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Seismic performance of R/C plane frames irregular in elevation

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Abstract

The paper addresses multistorey reinforced concrete (R/C) frame buildings, irregular in elevation. Two ten-storey two-dimensional plane frames with two and four large setbacks in the upper floors respectively, as well as a third one, regular in elevation, have been designed to the provisions of the 2004 Eurocode 8 (EC8) for the high (DCH) and medium (DCM) ductility classes, and the same peak ground acceleration (PGA) and material characteristics. All frames have been subjected to both inelastic static pushover analysis and inelastic dynamic time-history analysis for selected input motions. The assessment of the seismic performance is based on both global and local criteria. It is concluded that the effect of the ductility class on the cost of buildings is negligible, while the seismic performance of all irregular frames appears to be equally satisfactory, not inferior to (and in some cases superior than) that of the regular ones, even for motions twice as strong as the design earthquake. As expected, DCM frames are found to be stronger and less ductile than the corresponding DCH ones. The overstrength of the irregular frames is found to be similar to that of the regular ones, while DCH frames are found to dispose higher overstrength than DCM ones. Pushover analysis seems to underestimate the response quantities in the upper floors of the irregular frames.

Keywords: R/C buildings; Irregularity in elevation; Setbacks; Seismic performance; Pushover analysis; Time-history analysis; Eurocode 8

1. Introduction

The paper addresses multistorey reinforced concrete (R/C) frame buildings with setbacks, i.e. a reduction of the length of the building along its height (irregularity in elevation). It focuses on buildings with large setbacks in the upper floors (not on tower-like structures where one large setback occurs in the lowest part of the building). The former architectural form is quite common in cases where a relatively narrow road separates two multistorey buildings, in order to permit adequate sunlight exposure of the lower floors.

Irregular configurations either in plan or in elevation were often recognized as one of the main causes of failure during past earthquakes. Focusing on buildings with setbacks, observed damage after strong earthquakes indicates an inferior performance of this type of structure [1–3]. On the other hand, it has to be emphasized that most of these buildings were designed on the basis of rough 'hand-methods' of static analysis, and also the level of detailing required by the then applicable codes was quite low and poor construction practices often made it even lower. As opposed to the previously mentioned field evidence, experimental [4,5] as well as analytical [6,7] studies involving frames with setbacks designed and detailed to modern codes such as the ENV-version of Eurocode 8 (EC8) [8] showed a quite satisfactory seismic performance of this type of structure. Nevertheless, at least as far as the writer knows, the seismic behaviour of reinforced concrete multistorey buildings with setbacks designed to the final (EN) version of EC8 has not yet been studied.

The present paper focuses on the seismic performance of multistorey R/C frame buildings with setbacks in the upper stories, designed to the provisions of the EN-version of EC8 [9], which includes a number of significant changes with respect to the ENV-version of the same code [8], not least of which is a drastic reorganization of the ductility classes. In order to examine the influence of the design ductility class on the seismic behaviour of the buildings, all frames were designed for both the high (DCH) and the medium (DCM) ductility classes of EC8. Buildings designed for the low (L) ductility class of EC8 with low dissipation capacity and low ductility, designed by applying only the rules of Eurocode 2, have not

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been examined here since they are only recommended for low seismicity areas or for base-isolated structures.

2. Design and cost considerations

2.1. Structures studied

Six ten-storey R/C frame buildings were designed according to the requirements of EC8 [9], three of them (FRH, FRH-1 and FRH-2 Fig. 1) for the high (DCH) ductility class and the rest (FRM, FRM-1 and FRM-2—Fig. 1) for the medium (DCM) ductility class, with the same materials (C20/25 concrete and S400 steel) and the same peak ground acceleration (PGA) of $0.25g$. The geometric data of the typical plane frames of all buildings are shown in Fig. 1. As shown in Fig. 1, two of them (FRH and FRM) correspond to buildings regular in elevation, without any setbacks. The other four frames have the same configuration in the lower six stories and large setbacks (about 40% of the length of the lower storey) in the upper ones, two of them (FRH-1 and FRM-1) in the upper two stories, and the rest (FRH-2 and FRM-2) in the upper four.

