THE INFLUENCE OF MULTIPLE EARTHQUAKES ON STEEL STRUCTURES

Dimitri Loulelis
Civil Engineer, MSc
Department of Civil Engineering, University of Patras, Patras, Greece
e-mail: dloulelis@yahoo.gr

Christina Danessis
Civil Engineer, MSc
Consulting Engineer, Corinth, Greece
e-mail: xloyxloy@gmail.com

Panos Koulis
Civil Engineer, MSc
Department of Civil Engineering, University of Patras, Patras, Greece
e-mail: alexkoulis@yahoo.com

Andreas Thanasoulias
Civil Engineer, MSc
Department of Civil Engineering, University of Patras, Patras, Greece
e-mail: andreasth13a@hotmail.com

George Hatzigeorgiou
Assistant Professor
Department of Environmental Engineering, DUTH, Xanthi, Greece
e-mail: gchatzig@env.duth.gr

Dimitri Beskos
Professor
Department of Civil Engineering, University of Patras, Patras, Greece
e-mail: d.e.beskos@upatras.gr

ABSTRACT

In this work an extensive parametric study on the inelastic response of steel planar frames which are subjected to sequential strong ground motions is presented. 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 X-braced steel frames. These structures have been designed both for seismic and vertical loads according to European codes EC3 and EC8. The whole range of frames is subjected to forty artificial seismic sequences. In such cases, there is a significant damage accumulation as a result of multiplicity of earthquakes, and due to lack of time, any rehabilitation action is impractical. Comprehensive analysis of the created response databank is employed in order to derive important conclusions. It is found that the sequences of ground motions have a significant effect on the response and, hence, on the design of steel frames.

1. INTRODUCTION

Modern seismic codes are based on the isolated and rare 'design earthquake' and ignore the effects of the repeated earthquake phenomena. Recently, Hatzigeorgiou and Beskos [1] and Hatzigeorgiou [2-4] 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. [5] 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 [6], the repetition of the same record seems to be inappropriate for the realistic prediction of structural behaviour. Recently, Hatzigeorgiou and Liolios [7] 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 sequential strong ground motions. 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). The examined steel frames are subjected to numerous artificial seismic sequences and the created response databank is used to derive important conclusions. 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

The examined steel frames have been designed for seismic and gravity loads according to European codes [8, 9] by Karavasilis et al. [10, 11]. 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 and 6. Gravity load on the beams is assumed to be equal to 27.5 KN/m (dead and live loads of floors). The yield stress of the material was set equal to 235 MPa. The expected design ground motion was defined by the acceleration response spectrum of EC8 [9] with soil class B and peak ground acceleration (*PGA*) equal to 0.35g and 0.40g for MRF and CBF, respectively. For more information, the reader can consult Refs [10-11].

3. COMPUTATIONAL PROCEDURE

An inelastic structural MDOF system with viscously damping and a hysteretic elastoplastic with linear hardening force-deformation relationship is used to investigate its seismic response to actual records. The analysis has been performed using the RUAUMOKO program [12], which is an advanced finite element program for seismic analysis of framed structures. A brief description of the modelling details is provided in the following. Thus, in this work, a two-dimensional model of each structure is created in RUAUMOKO [12] 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 modelled 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. Characteristic input data for strength that are required by RUAUMOKO [12] are the bending moment-axial force interaction diagrams for columns and bending strength values for beams. For the braces of the CBF, the Remenikov-Walpole model [13] 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.

4. SEISMIC INPUT

The examined strong ground motion set that has been used here consists of forty (40) artificial seismic sequences. More specifically, 10 artificial accelerograms (R01 - R10) provided by the SRP program [14], which are compatible with the design process of the frames (see Section 1), are considered to generate:

a) 20 synthetic sequences of two seismic events with identical *PGA*, and
b) 20 synthetic sequences of three seismic events with identical *PGA*

These two subsets of records correspond to *Cases* 2 and 3 of seismic sequences which are analytically examined in Refs [1, 2]. Each sequential ground motion 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.

5. 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.

