EVALUATION OF MAXIMUM SEISMIC DISPLACEMENTS OF STEEL FRAMES FROM THEIR RESIDUAL DEFORMATION

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ABSTRACT

This paper presents a procedure for determining maximum seismic displacements from residual displacements. To this end, the seismic inelastic behaviour of 8 moment resisting steel frames (MRF) and 10 concentrically X-braced steel frames (CBF) is investigated. These structures are subjected to numerous artificial ground motions examining with different values of ground motions' scale, and there the incremental dynamic analyses (IDA) curves are recorded. On the basis of extensive parametric studies, empirical equations are constructed for simple and effective evaluation of maximum seismic deformation from residual displacements, which can be measured in-situ after strong seismic events. It is found that the measure of residual deformation can be effectively used to evaluate the post-earthquake performance level of structures.

1. INTRODUCTION

The past four decades have seen a rapid development of knowledge in seismic analysis. Thus, the evaluation of post-earthquake structural performance has recently received considerable attention in terms of safety assessment, maintenance and repair. The post-earthquake performance level of structures provides a very important source of information both for probable rehabilitation procedures and determination of structural response to probable oncoming aftershocks. In this respect, the dynamic characteristics of structures or their seismic response can be used to obtain one of the most important factors of structural performance, i.e., the damage index of the whole structure [1-3].

It should be recognized that residual deformations play an important role for the assessment of the seismic performance level of structures, as shown in Refs [4-10], which focus in quantifying and reducing residual displacements, mainly in a direct displacement-based design framework. After a strong ground motion, residual deformations can be measured in-situ using various methods of structural deformation measures, such as the digital image correlation technique [11], the global positioning system (GPS) [12], or the usage of robotic theodolites (RTS) [13].

Toussi and Yao [14] and Stephens and Yao [15] introduced a qualitative classification of damage, which is based on the residual inter-storey drift ratio (IDR) of structures. However, the damage level is directly defined by the ultimate state and available ductility levels of the structure. Thus, in the cases of a non-ductile and a ductile frame with the same residual IDR values, the corresponding damage levels are quite different. Therefore, it seems more appropriate to determine other than IDR important structural performance properties, such as the maximum displacements, which are directly related to damage and lead directly to the total IDR levels and ductility demands [16].

Recently, Hatzigeorgiou et al. [17] examined the seismic response of SDOF structures and proposed a method for evaluation of maximum displacements from residual displacements. This paper proposes a simple and effective method to evaluate the post-earthquake performance level of steel structures from their residual deformation. Thus, the dynamic inelastic behaviour of 8 moment resisting steel frames (MRF) and 10 concentrically X-braced steel frames (CBF), designed by Karavasilis et al. [18, 19], is investigated here by using the RUAUMOKO analysis program [20]. The proposed method provides empirical equations for evaluation of the maximum structural displacements as functions of residual deformations which can be measured in-situ after strong seismic events. These equations are constructed on the basis of an extensive parametric study concerning the determination of the seismic response of the aforementioned structures. Characteristic numerical examples illustrate the method and demonstrate its efficiency and applicability.

3. DESCRIPTION OF THE STRUCTURES

Thirty six structures (Family A—Frames) are considered to represent the MRF buildings under study. They consist of typical beam–column steel members and are located in a high-seismicity region of Europe with a design/peak ground acceleration (PGA) of 0.35g and soil class B according to EC8 [21]. Furthermore, thirty six steel structures (Family B - Frames) are also considered to represent the CBF buildings under study. It is assumed that they are subjected to a seismic action with PGA equal to 0.40g and founded in soil class B.

The examined MRF and CBF consist of 3 and 6 bays, and 3, 6, 9, 12, 15 and 20 stories where typical examples of them appear in Figs 1-2.

