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Evaluation of seismic response of soft-storey infilled frames

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Abstract. In this study two single-bay, three-storey space frames, one with brick masonry infill in the second and third floors representing a soft-storey frame and the other without infill were designed and their 1:3 scale models were constructed according to non-seismic detailing and the similitude law. The models were excited with an intensity of earthquake motion as specified in the form of response spectrum in Indian seismic code IS 1893-2002 using a shake table. The seismic responses of the soft-storey frame such as fundamental frequency, mode shape, base shear and stiffness were compared with that of the bare frame. It was observed that the presence of open ground floor in the soft-storey infilled frame reduced the natural frequency by 30%. The shear demand in the soft-storey frame was found to be more than two and a half times greater than that in the bare frame. From the mode shape it was found that, the bare frame vibrated in the flexure mode whereas the soft-storey frame vibrated in the shear mode. The frames were tested to failure and the damaged soft-storey frame was retrofitted with concrete jacketing and, subjected to same earthquake motions as the original frames. Pushover analysis was carried out using the software package SAP 2000 to validate the test results. The performance point was obtained for all the frames under study, therefore the frames were found to be adequate for gravity loads and moderate earthquakes. It was concluded that the global nonlinear seismic response of reinforced concrete frames with masonry infill can be adequately simulated using static nonlinear pushover analysis.

Keywords: reinforced concrete frames; soft-storey frame; shake table test; pushover analysis; seismic response; masonry infill.

1. Introduction

Many multi-storey buildings have open first storey as an important functional requirement. This is primarily being adopted to accommodate car parking. The frame bays in the ground storey are not infilled with masonry infills as it is done in the upper storeys. This open ground storey causes stiffness related soft-storey effect and strength related weak-storey effect, resulting in large earthquake demands and discontinuity in flow of lateral earthquake forces in the open ground storey. Recent earthquakes that occurred have shown that a large number of existing reinforced concrete stilt buildings are vulnerable to damage or even collapse during a strong earthquake. The

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soft-storey effect can happen also in uniformly infilled reinforced concrete frames, which was observed in the Kocaeli earthquake. The risk, measured both in terms of lives and property is very high. Hence, it is necessary to assess the vulnerability level of existing multi-storeyed buildings so that they can be retrofitted to possess the minimum requirements. This will help in minimizing the impending damages and catastrophes.

To evaluate the seismic performance of existing reinforced concrete frames, Indian code IS 1893 (Part I): 2002 "Criteria for Earthquake Resistant Design of Structures" provides both linear static (seismic co-efficient method) and linear dynamic (response spectrum method) procedures. Almost all the building codes adopt the static method of analysis because of the simplicity of its application. For important and complicated structures this method is only useful for the preliminary design. When a structure is large with significant irregularities, the seismic forces are determined based on dynamic analysis, usually a response spectrum analysis. The mass of each storey is replaced by a lumped mass at each floor level. Eigen value analysis is performed to obtain the natural frequencies and modes of the system.

Several researchers have investigated the behaviour of soft-storey reinforced concrete frames under seismic loading. Vasseva (1994) carried out a seismic analysis of frames taking into account the geometrical nonlinearities. The analysis of frame with a flexible first storey showed that the maximum displacements and restoring forces occurred at different time steps and the influence of large axial forces was very strong on the behaviour of structures. Arlekar, *et al.* (1997) highlighted the importance of explicitly recognizing the presence of the open first storey in the seismic analysis of buildings. The error involved in modeling such buildings as complete bare frames, neglecting the presence of infills in the upper storeys, was brought out with different analytical models. Elnashai (2001) analyzed the dynamic response of structures using static pushover analysis. It was suggested that the nonlinear static analysis can be used only as an alternative to predict the dynamic response of structure. The static nonlinear analysis results obtained were closer to the inelastic time-history analysis.

Dolsek and Fajfar (2002) presented a mathematical model of a three-storey reinforced concrete framed building with infill in the bottom two storeys using DRAIN-2DX. It was concluded that it is possible to obtain a fair simulation of displacement time-history with a wide range of mathematical models. However, a model which simulates both the displacements and the shear forces requires appropriate modeling of both the force-displacement relationships and the hysteretic rules of the diagonals representing the infill. The lateral stiffness of brick masonry infilled plane frames was analyzed by Asteris (2003). The influence of the masonry infill panel opening in the reduction of the infilled frame stiffness was investigated by means of a new finite element technique. Kanitkar R. and Kanitkar V. (2004) studied a five-storey building with soft storey with the intent of reviewing the new provisions for the earthquake resistant design of structures addressed in the code IS 1893:2002. It was observed that although the new soft storey provisions of IS 1893 are a step in the right direction, more investigations are required to completely define the resulting stilt buildings in terms of their ductility capacities and stable inelastic action under the expected seismic loads.

The information available on the behaviour of reinforced concrete frames are generally limited to two-dimensional frames and are mainly based on the results of quasi-static or pseudo-dynamic tests. In reality, the structures are three-dimensional and two-dimensional model studies can only approximately predict the behaviour of the prototype. Moreover, the complete understanding on the behaviour of structures can be obtained only through taking into account the dynamic nature of their seismic response. Therefore, more research is required to understand the global behaviour of structures subjected to dynamic loading. Towards this objective, analytical and experimental investigations are carried out on reinforced concrete space frames to study their seismic performance.

