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Permanent seismic drifts in steel moment frames

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ABSTRACT

This paper examines residual drift demands in steel moment-resisting frames incorporating the influence of degradation and ground motion frequency content. Detailed assessments are carried out using 54 multi-storey framed buildings, with a wide range of structural characteristics, which are designed according to the provisions of Eurocode 8. In order to identify the influence of cyclic and in-cycle degradation effects, the analysis is carried out with and without degradation modelling. Incremental dynamic analysis is employed in order to achieve various limits of lateral strength demand, using a suite of 56 ground motion records. It is shown that residual drifts are markedly higher in degrading models in comparison with non-degrading models, with the differences being more pronounced in relatively short period ranges, when higher rates of cyclic deterioration are employed, and for comparatively high lateral strength demand levels. The residual drift demand is also shown to increase with the increase in number of stories, and is often concentrated in the lower levels when degrading models are used. Overall, significant residual drift demands are observed in the structural systems considered, with a high likelihood of exceeding a 0.5% residual drift limit in most cases. Based on the results, two simplified prediction relationships are proposed to estimate the permanent drifts of multi-storey steel moment framed systems. The first is concerned with the design stage based on the results of elastic analysis, whilst the second is associated with post-earthquake structural assessment based on actual measurements of residual drifts.

1. Introduction

The prediction of seismic residual drifts, representing the permanent deformations of a structural system caused by inelastic deformations that remain after the ground shaking has ended, is important for the design of new structures as well as for the assessment of post-earthquake conditions. Studies available in the literature that highlight the significance of residual drifts as a structural index can be classified into two main groups. Firstly, studies that use residual drifts as an engineering demand parameter to perform seismic structural assessment of existing buildings (e.g., [1–5]) which, as expected, find a strong correlation between the damaged state and the residual drifts. Secondly, studies that use residual drifts in the design of new buildings according to current seismic codes, and which indicate apparent inconsistencies between the expected performance of the building and that observed or computed at the end of the seismic excitation (e.g., [5–10]). However, in contrast with these findings, most recent seismic standards for the design of new buildings only focus on the utilisation of maximum peak drifts as a structural index, whilst completely disregarding residual drifts. This is the case in Eurocode 8 (EC8) [11] as well as in ASCE 7–10 [12]. In the case of seismic assessment and rehabilitation of existing structures, most current codes do not explicitly consider residual drifts in the analysis. Instead, they account for the post-earthquake damaged condition through the levels of inelastic rotation of yielding elements (i.e., beams and columns), as is the case in Part 3 of Eurocode 8 [13] as well as in ASCE/SEI 41-13 [14]. In contrast, recent guidance documents such as FEMA P-58 [15] highlights the importance of evaluating residual drifts for the seismic assessment of buildings. In this case, the use of detailed numerical models that characterise structural performance more precisely at large nonlinear deformations, including representation of in-cycle and cyclic deterioration of strength and stiffness of structural members, is essential.

Research undertaken on the main parameters that influence the behaviour of residual drifts in different structural configurations can be categorised by the study of single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) systems. Likewise, two subcategories are typically utilised for the determination of absolute values of residual drifts, namely: the direct approach where residual drifts are directly obtained from dynamic analysis (i.e., ultimate recorded deformation), and the indirect approach where the residual drift is determined as a percentage of the maximum transient peak drift. In one of the earliest attempts to understand the behaviour of residual drifts for a wide range of fundamental periods, Kawashima et al. [16] developed a residual displacement response spectrum, where the hysteretic properties of SDOF oscillators were characterised by a simple bilinear hysteresis

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model (i.e., elasto-plastic with hardening). In this indirect approach, the residual drift ratio was found to be strongly dependent on the post-yield response, whilst the influence of fundamental period, soil condition, and ductility levels, were reported to be relatively insignificant. Nevertheless, Ruiz-García et al. [17] indicated a strong influence from the ductility demand level on the residual drifts, consistently using the indirect approach of assessment and hysteretic elasto-plastic systems.

Studies on MDOF systems typically focused on examining the amplitude and distribution of residual drifts over the height in multi-storey buildings, and emphasised its importance for existing structures [3, 10, 18, 19] as well as in the design of new structural systems [7, 8, 20, 21]. There is general agreement on the key characteristics that define the amplitude and distribution of residual drifts, namely: the hysteretic behaviour of the main dissipative structural components, ground motion intensity (i.e., ductility demand), typology of plastic mechanism, and the structural over-strength (e.g., [3, 4, 7, 16, 22]). However, in comparison, limited studies are available on the correlation between measurement of actual residual drift and levels of observed post-earthquake damage, which is also related to the lack of specific residual drift or reparability limits in most current seismic codes. After the 1995 Hyogoken-Nabu earthquake in Japan, Iwata et al. [23] assessed 12 damaged steel buildings considering technical and economic aspects in order to define clear criteria for potential reparability. The proposed limits included a maximum residual inter-storey drift of 1.4% and a maximum roof drift of 0.9%. Furthermore, research conducted in Japan by McCormick et al. [24] considered the comfort living conditions of residents in a building with permanent damage. A residual inter-storey drift of 0.5% was indicated, which was shown to be a suitable limit as a human comfort threshold as well as being associated with the requirements for extensive repair. Since there is a relationship between residual and peak drifts, and considering the significant available research on the latter (e.g., [25–29]), maximum inelastic displacement ratios are addressed herein as well.

