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Seismic fragility of open ground storey RC frames with wall openings for vulnerability assessment

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ABSTRACT

Reinforced concrete (RC) buildings with open ground storey (OGS) are characterized by accumulation of large lateral displacement at the ground storey. This is due to drastic reduction in relative stiffness of the ground storey compared to the upper stories, a phenomenon known as soft storey effect. Openings present in the masonry infill walls reduce both the lateral strength and stiffness of the fully infill RC frames. It is a general perception about OGS buildings that openings present in the infill walls reduce the stiffness of upper storeys, and thus, offsets the soft storey effect. In the present study, this issue is investigated by carrying out a simplified performance assessment of low- to mid-rise masonry infill RC frames with different infill configurations followed by fragility analyses. It is observed from fragility analyses that there is practically no influence of openings in masonry infill walls of OGS frames on lateral load behavior of such frames. OGS frames with any bay and storey configuration, even with large openings in infill walls, remain highly vulnerable to earthquakes. A new representation of fragility, Fragility Flow Plot, is proposed, independent of discrete damage states, where results of the fragility analyses can be shown for different parameters, such as, natural period of vibration, number of bays and storeys, and openings. The present study contributes towards quantification of seismic fragility and vulnerability of OGS building frames and establishes an initiative for seismic fragility based design of OGS frames using the Fragility Flow Plots.

1. Introduction

Masonry infill reinforced concrete (RC) buildings are commonly constructed in many countries. Although infills contribute large lateral strength and stiffness to the building, their influence on lateral load behavior depends greatly on their distribution in the building. One such example, where the influence of infill distribution in the frame is dominant, is an open ground storey (OGS) frame in which the masonry infill walls are present in all storeys except the ground storey. The ground storey is left open for various functional purposes, such as, parking or for shops and services. Providing infills only in the upper storeys of a building renders the ground storey relatively flexible and weaker compared to the upper storeys leading to high drift and strength demands on the ground storey columns. Generally, OGS columns lack adequate ductility capacity, stiffness, and strength needed to resist the high demand of storey shear [1]. This leads to an undesirable column-sway failure mechanism in OGS buildings subjected to earthquake excitations in which plastic hinges are mainly formed in the columns of the open ground storey. In contrast, the infills restrain most of the lateral deformation of the upper storey, and thus, little or no damage is incurred in the upper storeys. Such peculiar behavior of masonry infill RC frames, in which most of the lateral deformation is concentrated in the open ground storey and the upper storeys remain vertical and mostly undamaged, was observed in several past earthquakes (Fig. 1) as well as past analytical studies [2–7]. Fig. 1 shows two such OGS buildings collapsed during 2004 Sumatra and 2011 Sikkim earthquake; both buildings had big openings in infill walls of upper storeys but still both collapsed. Thickness of infill walls was varying from 115 mm to

Abbreviations: β_{dsi}, normalised standard deviation of the natural logarithm of displacement; β_{eff}, effective viscous damping; β_O, hysteretic damping; μ_d, ductility demand; κ, damping modification factor as in ATC 40; 3B-4S, three bay-four storey; ADRS, acceleration-displacement response spectrum; C, complete damage state; CSM, capacity spectrum method; d_b, diameter of longitudinal steel bar in m; ds, damage state; d_u, ultimate displacement; d_y, yield displacement; E, extreme damage state; E_D, energy dissipated by damping; E_{SO}, maximum strain energy; EDP, engineering demand parameter; FFP, fragility flow plot; FI, fully infill; f_y, yield strength of longitudinal steel in MPa; IM, intensity measure; L, half-length of member in meter; l_p, average plastic hinge length; M, moderate damage state; MPA, modal pushover analysis; N_B, number of bays; N_S, number of storeys; NRHA, nonlinear response history analysis; NSP, nonlinear static procedures; OGS, open ground storey; Op, central opening in infill walls; PGA, peak ground acceleration; PO, pushover; PP, performance point; S, slight damage state; S_a, spectral acceleration; $\overline{S_d}$, spectral displacement threshold; S_d, spectral displacement demand; S_{dy}, yield spectral displacement demand; S_{du}, ultimate spectral displacement demand

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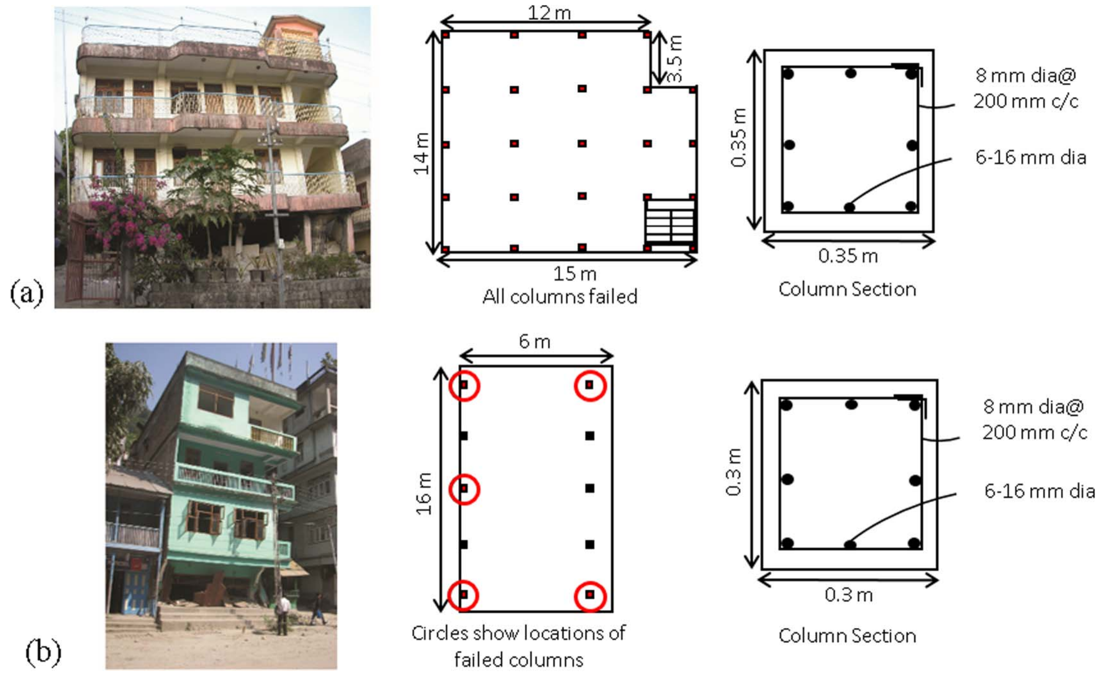