2. Experimental investigation

2.1. Frame details

Two one-bay, three-storey space frames, one with brick masonry infill in the second and third floors representing the soft-storey and the other without infill were selected for the study. Their models were fabricated to 1:3 reduced scale according to similitude law based on the capacity and dimension of the shake table used in the earthquake simulation tests. The plan dimension of the model was 1.5×0.75 m and the total height of the model was 2.90 m. The isometric view of the frames is shown in Fig. 1.

The grade of concrete used in the model was M 20. Since smaller aggregates were used for the model, concrete mix design was done according to ACI 211.1:1991-American Concrete Institute Guideline for Concrete Mix Design to achieve the required design strength. Fe 550 grade 5 mm ϕ reinforcing bars were used in the model corresponding to the Fe 415 grade 16 mm ϕ reinforcing bars used in the prototype. The infill chosen was ordinary clay bricks constructed in English Bond with openings for doors and windows. Horizontal bands are the important earthquake-resistant feature in buildings. It is known from past experience that the buildings with lintel band sustained the shaking very well with hardly any damage. Hence, a reinforced concrete continuous lintel was provided in the second and third floors in both the frames.

The compressive strength of concrete was determined at every stage of fabrication of the frames. The average compressive strength and unit weight of concrete cubes were found to be 30.79 N/mm^2 and 25.57 kN/m^3 respectively. The yield and ultimate strength of Fe 550 steel was found as 657 N/mm^2 and 687 N/mm^2. The compressive strength of brick masonry was found as 3.3 N/mm^2 and its Young's modulus was 0.1231×10^4 N/mm^2. Fig. 2 shows the reinforced concrete frame models with and without infill. The reinforcement detail of the frame is shown in Fig. 3.

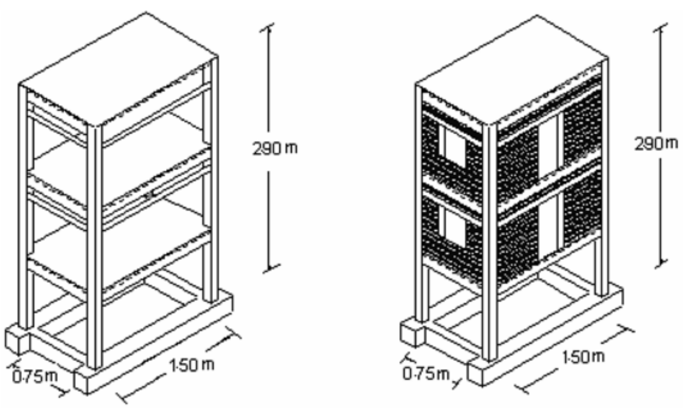
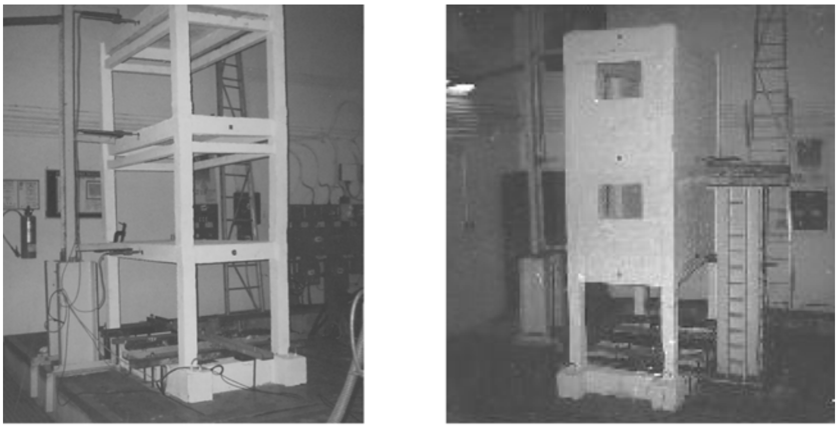