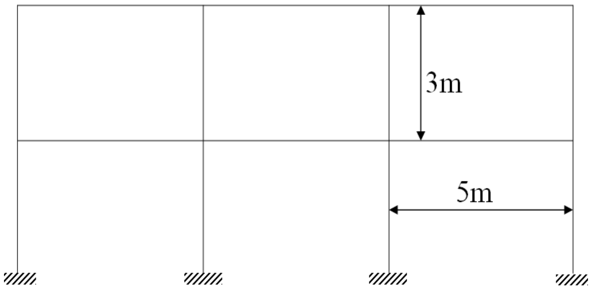

Fig. 1: Typical MRF (Family A)

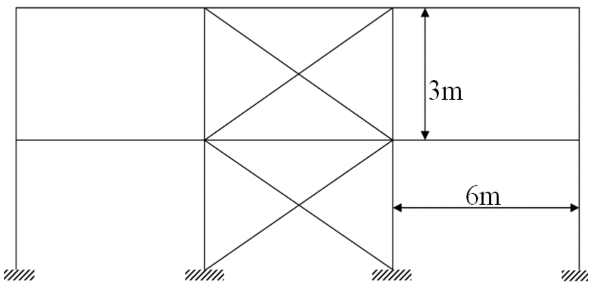

Fig. 2: Typical CBF (Family B)

An inelastic structural multi-degree of freedom (MDOF) system with viscously damped force-deformation relationship is used to investigate the structural response to actual records. The dynamic equilibrium equation of these systems is given in incremental form by

$$M\ddot{u} + C\dot{u} + K^T u = -Ma_g \quad (1)$$

where M is the mass matrix, u the relative displacement vector, C the viscous damping matrix, K^T the tangent (inelastic) stiffness matrix, a_g the acceleration vector of the ground motion and the upper dots stand for time derivatives. The solution of the equation of motion has been performed using the RUAUMOKO program [20], which is an advanced program for seismic analysis of framed structures.

4. SEISMIC INPUT

The strong ground motion database that has been used here consists of ten artificial earthquakes, which are compatible with the design process, i.e., with Type 1 spectrum of EC8 [21], Soil B local conditions and PGA=0.35g or PGA=0.40g, for MRF and CBF, respectively, as shown in Fig. 3. These records have been generated by the specialized software SRP [22].

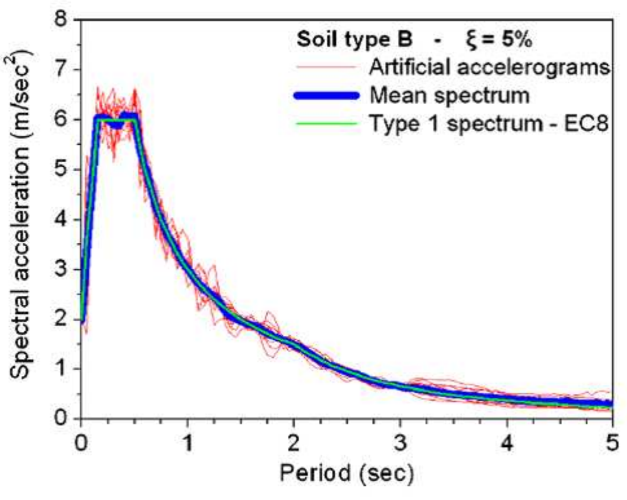

Fig. 3: Response spectra of the examined earthquakes

5. RESULTS

This study proposes a new method to evaluate the post-earthquake structural performance of MRF and CBF. It focuses on the maximum displacements which are directly related to the IDR values and the ductile damage. The proposed method evaluates the maximum displacements from the residual displacements, which can be measured in-situ after a strong ground motion. Thus, the aforementioned MRF and CBF are subjected to ten different artificial ground motions with ten different scale factors for each ground motion: 0.60, 0.70, 0.80, 0.90, 1.00, 1.20, 1.40, 1.60, 1.80 and 2.00, i.e., from 0.40g up to 0.80g. This means that, 100 analyses have been provided (10 accelerograms, 10 scale factors) and performed for each structure, and therefore, 3600 analyses for the whole gamut of the MRF structures and 3600 analyses for the whole gamut of the CBF structures. *Figures 4* and *5* show the permanent deformation vs. maximum displacements diagrams for the examined structures.

