Using Nonlinear Static Procedures for the Seismic Assessment of Irregular RC Buildings

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LISBOA 2012

R. Sousa
ROSE Programme, UME School, IUSS Pavia, Italy

T. Eroğlu
Earthquake Engineering Research Center, Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

D. Kazantzidou, M. Kohrangi, L. Sousa & R. Nascimbene
European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Pavia, Italy

R. Pinho
Civil Engineering and Architecture Department, University of Pavia, Italy

SUMMARY:
The application of Nonlinear Static Procedures (NSPs) to assess the seismic vulnerability of existing structures has become widely accepted and extensively used in the literature as well as in engineering practice. Nevertheless, their success in predicting the response of irregular buildings is not yet fully verified. The main goal of the present study is to evaluate the capability and accuracy of some of the existing nonlinear static procedures (N2 and ACSM, in this case) to estimate the seismic performance of irregular structures. In order to accomplish this objective, four existing buildings, irregular in plan and elevation, were subjected to an extensive number of nonlinear static and dynamic analyses. The comparisons, focused on both global and local response parameters provide first indications on the reliability of static procedures to estimate the actual response of irregular RC buildings.

Keywords: Nonlinear Static Procedures; Irregular 3D buildings

1. INTRODUCTION

Nonlinear Static Procedures (NSPs) represent relatively simplified approaches for the evaluation of the seismic response of existing structures, complementing well the more elaborate, or at least more time-consuming, nonlinear dynamic analysis procedures. Despite being considered a suitable approach for regular structures, their yet unproven applicability for the seismic assessment of irregular structures has been pointed out as one of the main shortcomings of NSPs.

As such, several authors recently presented successive improvements to existing procedures, offering advanced tools and methodologies that, directly or indirectly, try to adequately tackle the characteristics of the response of irregular buildings, particular their torsional behaviour (e.g. Fajfar *et al*. 2005 and Bath, 2012). Nevertheless, the validation of such nonlinear static procedures applied to assess irregular structures has so far been object of limited scrutiny, which limits its generalised application and, in a critical scenario, may lead to unconservative assessment of existing buildings.

In a recent study, Pinho *et al*. (2012) assessed the performance of five different Nonlinear Static Procedures (NSPs): CSM (Freeman *et al*., 1975), N2 (Fajfar and Fischinger, 1988), MPA (Chopra and Goel, 2002), ACSM (Casarotti and Pinho, 2007) and AMC (Kalkan and Kunnath, 2006). The study consisted in analysing 16 planar buildings with different structural and material properties. The validity of the static procedures was assessed with sets of records employed for dynamic analysis. Based on the response measured with the different NSPs, it was possible to observe that, despite the general trend for underestimation of the reference response, in general the values were reasonably close (considering their implicit simplifications) to those obtained with nonlinear dynamic analyses. Moreover, no single NSP demonstrated a clear supremacy, since their relative performance varied as a function of the measured response parameter.

Bhatt (2012) performed a set of parametric studies to assess the performance of different NSPs, namely the extended N2 (Fajfar *et al*. 2005), the CSM-FEMA440 (ATC, 2005), the MPA and the ACSM methods, applied to three existing plan-asymmetric reinforced concrete (RC) buildings. This study introduced the CSM-FEMA440 and the ACSM as the most reliable procedures, in the sense that they reproduce the nonlinear dynamic median response in a better manner compared to other methodologies. The good results obtained by the ACSM were justified by the use of an Adaptive Displacement Pushover (DAP) and an equivalent SDOF transformation based on the current deformed pattern. In addition, it is shown that the responses measured with the extended N2 method tend to overestimate the response on both sides of the building.

In summary, among all, the performance of ACSM, MPA and CSM (particularly in the procedure recommended by FEMA-440) proved similar in the generality of the response parameters evaluated. Moreover, procedures that incorporate torsional coefficients such as the extended N2 method, provide response parameters that are, in general, conservative with respect to nonlinear dynamic analysis. This last point is particularly important given the uncertainties involved in modelling the actual properties of structures. This way, and particularly in what practitioners activities are concerned, a safe evaluation of the buildings behaviour can be extremely valuable. On the other hand, given the complexity associated with such innovative static procedures, which are intended to be kept simple, its application can be too complex and demanding. For instance, Baros and Anagnostopoulos (2008) support that despite sophisticated extensions of NSPs to unsymmetrical buildings may be possible, it must be reminded that static methods were introduced as simple methods for checking potential weaknesses of new seismic designs and capacities of existing structures. Moreover, these authors state that refining them to a degree that may not be justified by their underlying assumptions and making them more complicated to apply than even nonlinear dynamic analysis, is certainly not justified and defeats the purpose of using such procedures.