Fig. 1. Elevation, column layout and section of collapsed OGS buildings during past earthquakes: (a) a three storey building in Port Blair, India after 26 December 2004 Sumatra earthquake, and (b) a four storey building at Singtam market in Sikkim after 18 September 2011 Sikkim earthquake (Photos by Hemant B. Kaushik).

230 mm in both the buildings. The sectional details and plan of the buildings show that the columns were inadequately detailed and almost all the ground storey columns failed. Considering this fact, past researchers (e.g., [5,8–14]) have reported the significant 'negative' influence of OGS on the overall seismic performance of such buildings. On several forums (for example, [15]), various stakeholders have expressed that it is a common perception that presence of openings in infill walls of OGS frames reduce the seismic fragility of such frames.

The seismic design codes of different countries are silent on specific design procedure to be followed for open ground storey buildings. Some, for example, the Indian seismic code [16], require the ground storey columns of such frames to be designed for higher member forces simply by using a multiplication factor of 2.5. However, it is reported that use of a single multiplication factor for any type of OGS frame does not reduce its vulnerability [5,17,18]. Previous studies, such as, those of Cosenza et al. [19] provide information on the influence of varying building parameters, e.g., number of bays and storeys on lateral load behavior of buildings.

There is a lack of specific literature that can assist in seismic assessment of OGS buildings with openings in infill walls. Influence of openings in infill walls on the overall seismic vulnerability of OGS frames has not been investigated yet. The primary objective of the present study is to quantify the fragility of low- to mid-rise OGS frames and demonstrate their vulnerability in comparison with corresponding FI and bare frames. An attempt was made to provide the designers with an easy interface to carry out fragility analysis that can assist in fragility based design of OGS buildings. In order to achieve these objectives, nonlinear static analyses of OGS frames were carried out by varying the number of bays (1–6) and storeys (2–6), size of central opening in infill walls (0–90%), and seismic hazard in terms of peak ground acceleration, PGA (0.05–1.0 g). As per HAZUS [20], low-rise and mid-rise concrete moment frames (with or without masonry infills) are those with 1–3 storeys and 4–7 storeys high, respectively. A new representation of fragility termed as Fragility Flow Plot (FFP) was developed. These plots are independent of consideration of any damage states and can combine the results of several fragility analyses and results of parameterized performance assessment for a given earthquake intensity. Further, possible use of these plots in seismic fragility quantification of masonry infill RC frames is discussed.

2. Seismic fragility assessment

The primary motivation of seismic fragility assessment is to obtain an estimate of the probability of exceedance of a given damage level in a building due to a seismic hazard to predict its vulnerability. The basic steps include building's capacity estimation for a given seismic hazard, followed by the fragility estimation for a given limit state or damage state. The interest is to quantify fragility of OGS frames in comparison to fully infill or bare frames under lateral loads using a consistent approach. Though recent past studies have used nonlinear response history analysis followed by more rigorous incremental dynamic analysis for estimation of seismic fragility of structures [21], nonlinear static procedures (NSPs) followed by simplistic HAZUS [20] procedure have also been effectively used in the past.

Pinho et al. [22] evaluated different nonlinear static procedures (NSPs), such as, capacity spectrum method (CSM) of ATC 40 [23] and N2 method [24]. It was concluded on the basis of the comparative study involving nonlinear response history analyses that all the NSPs are capable of effectively predicting the lateral displacements. The effectiveness of nonlinear static methods in predicting lateral load response has also been validated with respect to those obtained by nonlinear dynamic analysis for a wide range of frames by Bosco et al. [25]. It was observed that differences in seismic demand occurred in the two methods when the frames are well excited into the inelastic range but they are nearly always conservative in nonlinear static procedures. Calvi et al. [26] discussed pros and cons of various empirical and analytical methods of vulnerability assessment, and observed that none of the methods satisfy all the requirements necessary for an optimum vulnerability assessment methodology. Kaushik and Choudhury [27] elucidated a step-by-step procedure for estimation of seismic fragility and vulnerability of structures considering different performance assessment methodologies.

Fragiadakis et al. [28] observed that all NSPs are good predictor of lateral displacement and storey drifts for RC buildings of up to four storeys. Similarly, Dolšek and Fajfar [29] used simplified nonlinear static procedures for seismic analysis and fragility quantification of