5.1 Interstorey drift ratio (IDR)

The interstorey drift ratio (*IDR*) is the maximum relative displacement between two stories normalized by the storey height. *Fig. 1* shows the *IDR* values for a 9-storey CBF both for each single and for the sequential ground motions, corresponding to R01 and R09 records. It is evident that seismic sequences lead to larger *IDR* in comparison with the corresponding single events.

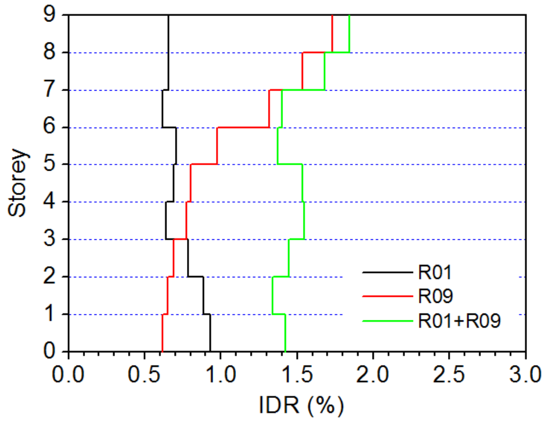

Fig. 1. IDR distribution for a 9-storey CBF under the R01 and R09 records

5.2 Local and global damage

This section examines the structural damage according to Park and Ang [15] approach. This damage model has been proposed for structural elements (local damage) but they can also be extended to storey and overall scales (global damage), by summation of damage indices using appropriate multiplication weights [16]. *Fig. 2* shows the maximum local damage of three CBF structures: a three-storey/three-bay (No. 3), a six-storey/three-bay (No. 6) and a nine-storey/three-bay (No. 9) structure. These steel frames are subjected to a triple seismic sequence, examining both the single seismic events and the seismic sequence. It is evident that seismic sequences lead to increased damage in comparison with the corresponding single seismic events.

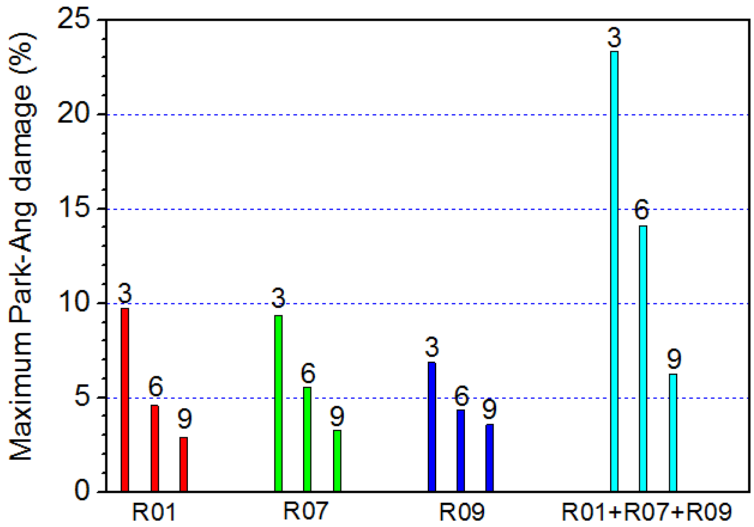

Fig. 2. Maximum local damage for a 3-, 6- and 9-storey CBF

5.3 Maximum and permanent displacements

The maximum horizontal displacement profiles, both for single and sequential ground motions appear in *Fig. 3*, which examines a 15-storey/6-bay MRF under the seismic sequence of records R10, R02 and R09.