In the current work, the performance of two well-known nonlinear static procedures is evaluated by comparing the results of different the NSPs against a large set of, more reliable, nonlinear dynamic analyses. As such, four existing irregular RC buildings, representative of traditional Mediterranean construction, were subjected to an extensive number of both nonlinear static and dynamic analyses. The results, appraised at both global and element level provide indications and guidance on critical issues that require urgent attention in order to overcome uncertainties associated with the application of NSPs for seismic assessment of existing RC buildings.

2. COMPARATIVE STUDY

2.1. Overview

To perform the present parametric study, four existing irregular structures, located in the Mediterranean area, were selected on the basis of their irregularity in plan and/or elevation. The material properties correspond to the mean values obtained from in-situ testing and are in line with the average characteristic values observed during a detailed assessment of the structural features of Turkish and Italian RC buildings (Bal *et al*., 2008; Mpampatsikos, 2008) The plan view of the models used in the current study is presented in Fig. 2.1.

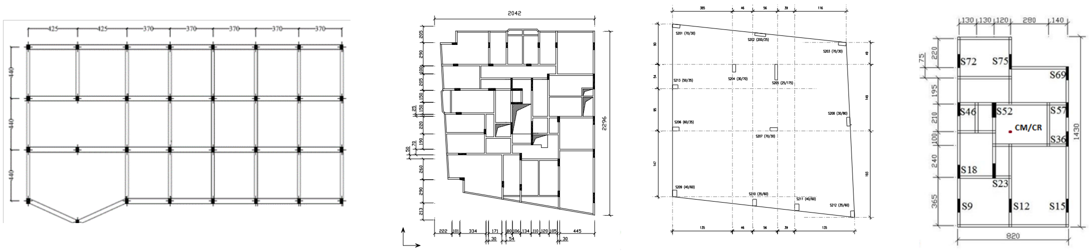

Figure 2.1. Plan view of the 2-, 4-, 5- and 8-storey building (left to right).

The evaluation of the different analysis options is measured at both global (total base shear and lateral top displacement) and element (shear forces and chord rotations) level, following the current seismic code prescriptions such as the ones presented in Eurocode 8 (CEN, 2005).

Finally, it is noted that the local responses measured in dynamic analyses were not selected according to the maximum performance (maximum top displacement and corresponding base shear), but instead based on the maximum response (element shear force and element chord rotation) experienced during the entire record.

2.2. Analysis Methodologies

2.2.1. Nonlinear static procedures

The NSPs selected to be assessed in the present study are the well-known N2 method and the ACSM. The N2 method is currently the NSP recommended by Eurocode 8 and one of the most popular and widely employed in design office applications. However, this procedure features some potential limitations in what concerns the consideration of higher mode effects and the progressive structural damage. Since the main interest of this work is focused in the assessment of irregular RC buildings, it is important to investigate if improved procedures such as ACSM, that features an adaptive pushover approach, are able to improve the results obtained with non-adaptive approaches.

In addition, in order to evaluate the effect of application of different load distributions on the performance of N2 method, different load distributions have been applied and the results have been compared. As such, two classical load distributions of first mode proportional and uniform suggested by Eurocode 8 as well as three other advanced load distributions of adaptive, multi-modal and triangular suggested by Italian code (DM, 2008) or the FEMA-356 (FEMA-356, 2000) are applied and the results based on different approaches are compared.

2.2.2. Nonlinear dynamic analysis

The most logical and insightful way of representing the seismic action is by means of accelerograms measured during a seismic event, without neglecting the seismic motion properties such as shape or energy content. For this reason, nonlinear dynamic analysis is widely accepted as being the most accurate method for the seismic assessment/design of structures.

The dispersion in the structural response resulting from the specific properties associated to each accelerogram implies that it is necessary to consider several records, in order to get a wide and reliable set of results. As a result, this method turns out to be significantly more time demanding, especially in the case of multi-storey and/or highly irregular buildings, when a 3D model is examined.