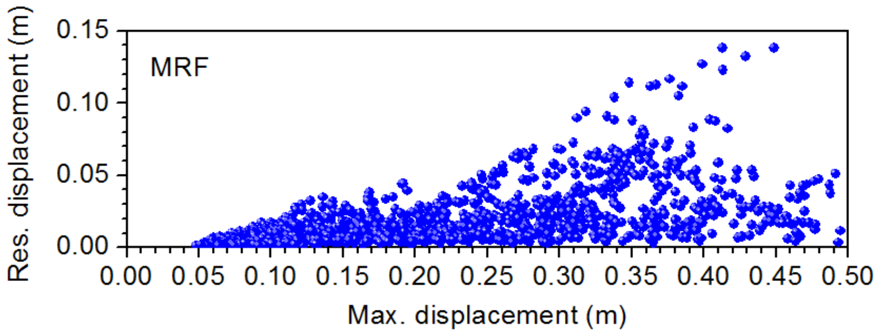

Fig. 4: Permanent deformation - maximum displacement diagram for the examined MRF

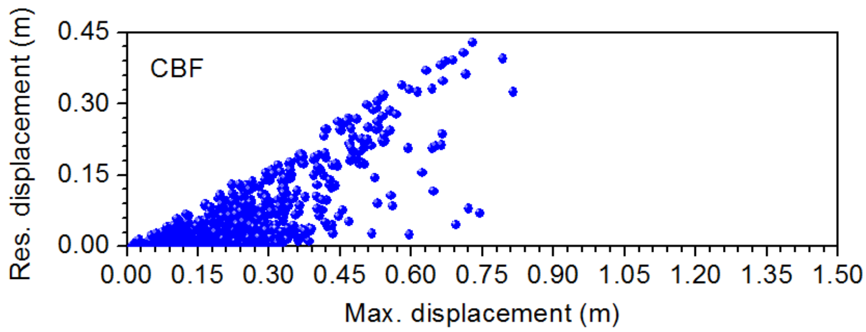

Fig. 5 Permanent deformation - maximum displacement diagram for the examined CBF

From the created databank of results, simple empirical equations providing the maximum structural displacements at the top of each structure as functions of residual deformations are developed. It should be noted that the statistical analysis takes into account all the data sets where the ratio between the permanent top displacement and the total height of structure is greater or equal to 0.01%, avoiding this way the cases that we have elastic structural behaviour. Residual deformations can also be measured in situ after an intense ground motion, as mentioned above. In this work, it is assumed that the maximum displacement, u_{max}, can evaluated from the residual displacement u_{res} as

$$u_{max} = a_1 + a_2\, ln(N) + a_3 u_{res} \tag{2}$$

where N is the number of storeys of each structure, and a_1, a_2 and a_3 are appropriate parameters which have been determined to have the best fit for Eq.(2). This empirical expression was one of the simplest equations which better described the numerical data following downward and upward concave curves, obtained by Table Curve 3D program [23] after testing about 8000 mathematical equations. The criterion for the selection of this equation has to do with its minimum absolute residual error using the Pearson VII limit, i.e., minimum sum of $\ln[\sqrt{(1+residual^2)}]$. Values of the parameters a_1, a_2 and a_3 have been determined for all the data sets (structures, records and scale factors for records). These parameters appear in *Table 1*, where the correlation coefficient R^2 is also provided.

	a1	**a2**	**a3**	$\mathbf{R^2}$
MRF(A1-A36)	-0.05571	0.11568	1.70633	0.767
CBF(B1-B36)	-0.07161	0.07690	0.87576	0.892

Table 1: Values of a_1, a_2 and a_3 parameters

The evaluation of maximum displacement from the permanent displacement using the 'exact' approach (from dynamic inelastic analysis) and the proposed method (using Eq. (2)) is shown in *Figs 6* and *7*. It is evident that the model results obtained from this study are in good agreement with those obtained from the 'exact' dynamic inelastic analyses.