Fig. 1 Isometric view of the frames



(a) Bare frame (b) Soft-storey infilled frame

Fig. 2 Reinforced concrete frame models

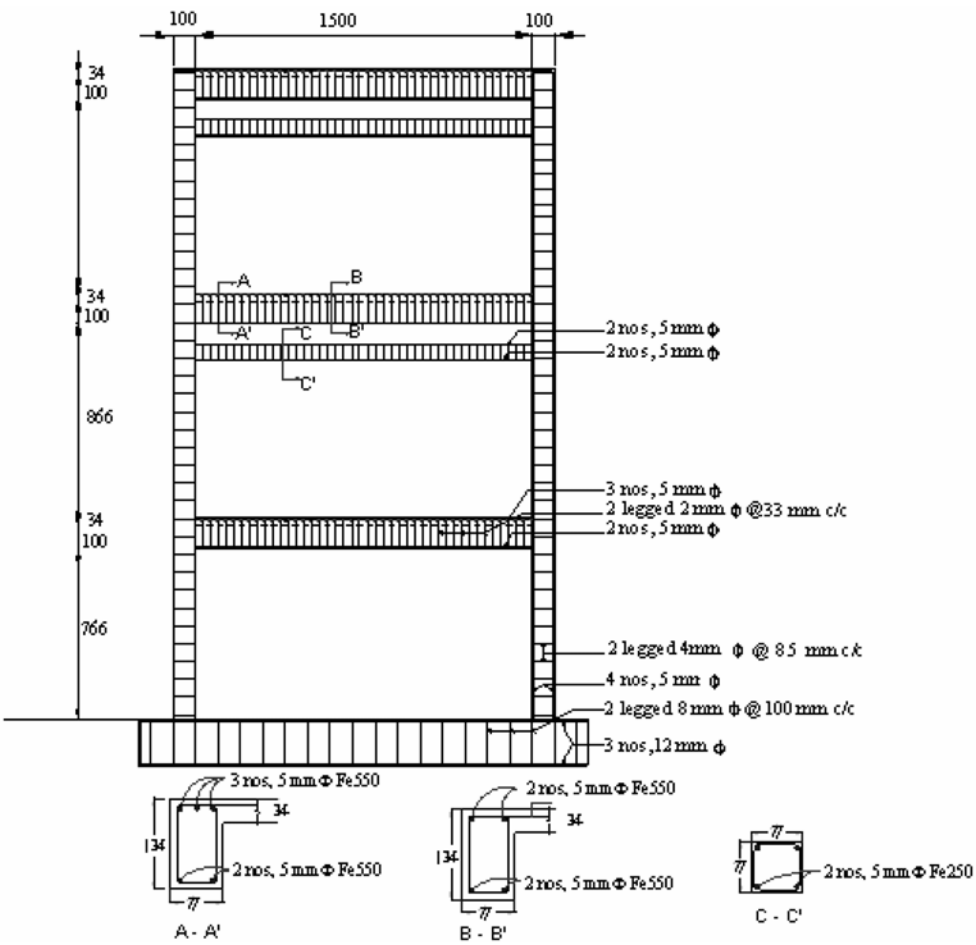


Fig. 3 Reinforcement details of the frame

2.2. Test program

The instrumentation for the shake table tests consisted of Accelerometers and Linear Variable Differential Transducers (LVDT) to measure the accelerations and the horizontal displacements of the frames respectively. Sweep sine test was carried out for the models to determine the system characteristics. The sweep was started at 2 Hz and went upto 100 Hz with a sweep rate of 0.01Hz/sec to fulfill the requirement of a steady state excitement and response. The acceleration data collected from the pair of accelerometers in the form of charge were transformed into voltage by compatible signal conditioners and sent to the 2-channel FFT-analyzer. The FFT analyzer computed the ratio of Fourier Spectrum between the base acceleration and the storey acceleration and directly transformed it to a frequency spectrum and the frequency response function (FRF) curves were obtained. Using the FRF curves, the resonant frequencies, mode shapes and corresponding modal damping values of the building frame were evaluated. The shake table used in the study was displacement controlled and the excitation was applied uni-axially. Fig. 4 shows the shake table of size 2.5 m $\times$ 2.5 m and weight 3 T on which the tests were conducted.

Seismic excitation tests were conducted by way of applying a spectrum compatible displacement time history of 60 second duration to the frame models along the transverse direction through the shaking table. The models were tested for simulated earthquakes of intensities 0.1 g, 0.16 g, 0.36 g, 0.56 g, 0.76 g and 0.96 g. The responses of the frames were collected by Accelerometers and Linear Variable Differential Transducers (LVDT) and were directly fed into a digital computer and thus giving time histories of the acceleration and displacement at each storey level of the frames.

Higher intensities of earthquake motions were applied to cause failure of the frames. During the lower level of earthquakes, minor cracks were detected at the top and bottom of the ground floor column and there were no cracks in the second and third floors. When the excitation was 0.96 g, a hinge was formed at the top and bottom of the ground floor column in both the frames; spalling of concrete cover near beam-column joint was also seen. Fig. 5 shows the damaged frames due to the excitation of different intensities of earthquakes.

The damaged infilled frame was repaired and strengthened by providing reinforced concrete jacketing at the base of the columns in the ground floor and additional shear reinforcement at the beam-column joint in the first floor. Since there was no significant damage in the brick infill, the