The first objective of this paper is to provide a detailed insight into the salient parameters that influence the magnitude and distribution of seismic residual drift demands in steel moment frames designed according to the provisions of Eurocode 8, using extensive dynamic analysis on SDOF and MDOF systems. Secondly, the investigation aims to provide detailed quantification of the influence of cyclic and in-cycle degradation on residual drift demands, with direct comparison between the results of degrading and non-degrading systems. Thirdly, based on the results, predictive models are proposed in order to determine the maximum residual drift demands directly, as well as for estimating maximum drift demands indirectly when residual drifts are known. Finally, the results are analysed collectively in the light of provisions of current seismic codes and guidelines, for which permanent drift demand limitations are either non-existent or only indirectly considered by proxies such as through maximum deformation limits.

2. Structural systems and ground motions

In this section, a detailed description of the SDOF and MDOF structural systems used in this study is presented, along with the modelling details. Subsequently, the selection criteria for the earthquake records and the final ensemble of ground motions are provided.

2.1. Mechanical model of SDOF systems

Preliminary assessment of residual drifts is carried out using equivalent single-degree-of-freedom systems (ESDOF) instead of simple oscillators. The term 'equivalent' stands for systems that represent globally the behaviour of multi-storey systems and, to serve this purpose, they have been calibrated as discussed below. The mechanical model shown in Fig. 1(a) corresponds to an inverted pendulum with mass (m) at its tip, and the rod is a massless element pinned at the base. The properties of the moment-rotation hysteretic model are assigned to a rotational spring at the base. Viscous damping is considered using a rotational dashpot damper acting in parallel with the main rotational spring. Unlike conventional simplified SDOF idealisations (e.g., oscillating mass attached to a damped spring), this represents a more versatile model that enables the inclusion of equivalent gravity loads and therefore is capable of capturing lateral instability effects (i.e., $P-\Delta$). The model also readily allows for a change of the structural properties of the system, either by tuning the mass or the initial elastic stiffness of the spring at the base to represent different fundamental periods.

To provide a basis for comparison, the parametric study was undertaken for two constitutive hysteretic models: a non-degrading model, and a stiffness- and strength-degrading model. The non-degrading model includes a post-yield isotropic strain-hardening branch without in-cycle strength and stiffness degradation. This model is adopted over simpler non-degrading bilinear hysteretic models since it is comparatively more realistic as it incorporates a curved yield transition zone. The outcome of a cyclic pushover analysis of the non-degrading model is shown in Fig. 1(b). Likewise, the Modified Ibarra-Medina-Krawinkler (IMK) bilinear model [30] is adopted to represent the behaviour of the degrading systems. This model has been calibrated by Lignos and Krawinkler [31] and shown that it is capable of capturing cyclic and in-cycle deterioration based on the dissipation of cumulative hysteretic energy, for reproducing the moment-rotation behaviour of steel components with local buckling phenomena being the main source of degradation.

The N2 method adopted in EC8 [11] was partially followed to obtain the equivalent structural properties of the SDOF. Given that the EC8 version of the method is limited to perfectly plastic systems, an updated multi-linear fit of the MDOF static pushover capacity curve to obtain the equivalent SDOF curve, as proposed by De Luca et al. [32] was used herein. In the case of the IMK degrading model, to calibrate the equivalent rate of cycling degradation (Λ), a cyclic pushover analysis

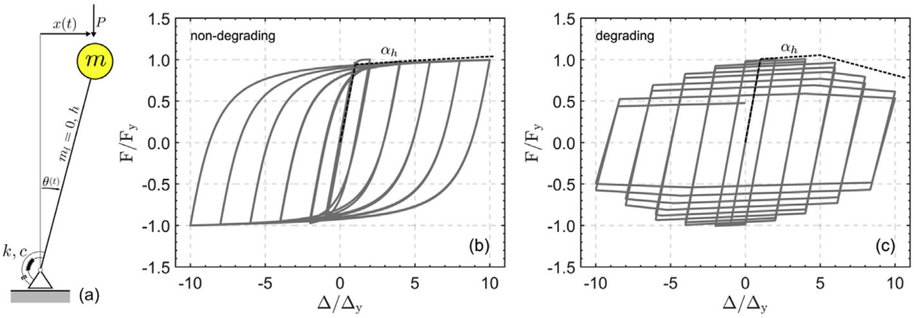

Fig. 1. (a) Mechanical model of the ESDOF, cyclic normalised pushover and pushover/backbone of both hysteretic behaviour models assigned to the base of the mechanical model for non-degrading (b) and degrading (c) systems.