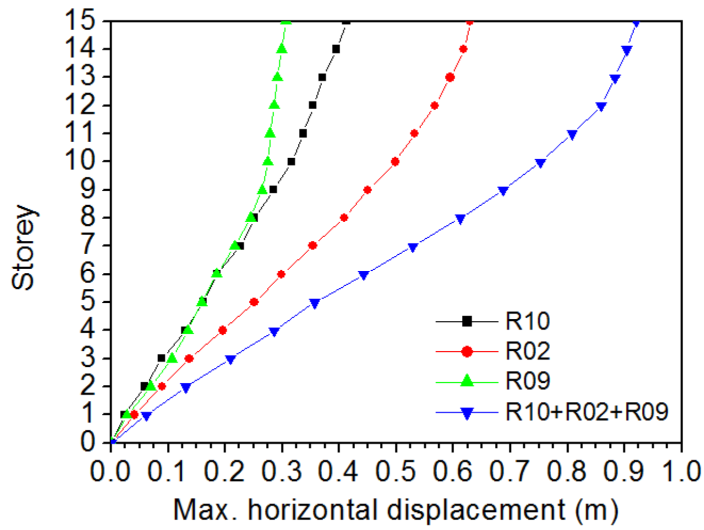

Fig. 3. Maximum hor. displacements for a 3-storey MRF under the Imperial Valley (1979)

It is evident that due to the multiplicity of earthquakes, increased displacement demands are required. It should be noted that inelastic systems present permanent displacements. In the case of repeated earthquakes, permanent displacements are accumulated. For example, *Fig. 4* shows the time history of top horizontal displacement for a 12-storey/3-bay CBF under the seismic sequence R02-R05, where the cumulative permanent displacement is obvious.

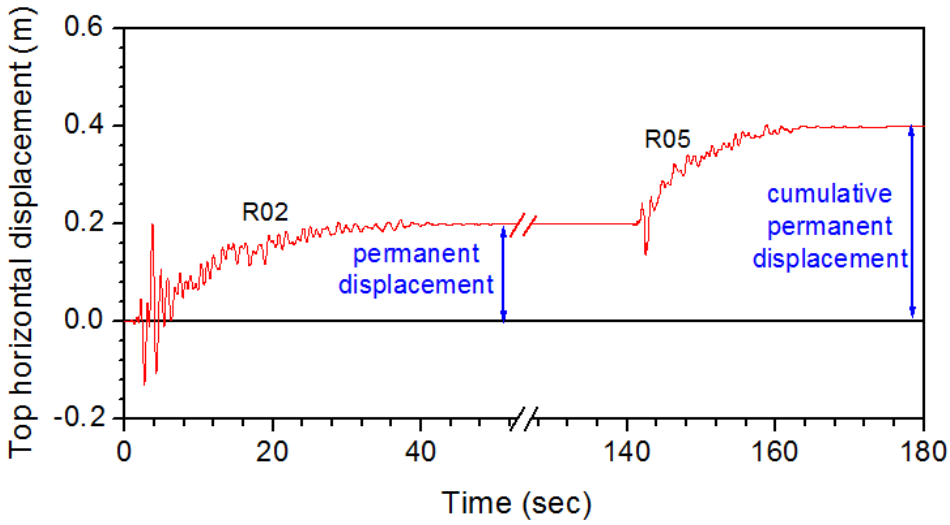

Fig. 4. Displacement time history for a 12-storey CBF under the R02-R05 sequence

6. DUCTILITY DEMANDS FOR MULTIPLE EARTHQUAKES

This section examines the estimation of ductility demands for sequential strong ground motions. As shown in Section 5, multiple earthquakes require increased displacement and ductility demands in comparison with the corresponding single events. The global displacement ductility factor, μ, can be defined in terms of the maximum displacement u_{max} at the top level of the examined buildings and the corresponding yield displacement u_y, as

$$\mu = \frac{u_{max}}{u_y} \tag{1}$$

The definition of yield displacement is that according to Hatzigeorgiou and Liolios[7]. In order to estimate the cumulative ductility for a sequence of strong ground motions, various empirical expressions can be developed. This work proposes the following simple and rational relation [7]

$$\mu_{seq} = 1 + \left[\sum_{i=1}^{n} \langle \mu_i - 1 \rangle^p \right]^{1/p} \tag{2}$$