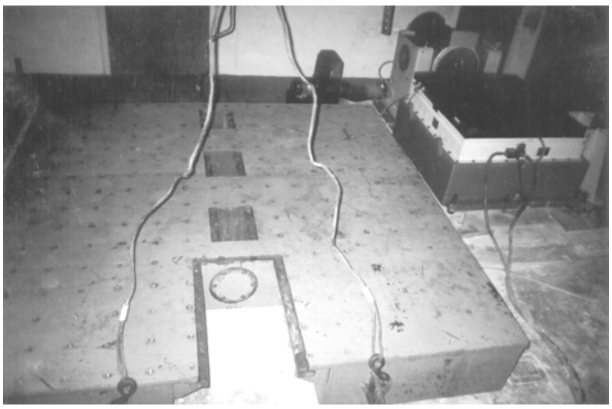


Fig. 4 Shake table

(a) Bare frame (b) Infilled frame at top (c) Infilled frame at bottom

Fig. 5 Damaged frames

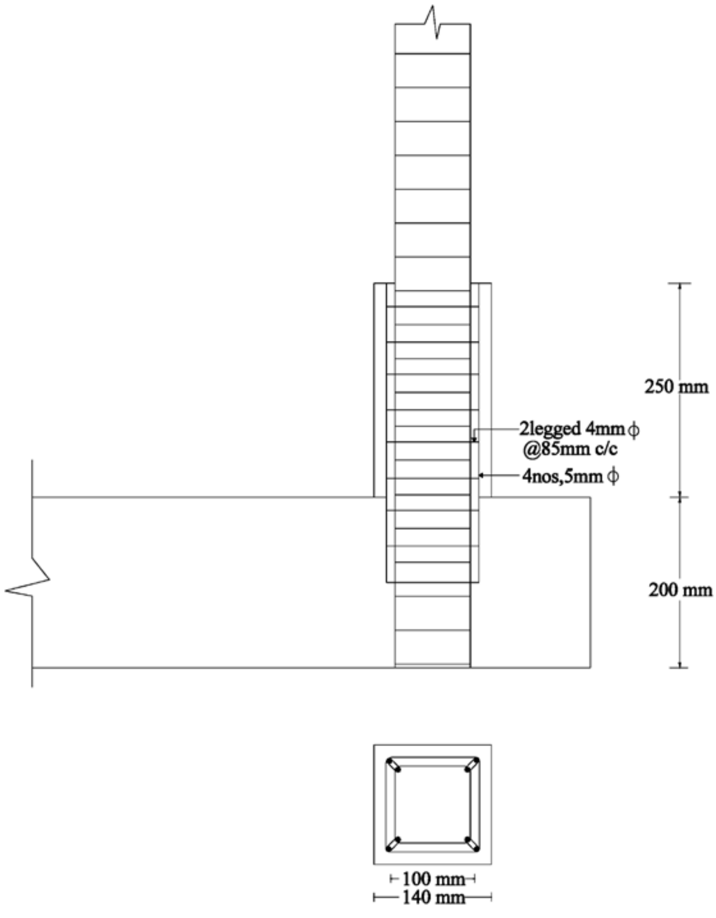


Fig. 6 Retrofitting details of the frame

retrofitting was not done for infill. Fig. 6 shows the retrofitting details of the soft-storey frame. The retrofitted frame was again tested under the same earthquake motions to study the effect of retrofit technique. In the retrofitted frame severe shear cracks were witnessed at top and bottom of the ground floor columns and the cracks were extended to the second storey also. Separation of brick panel from the bounding frame was also seen in the first floor. The failure pattern of the retrofitted frame is shown in Fig. 7.

(a) Retrofitted frame at top

(b) Retrofitted frame at bottom

Fig. 7 Failure pattern of retrofitted frame

3. Analytical investigation

A number of computer programs dealing with structural analysis now include pushover analysis (Capacity Spectrum Method). For this study, pushover analysis was performed for the frames using software package SAP 2000. Pushover analysis is a nonlinear static analysis procedure that provides a graphical representation of the expected seismic performance of the existing structures by the intersection of structure's capacity spectrum with a demand spectrum. Thus the method needs to determine the capacity of the structure and the seismic demands. The relationship of base shear and roof displacement represents the capacity spectrum of the frames. The demand curve is the reduced response spectrum used to represent the earthquake ground motion in the capacity spectrum method. The performance of the structure is evaluated in view of global response. ATC-40 provides different procedures to estimate the deformation demands during earthquake excitations.

The capacity of the structure can be determined from either nonlinear analysis or experiment. In the present study, the capacity of the frames was determined from nonlinear analysis. A 3-D model of bare frame and soft-storey frames were developed. The beams and columns were modeled as frame elements and the slab as a shell element. M 20 concrete and Fe 550 steel were used in the model. The brick wall was modeled as a diagonal strut element. The effective width of the strut was calculated based on Mainstone's formula. The stiffness reduction factor due to openings was taken from the charts given by Asteris. The properties of brick masonry used in the model were taken from the experiments. The live and dead loads of the elements were calculated and were assigned to each element. The seismic mass was lumped at each floor level at the centre of mass. The seismic weight of the bare and soft-storey frame was 10.976 kN and 25.616 kN respectively. The seismic weight of each floor of the structure included the dead load and fraction of the live load acting on the floor. The tributary height was between the centerline of the storey above and centre line of the storey below.

To identify the dynamic characteristics of the frames, modal analysis was conducted first. In the present study, the seismic response of reinforced concrete frames was evaluated using the design level earthquake (0.16 g) of zone III as specified in the Indian Seismic Code. The frames were assumed to be located on medium soil site. The input base motion is shown in Fig. 8.

The pushover hinges were assigned for beams and columns. Figs. 9 and 10 show the hinge properties in the form of moment rotation curve for beams and columns. The plastic hinge

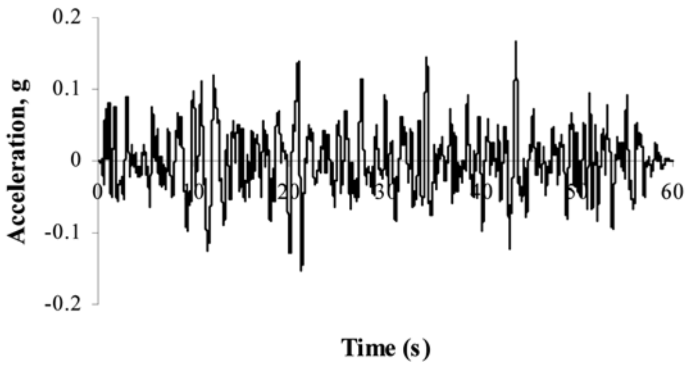


Fig. 8 Input base motion

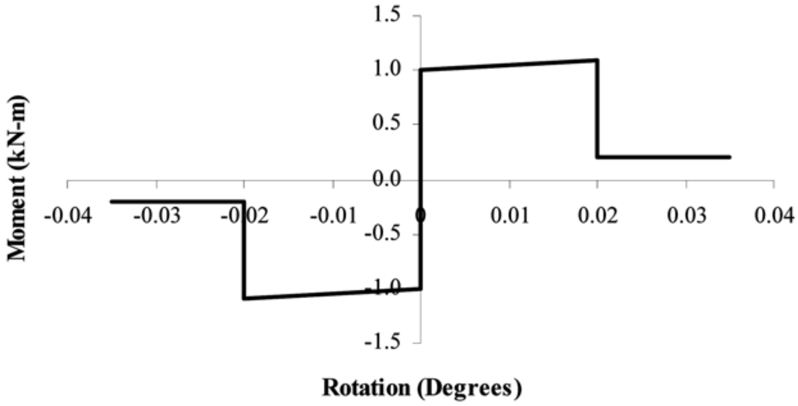


Fig. 9 Moment rotation behaviour for beams

properties of each member in SAP 2000 are computed based on the above figures. The elastic behaviour of the frame element is determined by the frame section assigned to the element. The reason for this is so that the linear behaviour of the structure is not changed by the assignment of hinges to the frame elements.

