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Inelastic Behaviour of Steel Structures Subjected to Multiple Earthquakes

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Abstract: In this paper, a systematic investigation is carried out on the seismic behaviour of plane moment resisting steel frames (MRF) and plane concentrically X-braced steel frames (CBF) to multiple strong ground motions. Such a sequence of earthquakes results in a significant damage accumulation in a structure because any rehabilitation action between any two successive seismic motions cannot be practically materialised due to lack of time. In this work, thirty-six MRF and thirty-six CBF which have been designed for seismic and vertical loads according to European codes are subjected to five real seismic sequences which are recorded at the same station, in the same direction and in a short period of time, up to three days. This investigation shows that the sequences of ground motions have a significant effect on the response and, hence, on the design of MRF and CBF.

Keywords: Steel framed structures, inelastic behavior, multiple earthquakes.

1 Introduction

An important drawback of modern seismic codes is the exclusively adoption of rare 'design earthquake', ignoring the effects of the repeated earthquake phenomena. Recently, Hatzigeorgiou and Beskos (2009) and Hatzigeorgiou (2010) examined the influence of multiple earthquakes on the response of numerous single-degree-of-freedom (SDOF) systems and found that seismic sequences lead to increased displacement demands in comparison with the 'design earthquake'. Examining multi-degree-of-freedom (MDOF) systems under seismic sequences, only few research works can be mentioned. The first one is the work of Fragiacomo et al. (2004) dealing with two low rise steel frames (three and five-storey high) under four different seismic sequences characterized by the repetition of one, two, and three ground motions. However, according to Garcia and Negrete-Manriquez (2011), the repetition of the same record seems to be inappropriate for the realistic predic-

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tion of structural behaviour. Recently, Hatzigeorgiou and Liolios (2010) examined eight reinforced concrete planar frames under numerous real and artificial sequential ground motions. Thus, the need for the study of the inelastic seismic response of low-, medium- and high-rise steel framed structures to sequential ground motions is apparent.

This paper presents an extensive parametric study on the inelastic response of steel planar frames which are subjected to five real seismic sequences and the created response databank is used to derive important conclusions. Two families of steel framed structures are examined. The first family consists of moment resisting steel frames (MRF) and the second one of multi-storey tension-compression concentrically X-braced steel frames (CBF). It is found that the sequences of ground motions have a significant effect on the response and, hence, on the seismic design of steel frames.

2 Description of the frames and their modeling

The examined steel frames have been designed for seismic and gravity loads according to European codes EC3(1993) and EC8(2005) by Karavasilis et al. (2007a, b). The first family of them consists of thirty-six planar steel framed structures to represent low-, medium- and high-rise MRF. These frames are regular and orthogonal with storey heights and bay widths equal to 3 m and 5 m, respectively. Furthermore, they have the following characteristics: number of stories: 3, 6, 9, 12, 15, and 20; number of bays: 3 and 6. The second family also consists of thirty-six planar steel structures to represent low-, medium- and high-rise CBF. These frames are also regular and orthogonal with storey heights and bay widths equal to 3 m and 6 m, respectively. Moreover, they have the following characteristics: number of stories: 3, 6, 9, 12, 15, and 20; number of bays: 3. An inelastic structural MDOF system with viscously damping and a hysteretic elastoplastic with linear hardening force-deformation relationship are used to investigate its seismic response to actual records. The analysis has been performed using the Ruaumoko program (Carr 2008), which is an advanced finite element program for seismic analysis of framed structures. A two-dimensional model of each structure is created in Ruaumoko to carry out nonlinear dynamic analysis. Each finite element has two nodes and three degrees of freedom at each node. The soil-structure interaction phenomenon is not taken into account, considering fixed base conditions. Second-order effects (P-Δ effects) and large displacements are taken into account. Beam and column elements are modeled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of the beams and columns. On the beams, axial forces were assumed to be zero since all floors are assumed to be rigid in plan to account for the diaphragm action of floor slabs. For the braces of the CBF, the Remenikov-

Walpole model (1997) is adopted. Each of these frames is firstly analyzed for the vertical loads. Then, with the deformed shape taken as the initial displaced shape, nonlinear time history analysis is carried out for the whole gamut of the seismic input, which is examined in the next section.