2.3. Definition of seismic input

In order to obtain realistic structural response estimations, which will be used to appraise the different NSPs, several nonlinear dynamic analyses have been performed in SeismoStruct (Seismosoft, 2010a). The characterisation of the seismic action for both static and dynamic analysis is defined based on the actual performance of the building, rather than the hazard corresponding to the location where the building is sited. This way, the seismic hazard, defined according to the Eurocode 8 prescription, is such that the acceleration response spectrum corresponding to the Limit State of Significant Damage (probability of exceedance of 10% in 50 years) leads to a target roof displacement that imposes a structure stage close to collapse. In addition, the response spectrum was defined according to the ground type C in order to widen the maximum acceleration plateau, highlighting this way the higher mode effects.

Following the definition of the acceleration response spectra for each building, a set of 7 bi-directional accelerograms was selected to apply in both directions. For each building, the selected set of records was matched as close as possible with the acceleration response spectrum defined for each case, featuring a mean acceleration spectrum matching with respect to code response spectrum. In order to avoid a high dispersion on the results, the records were matched, using the software SeismoMatch (Seismosoft, 2010b), adjusting ground-motion records so that their spectral acceleration response matches the target response spectrum. Since the records have different intensities for the two directions, the stronger component with higher PGA was matched to the defined response spectrum while the weaker component with a lower PGA was matched to a spectrum that is reduced based on the ratio of the peak ground accelerations observed in each direction. Finally, with the purpose of reducing the analyses time, the records were shortened to their significant duration, which is defined as the interval between the build up of 5% and 95% of the total Arias Intensity, as recommended by Bommer and Martinez-Pereira (1999).

3. STRUCTURAL RESPONSE

In this section, the results obtained for the different NSPs are compared with the benchmark nonlinear dynamic analysis. The main goal is to identify, based on the relative performance and applicability, the pros and cons of the analysed NSPs and conclude about the applicability of such static procedures to assess irregular RC buildings. Due to the large volume of results, only some representative plots are presented (a full set of results will soon be published in a research report).

3.1. N2 method

The N2 method is currently the NSP recommended by Eurocode 8 and one of the most applied method to assess the seismic performance of structures. As previously mentioned, NTC-08 and FEMA-356 promote the use of different lateral load distributions, in particularly the multi-modal, and adaptive to perform nonlinear static analyses. Thus, in order to evaluate the performance and superiority of each different load distribution, the capacity curves obtained for each distribution are compared with the dynamic results. Fig. 3.1 shows the results of a global comparison between different load distributions.