The design lateral force was first computed for the building as a whole and latter distributed to the various floor levels using the procedure given in the Indian Seismic Code IS-1893: 2002. Fig. 11 shows the distribution of lateral forces for the frames. The lateral forces were applied at each floor level at the centre of mass.

Three different pushover cases were defined. They were gravity push, lateral push in the X and Y directions. The pushover cases may be force controlled or deformation controlled. Generally, gravity load pushover is force controlled while the lateral push is deformation controlled. In pushover analysis, it is necessary to model the non-linear load-deformation behaviour of the elements. An idealized load-deformation curve is shown in Fig. 12. The range AB is the elastic range, B to IO is the range for immediate occupancy, IO to LS for life safety and LS to CP for collapse prevention. If all the hinge formation is within the range of CP for full gravity load and earthquake load conditions, then the building will not suffer total collapse. If the hinge formation exceeds that point, it is unsafe and those elements need to be retrofitted. Thus, the basic idea of the plot is that in a safe structure, all the hinges will lie within the limit CP.

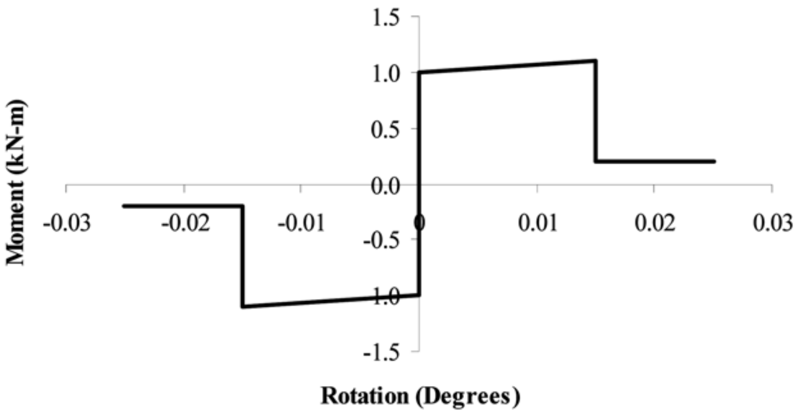


Fig. 10 Moment rotation behaviour for columns

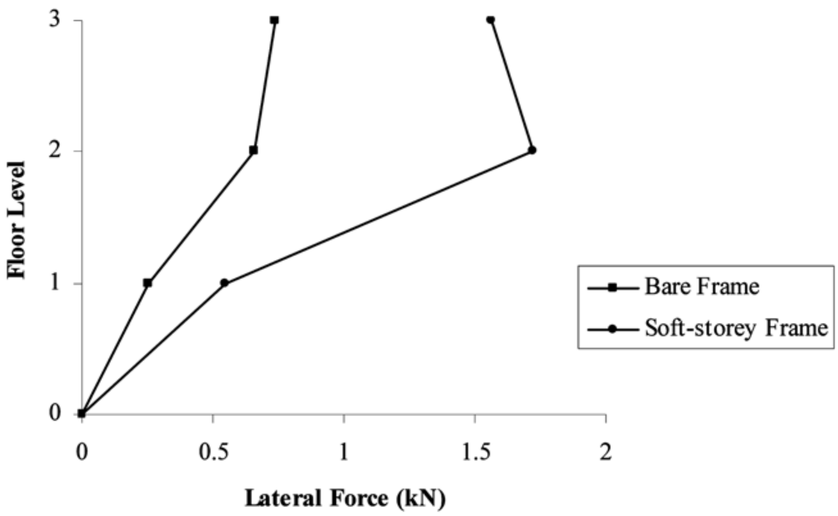


Fig. 11 Distribution of lateral forces for the frames

The pushover analysis was conducted for the frames considering the P-Δ effect. The capacity and demand curves were converted into spectral displacement and spectral acceleration format to obtain the performance point. The performance point is the intersection point of the capacity and demand curves.

4. Results and discussion

The seismic behaviour of reinforced concrete infilled space frames were investigated using shake table tests and pushover analysis. Fig. 13 shows the comparison of natural frequency obtained from the experiment and modal analysis of the original and retrofitted frames. The presence of open ground floor in the soft-storey infilled frame reduces the natural frequency by 30%. It can be seen that, the natural frequency of the frames obtained from experiment and analysis reasonably agreed well and this provides the adequacy of the appropriate modeling of the structural elements and

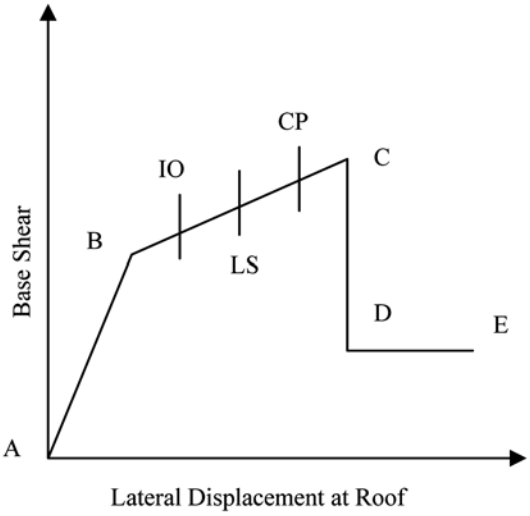


Fig. 12 Idealized load-deformation curve

retrofitting of reinforced concrete frames.