3 Seismic input

The examined steel structures are subjected to 13 single natural records and 5 real seismic sequences (totally, 18 strong ground motions), which have been recorded during a short period of time (up to three days), by the same station, in the same direction, and almost at the same fault distance. These seismic sequences are namely: Mammoth Lakes (May 1980 - 5 events), Chalfant Valley (July 1986 - 2 events), Coalinga (July 1983 - 2 events), Imperial Valley (October 1979 - 2 events) and Whittier Narrows (October 1987 - 2 events) earthquakes. These records are compatible with the soil class B, and therefore compatible with the design process as mentioned in the previous section. Every sequential ground motion records from the PEER database becomes a single ground motion record (serial array) with a time gap equal to 100sec between two consecutive seismic events. This gap has zero acceleration ordinates and is absolutely enough to cease the moving of any structure due to damping.

4 Selected results

This study focuses on the following basic seismic response parameters: local or global damage index, maximum horizontal floor displacements and interstorey drift ratios. Furthermore, the development of permanent displacements is also examined. Due to lack of space, only selected results are presented.

4.1 Interstorey drift ratio (IDR)

The interstorey drift ratio (*IDR*) is the maximum relative displacement between two stories normalized by the storey height. Figure 1 shows the *IDR* values for a 20-storey CBF both for each single and for the sequential ground motions, corresponding to the Mammoth Lakes earthquakes. It is evident that seismic sequences lead to larger *IDR* in comparison with the corresponding single events. According to SEAOC Blue Book (1999), for ordinary steel braced-frames, *IDR* less or equal to 0.4% corresponds to performance level SP1, i.e., to negligible structural damage, as in the case of the examined single/isolated earthquakes. However, the sequential ground motion leads to $IDR \cong 1\%$ in many storeys, which corresponds to performance level SP3, i.e. to moderate up to major structural damage.

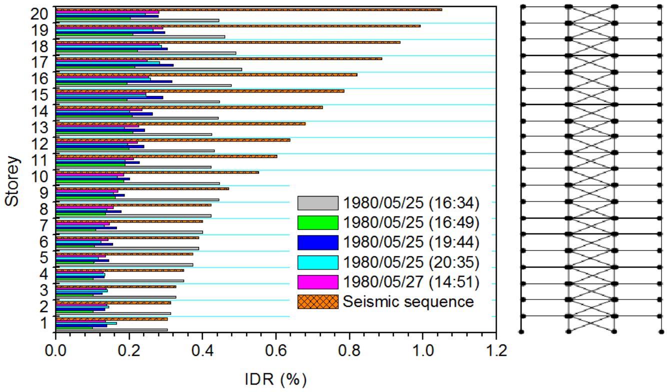

Figure 1: IDR distribution for a 20-storey CBF under the Mammoth Lakes earthquakes

4.2 *Local and global damage*

This section examines the structural damage according to Park and Ang (1985) and Krawinkler and Zohrei (1983) approaches. These damage models have been proposed for structural elements (local damage) but they can also be extended to storey and overall scales (global damage). Figure 2 shows the local damage of the upper-left beam of a three-storey / three-bay MRF under the Imperial Valley earthquakes, examining both the isolated seismic events and the seismic sequence.

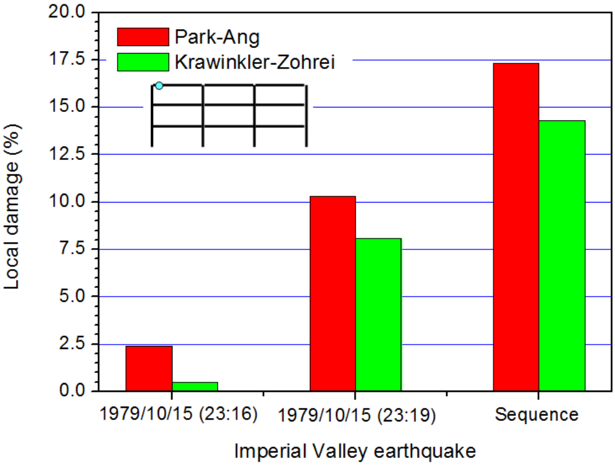

Figure 2: Local damage for a 3-storey MRF (Imperial Valley earthquakes)

Furthermore, Fig. 3 shows the global (total) damage of a six-storey / three-bay MRF under the Coalinga earthquakes, examining both the isolated seismic events and the seismic sequence.