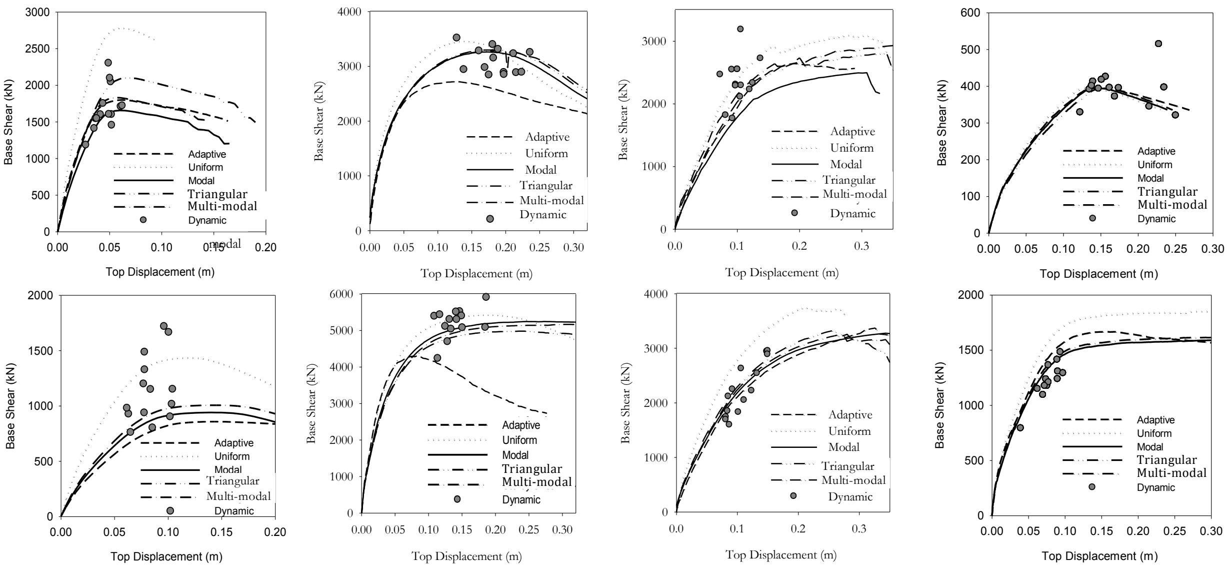

Figure 3.1. Capacity curves and dynamic performance for 2-, 4-, 5- and 8-storey building (left to right), assuming the most realistic simulation, in X (top) and Y (bottom) directions.

Supported by the results provided by each load distribution, one can conclude that in general, the modal and uniform distribution define, respectively, the lower and upper limit of the buildings capacity, while the triangular, adaptive and multi-modal tend to provide an intermediate response. In addition, the pushover curves obtained for each building indicate good agreement with the set of 7 records used in each direction to perform the dynamic analyses. The dynamic points represent the combination of maximum top displacement with the corresponding base shear measured in an interval of 0.5 seconds before and after the peak displacement. Despite the good correlation observed, given the variability associated with each accelerogram, it is not possible to distinguish one load distribution that performs better for the four different buildings in both orthogonal directions.

Given the good correlation observed in global quantities, it is now important to assess the performance of the N2 method for what concerns the elements shear forces and chord rotations. In this case, and contrarily to the determination of global parameters, the elements performance computed for dynamic analyses denotes the maximum response (element shear and chord rotations) measured during the entire record. Fig. 3.2 shows the results of the shear forces and chord rotations obtained for the 5-storey building. In this figure the maximum, minimum and mean of the results obtained from 14 dynamic analyses along with the results of three load distributions (modal, uniform and adaptive) are depicted. The results of the NSPs are corresponding with the performance point derived based on N2 method for each approach.