where the cumulative ductility, μ_{seq}, for a sequence of strong ground motions consists of n-seismic events, results from the corresponding ductility demands, μ_i, for each one of them. Furthermore, p is a parameter controlling the combination of single ductilities and $\langle\ \rangle$ symbolizes the Macauley brackets used here in order to eliminate the influence of weak ground motions, i.e., those for μ_i<1. For example, for a triple seismic sequence with μ_1 >1.0, μ_2 <1.0 and μ_3 <1.0, Eq. (2) provides with the expected ductility demand, $\mu_{seq}=\mu_1$. In order to achieve the best fit for parameter *p* and for the examined structures, this work uses the nonlinear solver of the MS-EXCEL program, which gives the optimum value of parameter p = 1.322 for MRF and p = 1.206 for CBF, examining the whole gamut of steel frames and records. These values are quite similar with that proposed by Hatzigeorgiou and Liolios [7], i.e., p = 1.305, for reinforced concrete structures.

7. 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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Η ΕΠΙΔΡΑΣΗ ΤΩΝ ΠΟΛΛΑΠΛΩΝ ΣΕΙΣΜΩΝ ΣΤΙΣ ΠΛΑΙΣΙΩΤΕΣ ΜΕΤΑΛΛΙΚΕΣ ΚΑΤΑΣΚΕΥΕΣ

Δημήτριος Λουλέλης
Πολιτικός Μηχανικός, ΜΔΕ
Τμήμα Πολιτικών Μηχανικών, Πανεπιστήμιο Πατρών, Πάτρα, Ελλάδα
e-mail: dloulelis@yahoo.gr

Χριστίνα Δανέση
Civil Engineer, MSc
Σύμβουλος Μηχανικός, Κόρινθος, Ελλάδα
e-mail: xloyxloy@gmail.com

Παναγιώτης Κούλης
Πολιτικός Μηχανικός, ΜΔΕ
Τμήμα Πολιτικών Μηχανικών, Πανεπιστήμιο Πατρών, Πάτρα, Ελλάδα
e-mail: alexkoulis@yahoo.com

Ανδρέας Θανασούλιας
Πολιτικός Μηχανικός, ΜΔΕ
Τμήμα Πολιτικών Μηχανικών, Πανεπιστήμιο Πατρών, Πάτρα, Ελλάδα
e-mail: andreasth13a@hotmail.com

Γεώργιος Χατζηγεωργίου
Επίκουρος Καθηγητής
Τμήμα Μηχανικών Περιβάλλοντος, ΔΠΘ, Ξάνθη, Ελλάδα
e-mail: gchatzig@env.duth.gr

Δημήτριος Μπέσκος
Καθηγητής
Τμήμα Πολιτικών Μηχανικών, Πανεπιστήμιο Πατρών, Πάτρα, Ελλάδα
e-mail: d.e.beskos@upatras.gr

ΠΕΡΙΛΗΨΗ

Το παρόν άρθρο αφορά στην διερεύνηση της ανελαστικής σεισμικής συμπεριφοράς μεταλλικών κατασκευών υπό την επίδραση πολλαπλών σεισμών. Εξετάζεται η περίπτωση των καμπτικών μεταλλικών πλαισίων αλλά και των μεταλλικών διασυνδεδεμένων πλαισιωτών κατασκευών με συνδέσμους δυσκαμψίας τύπου-Χ. Η διερεύνηση είναι κυρίως συγκριτική σχετίζοντας τα αποτελέσματα της δράσης της αλληλουχίας σεισμικών δράσεων με τα αντίστοιχα αποτελέσματα για τα ίδια μεταλλικά πλαίσια όταν σε αυτά δρουν οι αντίστοιχοι μεμονωμένοι σεισμοί μόνο. Τα εν λόγω αποτελέσματα αφορούν στις μέγιστες μετατοπίσεις, στις σχετικές γωνιακές παραμορφώσεις ορόφων, στην πλαστιμότητα και στα τοπικά και καθολικά επίπεδα βλαβών. Από την εργασία αυτή γίνεται φανερό ότι το φαινόμενο των πολλαπλών σεισμών θα πρέπει να λαμβάνεται υπόψη στο σχεδιασμό των μεταλλικών κατασκευών αφού οδηγεί σχεδόν πάντοτε σε δυσμενέστερη καταπόνηση, σε σύγκριση με τον σεισμό σχεδιασμού.