Fig. 14 shows the experimental and analytical mode shapes of the bare frame, soft-storey frame and retrofitted frame. It can be seen that, the bare frame vibrated in the flexure mode whereas the soft-storey frame vibrated in the shear mode. In the first mode, both the experimental and analytical mode shapes show large magnitude at the third storey level. For the soft-storey frame, in the third storey, the experimental values are more than twice as that of the analytical values. A similar behaviour is noticed in the case of retrofitted frame.

The location of hinges formed in the bare frame and the soft-storey frames during the pushover analysis are shown in Fig. 15. The hinges are uniformly distributed throughout the bare frame whereas in soft-storey frame the hinges are concentrated in the open first storey. This indicates that

Fig. 13 Natural frequencies of the frames

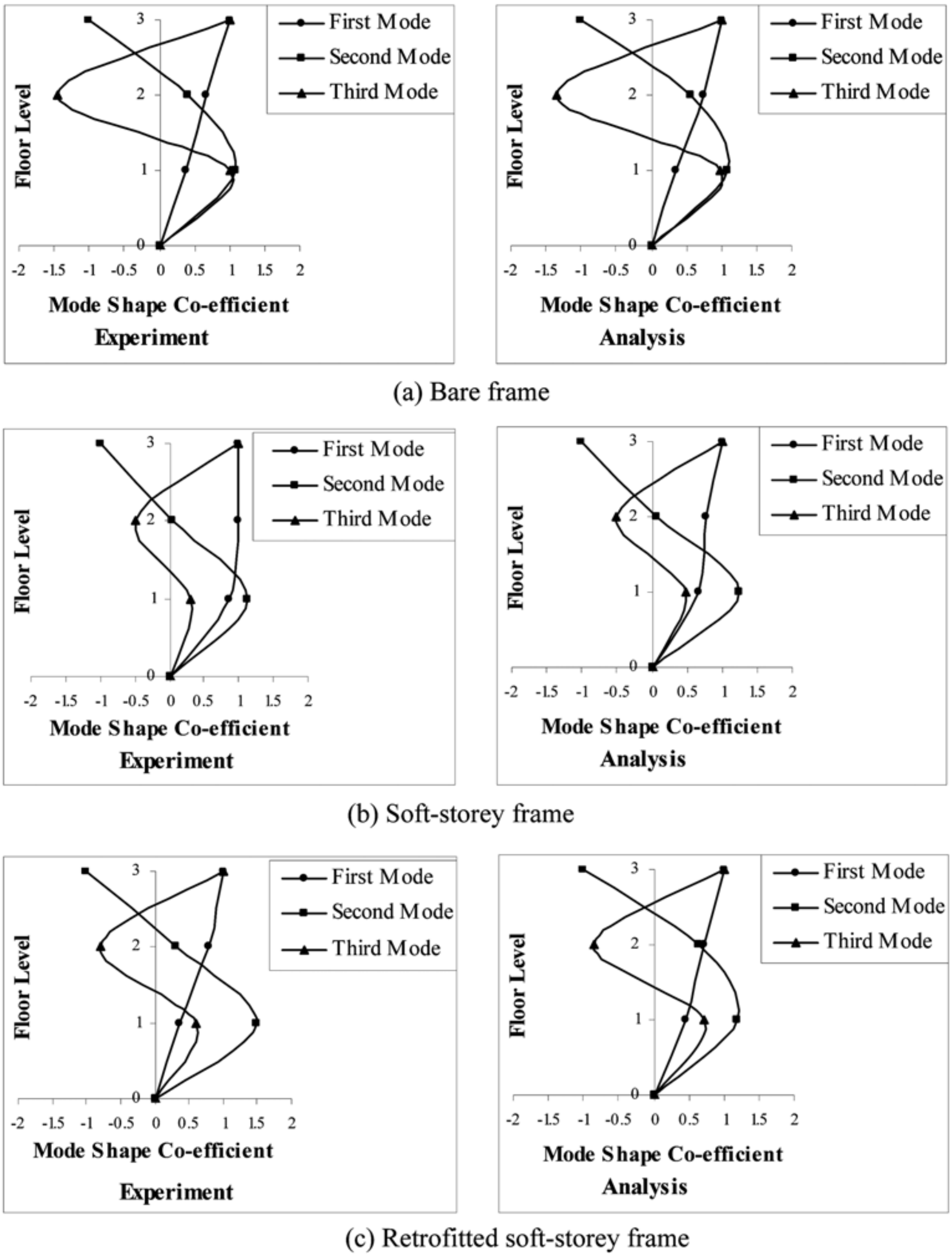


Fig. 14 Mode shapes of the frames

the concentration of damage is within the ground floor. After retrofitting, the hinges are propagated from open first storey into the upper storeys, distributing the load within the frame. The similar behaviour was witnessed during the shake table tests on the frames.