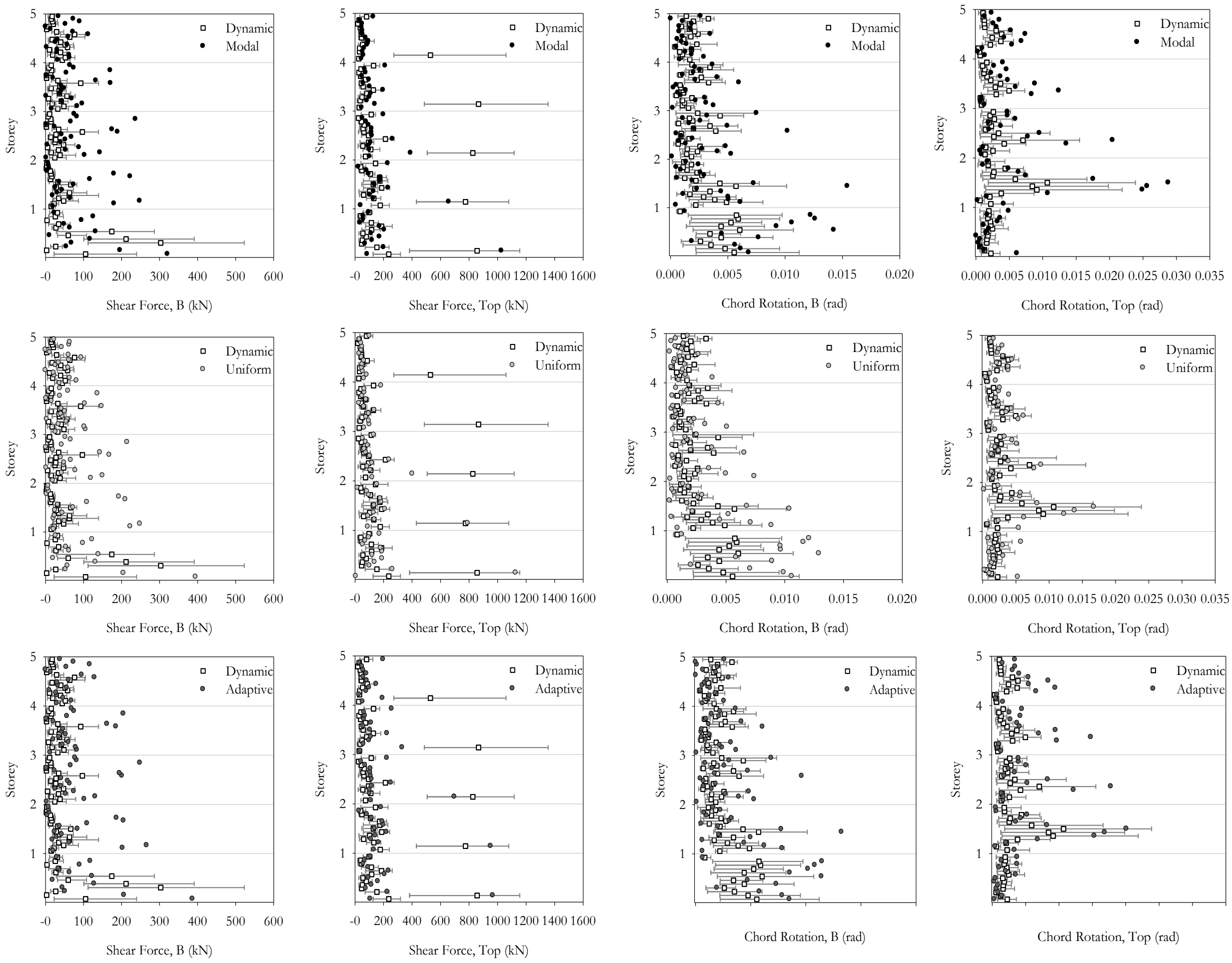

Figure 3.2. Beams' (1st and 3rd column) and columns' (2nd and 4th column) shear forces and chord rotations for the 5-storey building analysed under static (N2 method with different load distributions) and dynamic analyses, in X directions.

As can be seen in Fig. 3.2 the elements shear forces measured for modal, uniform and adaptive load distributions indicate a good agreement with the mean of maximum shear forces obtained with dynamic analyses for most of the cases. Moreover, apart from some specific cases, the elements responses estimated by N2 method are overestimated with respect to dynamic analyses. In accordance with the results obtained in terms of shear forces, the generality of chord rotations estimated with the N2 method are in a good agreement with the ones obtained with dynamic analyses. Moreover, it seems difficult to identify one load distribution that performed consistently better with respect to the others. Given the relative simplicity of static analyses with respect to their dynamic counterpart, the apparent overestimation of the deformations provided by the static procedure is seen as a positive outcome.

3.2. Adaptive Capacity Spectrum Method

In this section, the performance of the Adaptive Capacity Spectrum Method (ACSM) is subjected to scrutiny by comparing the response of the 2-storey building obtained with two static procedures and dynamic analysis. Fig. 3.3 shows the results for the shear forces and chord rotation obtained with N2, ACSM and dynamic analyses.