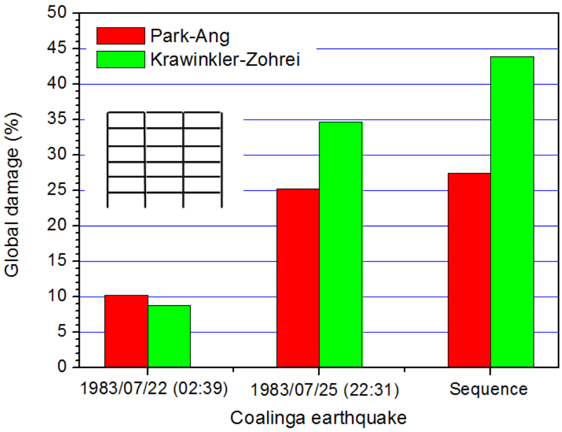

Figure 3: Global damage for a 6-storey MRF under the Coalinga earthquakes

It is evident that seismic sequences lead to increased damage, both at local and global level, in comparison with the corresponding single seismic events.

4.3 Maximum and permanent displacements

The maximum horizontal displacement profiles, both for single and sequential ground motions appear in Fig. 4, which examines a three-storey/three-bay MRF under the Imperial Valley earthquakes.

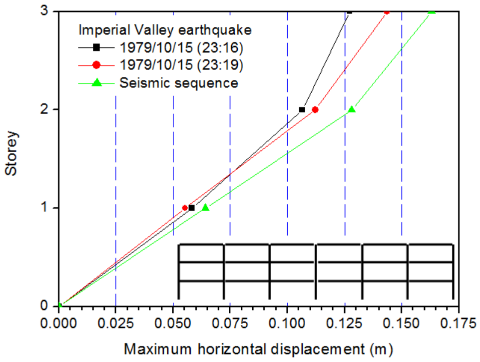

Figure 4: Maximum hor. displacements for a 3-storey MRF

It is evident that due to the multiplicity of earthquakes, increased displacement demands are required. Furthermore, it is well-known that inelastic flexible systems present permanent displacements. In the case of repeated earthquakes, permanent displacements are accumulated. For example, Fig. 5 shows the time history of top horizontal displacement for a 12-storey / 3-bay CBF under the Whittier Narrows seismic sequence, where the cumulative permanent displacement is obvious.

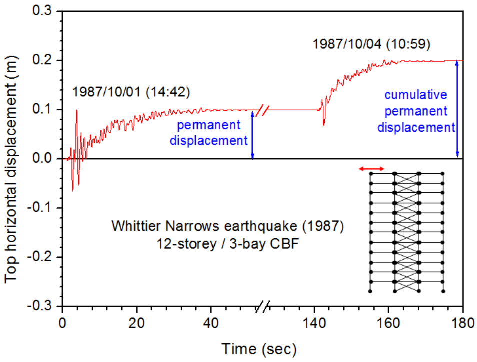

Figure 5: op displacement time history for a 12-storey CBF

5 Conclusions

This paper examines the inelastic behaviour of planar steel frames under repeated earthquakes. Two families of frames are examined, moment-resisting frames and concentrically X-braced frames, which have been designed according to European codes. A detailed study of the problem leads to the following conclusions:

- Multiple earthquakes require increased displacement demands in comparison with single seismic events.
- The seismic damage for multiple earthquakes is higher than that for single ground motions.
- Repeated strong ground motions accumulate permanent displacements.

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