Base shear versus top displacement behaviour (capacity curves) of all the frames is shown in Fig. 16. It can be seen that, the behaviour of all frames is bi-linear. Though the initial stiffness of the

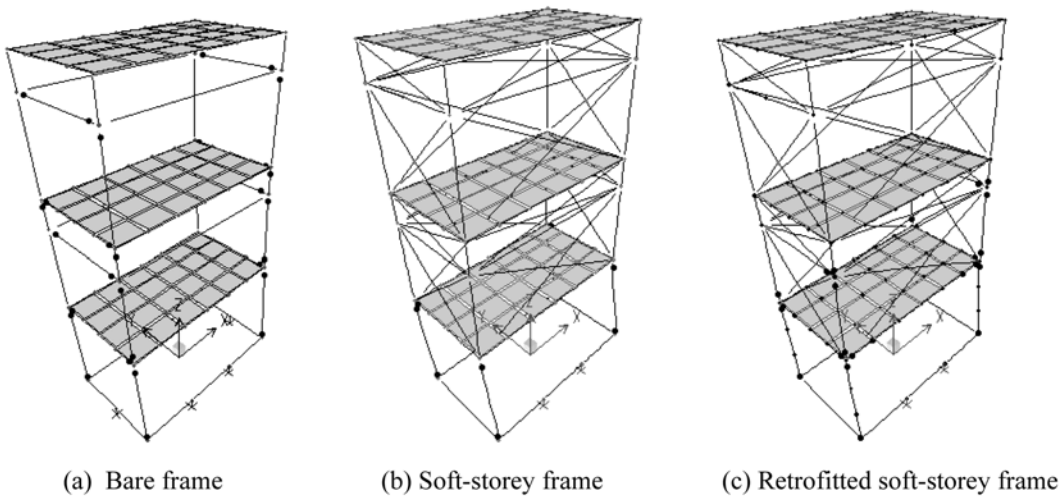


Fig. 15 Location of hinges in the frames

soft-storey frame is higher than that of the bare frame, the ductility is comparatively much smaller. This leads to the decreasing lateral capacity of soft-storey frame. The retrofitted soft-storey frame shows better behaviour in initial stiffness and ductility than the other frames.

The demand and capacity spectrum for the lateral push along the transverse direction of the bare frame, original soft-storey frame and retrofitted frame are shown in Figs. 17, 18 and 19 respectively. The seismic input was only 0.16 g and hence the demand curves shown in figures are much lower than the capacity. For the given excitation all the hinges lie in the elastic range AB and therefore the behaviour of the frames is linear. The performance point was obtained for all the frames under study, therefore the frames were found to be adequate for gravity loads and moderate earthquakes. Very few minor cracks were observed in the frames during this excitation and the frames remained in elastic stage. When the intensity of excitation was approaching 0.96g the plastic hinges were formed in the frames at the top and bottom in the ground floor.

Fig. 20 shows the comparison of shear demand obtained from experiment and analysis for both