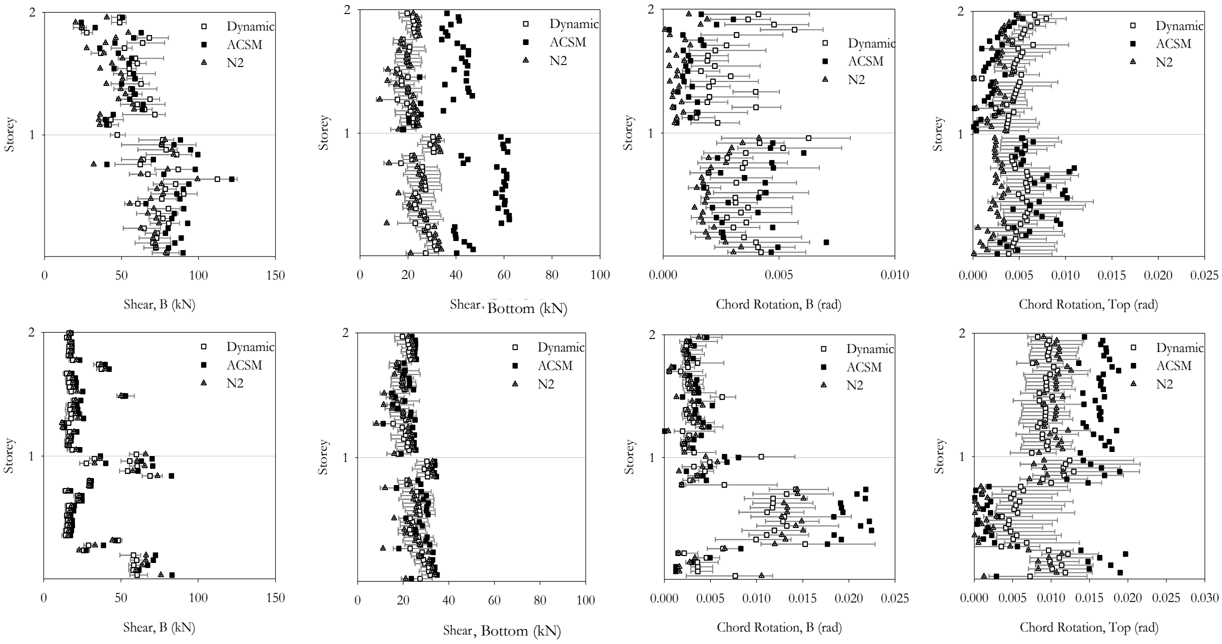

Figure 3.3. Beams and columns shear forces and chord rotations measured for the 2-storey building, analysed under static (ACSM and N2-modal distribution) and dynamic analyses in X (top) and Y (bottom) directions.

Supported on the results presented in the figures above, it is clear that the ACSM estimates both shear forces and chord rotations in a more conservative manner, compared with N2 method. If in some cases (e.g. columns shear forces in X direction) the responses are significantly higher than the ones estimated by dynamic analysis, on the other hand, the underestimation of chord rotations observed in some elements in X direction are, with this approach, determined in a more accurate manner.

The main reason behind this fact is a result, not by application of different load distributions applied that, as previously seen lead to relatively similar capacity curves, but instead in the different approaches followed by different NSP to determine the performance points for each limit state. Focused on Fig. 3.4, it is clear that the performance points determined for the 2-storey building by ACSM occur for significantly higher lateral displacements than the ones computed by the N2 method. Consequently, the local responses measured with the ACSM, in especially the elements' chord rotations, are substantially higher than the ones provided by N2 method.

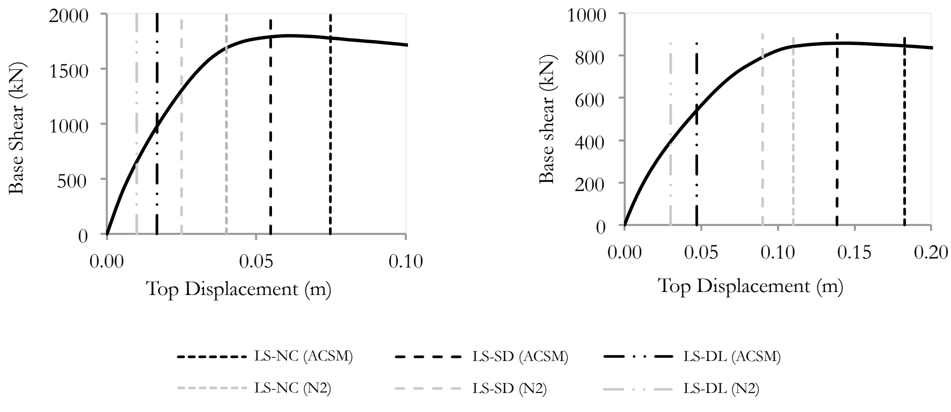

Figure 3.4. Performance points resulting from the application of the N2 method and ACSM for the 2-storey building in X (left) and Y (right) directions.

3.3. Overview

In the previous sections the performance of each individual NSP was evaluated based on the selection of the responses measured for different buildings. The results indicate that the analysed NSPs are generally able to predict the overall response of the buildings under analysis. Nevertheless, as the buildings become more irregular, the correlation between static and dynamic analysis reduces in certain elements. In Fig. 3.5 and 3.6, the results obtained for the 8-storey building in X and Y direction are presented for both N2 (with adaptive load distribution) and ACSM.