It is pointed out that, according to EC8, the behaviour factor (q) used to derive the design seismic actions is reduced by 20% in the case of irregular structures. The derived values of the behaviour factor q of the DCH frames were $q_r = 5.85$ and $q_i = 4.68$ for the regular FRH and the irregular FRH-1 and FRH-2 frames respectively, while the corresponding values for the DCM frames were 33% lower, i.e. $q_r = 3.90$ and $q_i = 3.12$ for the regular FRM and the irregular FRM-1 and FRM-2, respectively. Besides, irregular frames FRH-1, FRH-2, FRM-1 and FRM-2 were designed with the aid of modal response spectrum analysis, the reference method for determining the seismic effects according to EC8, whereas in the cases of the regular FRH and FRM frames the (static) 'lateral force method of analysis' was used, the application of which is only permitted for buildings regular in elevation. The first 4 modes of vibration were considered in the multimodal analysis of all irregular frames, with total contributing masses more than 95% in all cases. The natural periods of the frames were found to be 1.01 s, 0.92 s and 0.90 s for FRH, FRH-1 and FRH-2 respectively, and 1.01 s, 0.92 s and 0.87 s for FRM, FRM-1 and FRM-2 respectively. The, strange at first sight, fact that stiffer frames have longer natural periods than the less stiff ones can be attributed to the reduction of mass (because of the setbacks) at a rate greater than the one of stiffness.

2.2. Effect of ductility class on cost

Fig. 2 summarizes the results of a detailed estimation of the required steel quantities (total weight of the required reinforcement, as well as the distribution into longitudinal and transverse) for the plane structures shown in Fig. 1. The required concrete volume has not been plotted since, as can be seen in Fig. 1, FRM and FRM-1 have exactly the same cross-section dimensions with FRH and FRH-1 respectively, while the only difference between FRM-2 and FRH-2 concerns the cross-section dimensions of the interior columns of the lower four stories, which results to a 3% increase of required concrete volume in FRM-2 in comparison with FRH-2.

As can be seen in Fig. 2, DCH structures generally require less longitudinal and more transverse reinforcement than the corresponding DCM ones. This is a very significant effect of the ductility class, the clear trend being that the percentage of (flexure dominated) longitudinal steel decreases, while that of the (shear and confinement dominated) transverse reinforcement increases with increasing ductility class. The difference is more pronounced in irregular structures, as can be seen in Fig. 2. On the other hand, ductility class seems not to affect significantly the total amount of the required reinforcement (differences up to 5%).

Based on the foregoing comparisons, it appears that from the economy point of view both ductility classes recommended by EC8 for medium and high seismicity areas are essentially equivalent.

3. Assessment of seismic performance—procedure

3.1. Modelling assumptions

All frames have been subjected to both inelastic dynamic time-history analysis and inelastic static pushover analysis. Inelastic dynamic time-history analysis of the structures was carried out with the aid of the DRAIN-2000 computer code [10], an extended version of the well-known DRAIN-2D program, including several new features and elements, as well as capability for seismic reliability analysis. The dynamic input has been given as a ground acceleration time-history which was applied uniformly at all the points of the base of the structure; only one (horizontal) component of the ground motion has been considered while dynamic soil–structure interaction was neglected. P–Δ effects were also neglected. Due to the large number of analyses required for the assessment of the seismic performance of the six frames, standard point hinge modelling was used for R/C members, with phenomenological hysteresis laws governing the behaviour of each hinge. The two-component model which has only the ability of handling bilinear hysteresis (Fig. 3a) but accounts for yield moment (M_y)–axial force (N) interaction (Fig. 3b), was used for the exterior columns where a significant variation of the axial load takes place during the seismic excitation, while the one-component model which is able to handle more refined Takeda-type hysteresis laws (Fig. 4), but does not account for M_y–N interaction, was used for the other members of the structures (beams, interior columns). The results of the analyses showed that column hinging was rather limited, hence the crudeness in the hysteresis law assumed for column elements did not affect significantly the response of the structures.

Inelastic static pushover analysis was carried out with the aid of the well-known SAP2000 computer code [11]. The moment–rotation relationship diagram as well as the M–N interaction diagram assumed in the pushover analysis are shown in Fig. 5. Two vertical distributions of the lateral loads were applied: a 'uniform' pattern, based on lateral forces proportional to mass regardless of elevation, and a 'modal'