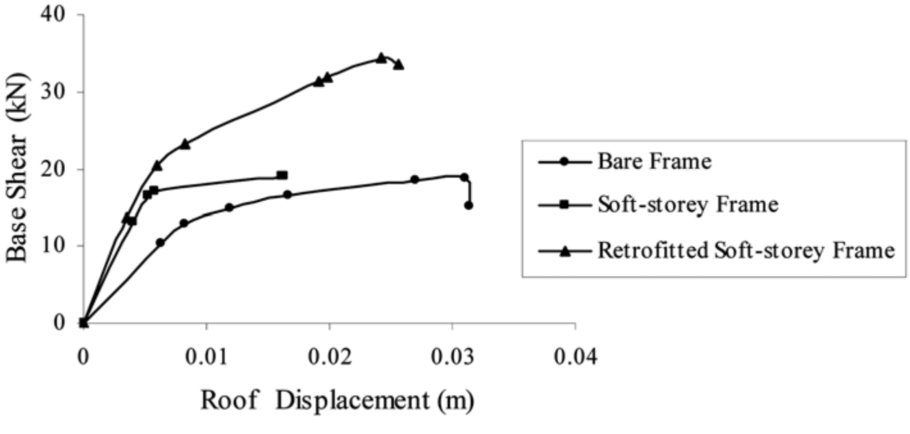


Fig. 16 Base shear versus top displacement behaviour of the frames

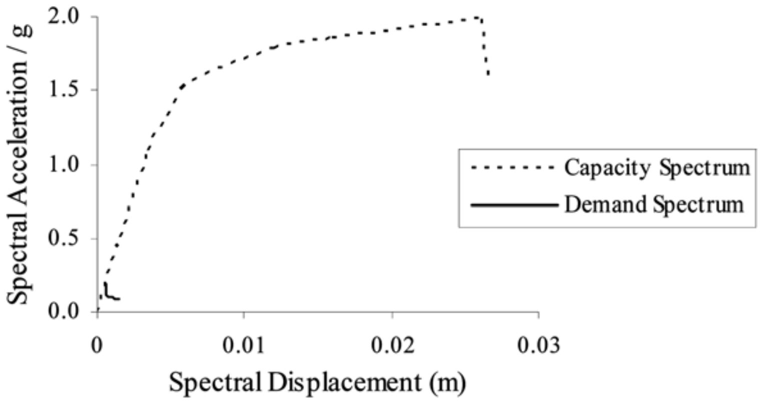


Fig. 17 Demand and capacity spectrum of bare frame

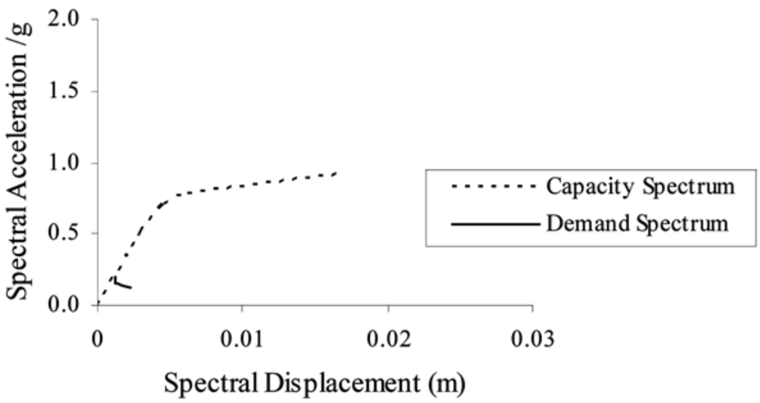


Fig. 18 Demand and capacity spectrum of soft-storey frame

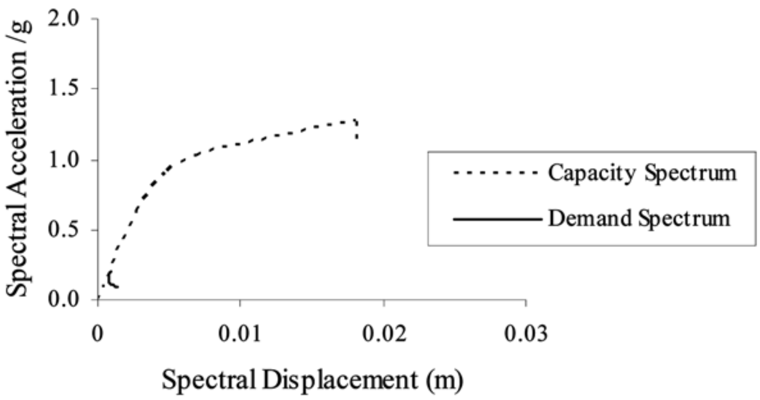


Fig. 19 Demand and capacity spectrum of retrofitted soft-storey frame

original and retrofitted frames. It can be seen that, the difference found is meager of the order of 2 to 5%.

Fig. 21 shows the spectral displacement demand of the original and retrofitted frames. The

Fig. 20 Shear demand of the frames

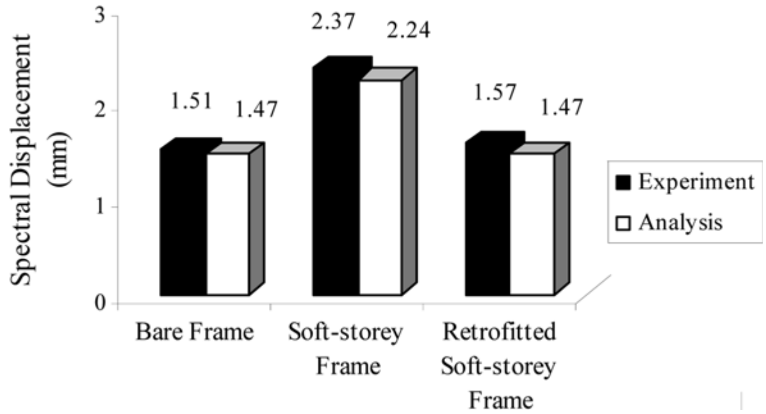


Fig. 21 Spectral displacement demand in the frames

analysis underestimated the displacement demand of the frames, however the difference is very small.

5. Conclusions

Based on the experimental and analytical investigations on bare and soft-storey reinforced concrete frames, the following are the conclusions.

- Reinforced concrete frames with brick infill exhibit significantly higher initial stiffness and strength. The initial stiffness of the soft-storey frame is twice that of the bare frame and the retrofitting of the severely damaged soft-storey frame increases the stiffness by more than 20%.
- The bare frame exhibits ductile behaviour than the soft-storey frame. The ductility ratio of the bare frame is one and a half times greater than the soft-storey frame which demonstrates the ductility demand in the columns of the soft-storey frame.

- The frames are found to be adequate for gravity loads and for moderate earthquakes. However, the shear demand in the soft-storey frame is more than two and a half times greater than that in the bare frame.
- The number of hinges formed in the beams and columns at the performance point can be used to study the vulnerability of the building.
- The results of the investigation suggest that the soft-storey frames with masonry infills can be adequately simulated using static nonlinear pushover analysis.

References

Arlekar, J. N., Jain, S. K. and Murty, C. V. R. (1997), "Seismic response of RC frame buildings with soft first storeys", *Proc. CBRI Golden Jubilee Conf. on National Hazards in Urban Habitat, New Delhi,* 13-24.

Asteris, P. G. (2003), "Lateral stiffness of brick infilled plane frames', *J. Struct. Eng.,* ASCE, **129**(8), 1071-1079.

Dolsek, M. and Fajfar, P. (2002), "Mathematical modeling of an infilled RC frame structure based on the results of pseudo-dynamic tests", *J. Earthquake Eng. Struct. Dyn.,* **31**(6), 1215-1230.

Elnashai, A. S. (2001), "Advanced inelastic static (pushover) analysis for earthquake applications", *J. Struct. Eng. Mech.,* **12** (1), 51-69.

IS-1893, Part-1 (2002), "Criteria for earthquake resistant design of structures".

Kanitkar, R. and Kanitkar, V. (2004), "Seismic performance of conventional multi-storey buildings with open ground floors for vehicular parking", *The Indian Con. J.,* **78**(2), 99-104.

Vasseva, E. N. (1994), "Investigation on the behaviour of reinforced concrete frames with first story reduced strength subjected to seismic excitations", *Proc. Int. Conf. on Earthquake Resistant Construct. & Design, Savidis (ed.),* 707-713.

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