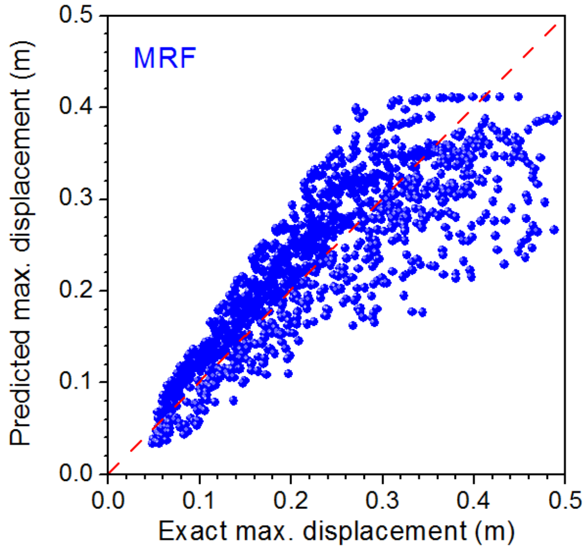

Fig. 6: Evaluation of maximum displacements for the examined MRF

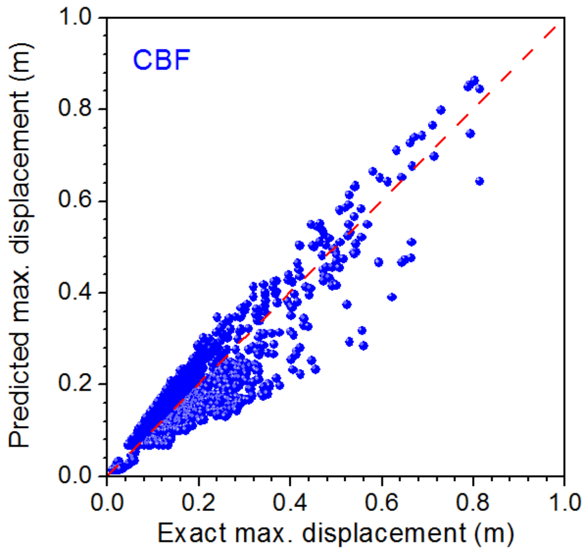

Fig. 7: Evaluation of maximum displacements for the examined CBF

Furthermore, *Figs 8* and *9* present the time history of top-horizontal displacement of characteristic frames where the permanent displacement and the maximum displacement prediction are also shown.

