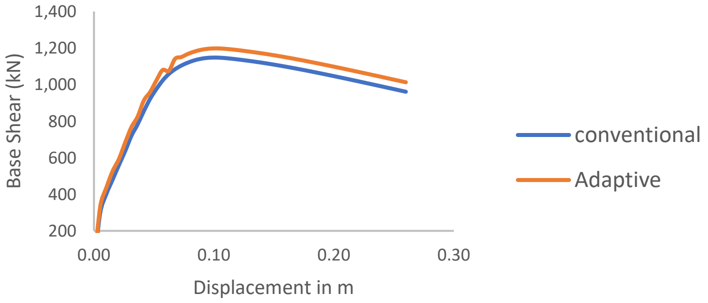

Fig. 10: Conventional and Adaptive Pushover curves obtained for open ground storey frame

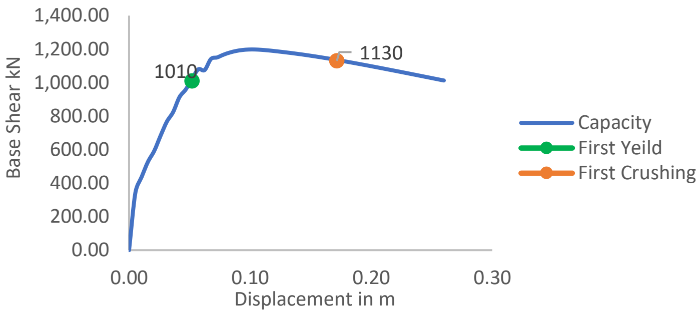

Fig.13: Yield of steel and crushing of unconfined concrete in open ground storey frame

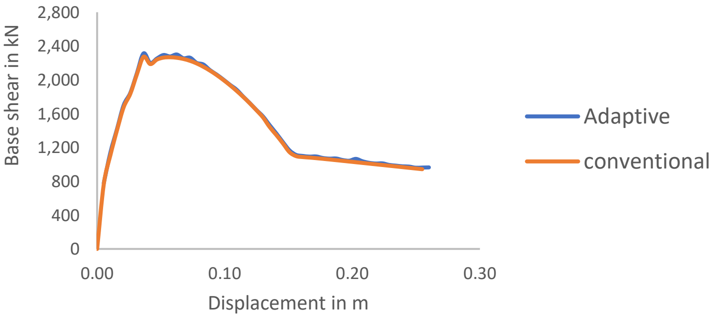

Fig. 11: Conventional and Adaptive Pushover curves obtained for full infill frame

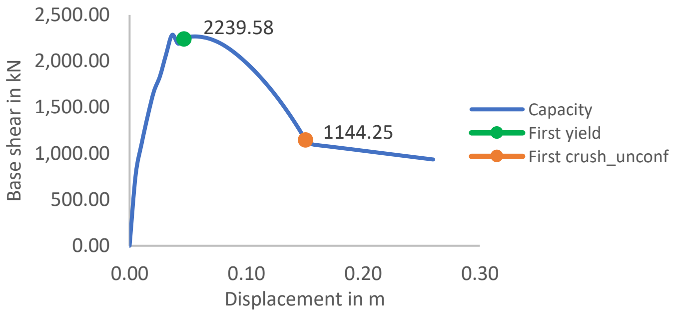

Fig.14: Yield of steel and crushing of unconfined concrete in full infill frame

Table 3. Seismic Parameters: ***Rμ, Ω, R***

Material Strain Level	**Bare Frame**		**Open Ground Storey**		**Full Infilled frame**	
	Displacement	**Base Shear**	**Displacement**	**Base Shear**	**Displacement**	**Base Shear**
First yielding of steel	52	975.25	36	1075	46.8	2239.58
First crushing of unconfined concrete	171.6	1083.86	142	1112.5	150.8	1144.25

Table 4. Damage pattern for different infill conditions

Parameters	Bare Frame	Open Ground Storey	Full Infilled frame
Ultimate capacity	1197.70 kN	1381.53 kN	2283.31 kN
Yield displacement	69.5 mm	60.1 mm	22 mm
Maximum Displacement	98.8 mm	72.8 mm	36.4 mm
Ductility	1.42	1.21	1.65
Ductility reduction factor($R\mu$)	1.35	1.19	1.51
Overstrength factor(Ω)	5.24	3.61	6.17
Time period	0.29 s	0.29 s	0.29 s
***R*-factor**	3.53	2.14	4.65

1. Bare Frame

The first yielding of reinforcing steel occurred at base shear of 975.25 kN and displacement of 52 mm. First crushed unconfined concrete, i.e., spalling of cover concrete occurred at base shear of 1083.36 kN and displacement of 171.6 mm.

2. Open Ground Storey

The first yielding of steel occurred at base shear of 1075 kN and displacement of 36 mm. First crushed unconfined concrete, i.e., spalling of cover concrete occurred at base shear of 1112.5 kN and displacement of 142 mm.

3. Full Infilled Frame

The first yielding of reinforcing steel occurred at base shear of 2239.58 kN and displacement of 46.8 mm. First crushed unconfined concrete, i.e., spalling of cover concrete occurred at base shear of 1144.25 kN and displacement of 150.8 mm

6. Conclusions

Most seismic design procedures include the nonlinear response of a structure through the use of a response reduction factor. This allows a designer to use a linear elastic force-based design while accounting for nonlinear behaviour and deformation limits. In fact, the response reduction factor is used in modern seismic codes to scale down the elastic response of a structure., the beam column capacity ratio on the building ductility. Identification of the performance state of a given structure when compared with other existing methods. It is possible in the SeismoStruct program because, in this software, the distributed inelasticity (i.e., realistic phenomena) is given to each structural member, so it is easy to identify the actual damage phenomena based on the materials in a structure.

1. The pushover analysis proves to be an effective tool to assess the seismic behaviour of RC structure due to its ease of calculations and easy to understand procedure.
2. Pushover analysis done by considering the effects of higher modes of vibrations rather than just first mode gives more reliable and accurate results.
3. Conventional pushover analysis and adaptive pushover analysis when compared together shows slight variation in base shear and displacement.
4. The values of base shear and displacement based on different infill conditions when compared shows that infills provide more stiffness to the structure thus improving the overall performance of the structure under seismic activity.
5. The results also show that the ‘*R*’ factor is sensitive to both geometric configuration and material strength.

6. It is also evident that the stiffer the frame, due to the geometrical and structural configuration, the greater the ‘*R*’ value.
7. The computed values of ‘*R*’ obtained by employing nonlinear analysis for different geometrical configurations is less than those suggested in the IS 1893 (2016).
8. Bare frame and open ground storey frame gives R-value less than what they are actually designed for whereas in case of full infill frame the computed R-value is found to be higher than what is suggested in the IS 1893 (2016).
9. The provided strain limits for the predicting failure of concrete and steel gives the actual failure points of structure in terms of first yielding of steel and first unconfined crushing of concrete.
10. For the members found weak in performance criteria check suitable local and global retrofit options can be suggested.
11. The base shear is lower in the open ground storey RC infilled frame as compared with the full RC-infilled frame due to the absence of masonry infills at the ground storey.

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