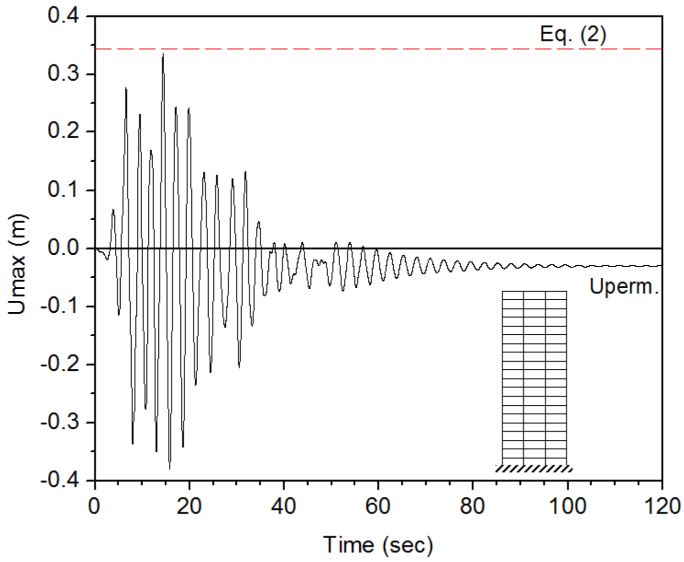

Fig. 8. Displacement time history for a typical MRF

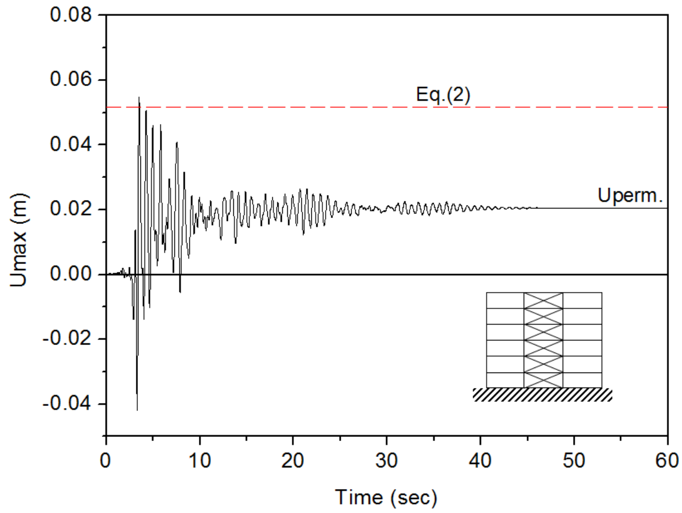

Fig. 9. Displacement time history for a typical CBF

6. CONCLUSIONS

This paper derives empirical equations for the evaluation of maximum displacements from permanent displacements for planar MRF and CBF frames under strong ground motions. A detailed study of the problem leads to the following conclusions:

- The maximum displacements can be effectively evaluated from known residual displacements. The proposed method requires only the knowledge of residual displacement and the fundamental period of the structure.
- The proposed method can be used both for MRF and CBF frames. Furthermore, it can be applied to low-, medium- and high-rise frames.

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ΕΚΤΙΜΗΣΗ ΤΩΝ ΜΕΓΙΣΤΩΝ ΣΕΙΣΜΙΚΩΝ ΜΕΤΑΤΟΠΙΣΕΩΝ ΤΩΝ ΜΕΤΑΛΛΙΚΩΝ ΠΛΑΙΣΙΩΝ ΑΠΟ ΤΙΣ ΠΑΡΑΜΕΝΟΥΣΕΣ ΜΕΤΑΤΟΠΙΣΕΙΣ

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ΠΕΡΙΛΗΨΗ

Το επίπεδο επιτελεστικότητας των κατασκευών μετά έναν ισχυρό σεισμό παρέχει μια πολύ σημαντική πηγή πληροφόρησης τόσο για τις πιθανές διαδικασίες αποκατάστασης όσο και για τον προσδιορισμό της απόκρισης σε πιθανούς επερχόμενους μετασεισμούς. Η επιτελεστικότητα αυτή περιγράφεται κυρίως από τις μέγιστες μετατοπίσεις των κατασκευών οι οποίες σχετίζονται άμεσα με τις βλάβες στα φέροντα και μη-φέροντα στοιχεία. Με βάση εκτενείς παραμετρικές διερευνήσεις σε μεταλλικές διασυνδεδεμένες πλαισιωτές κατασκευές με συνδέσμους δυσκαμψίας τύπου-Χ, στην εργασία αυτή προτείνονται απλές εμπειρικές εξισώσεις οι οποίες οδηγούν σε μια απλή και αποτελεσματική εκτίμηση των μέγιστων σεισμικών μετατοπίσεων από τις παραμένουσες μετατοπίσεις. Οι τελευταίες μπορούν να μετρηθεί επί τόπου, μετά από ισχυρές εδαφικές κινήσεις λόγω σεισμού. Από την εργασία αυτή γίνεται φανερό ότι οι παραμένουσες μετατοπίσεις μπορούν να χρησιμοποιηθούν αποτελεσματικά για να αξιολογηθεί το επίπεδο επιτελεστικότητας μετά τους σεισμούς των πλαισίων από χάλυβα με διαγώνιους συνδέσμους.