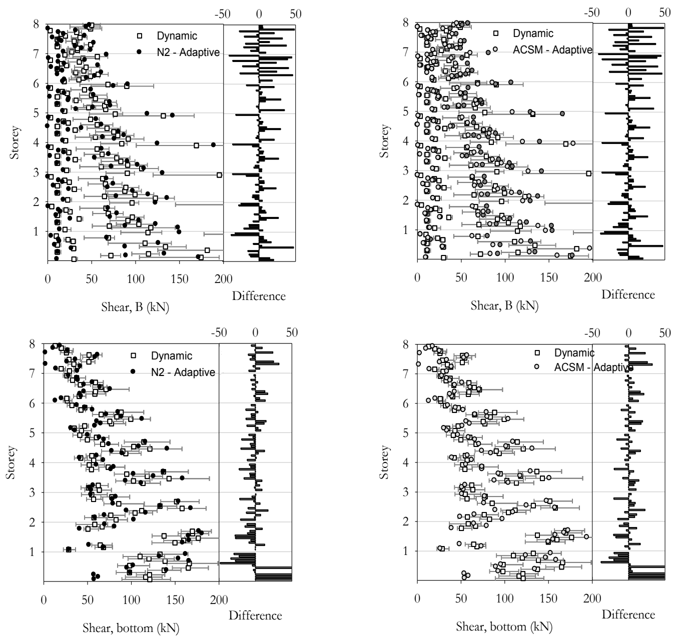

Figure 3.5. Beams' (top) and columns' (bottom) shear for the 8-storey building analysed under static (N2 method, ACSM) and dynamic analyses, in X directions.

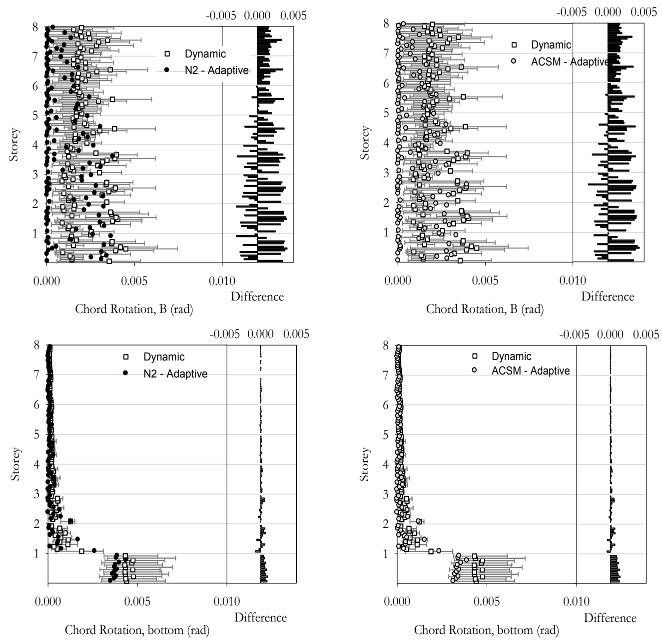

Figure 3.6. Beams' (top) and columns' (bottom) chord rotations for the 8-storey building analysed under static (N2 method, ACSM) and dynamic analyses, in Y directions.

After analysing the performance of the 8-storey building, it is clear that, as the irregularity and the height of the buildings increase, the performance of the static procedures become less accurate. Moreover, the different methods provide similar responses that considerably diverge, being not consistently higher or lower than the ones furnished by dynamic response. This observation leads to the conclusion that, despite the incorporation of an adaptive pushover by ACSM, as the buildings becomes more complex and sensitive to higher modes effects, the results provided by both static procedures become less accurate.

4. CONCLUSIONS

The applicability of nonlinear static procedures to assess the seismic behaviour of structures is a topic of large discussion among the scientific community. In this preliminary study, the response of four existing irregular RC buildings measured with two different NSPs was compared with a set of dynamic analyses. In general, the results obtained following a static approach indicate a good agreement with the dynamic counterpart, in particular for what global response is concerned. However, as the buildings become more irregular and/or the influence of higher modes and the changes in the mode shapes increase, the ability to accurately predict the elements response following static procedures becomes more uncertain. Yet, the ACSM seems to benefit from the use of a DAP and perform relatively better than the conventional single mode N2 method.

In addition, the results obtained by N2 method based on different load distributions of uniform, modal, triangular, multi modal and adaptive are compared in global and element levels. The results show that for the examined cases although adaptive and modal load distributions manage to provide more reliable results compared with dynamic analysis, no load distribution can be identified as the most preferable one.

In conclusion, it seems clear that, independent of the developments introduced in recent static procedures, the performance of such methods is limited when applied to assess irregular and/or buildings whose response is significantly affected by higher modes. Nevertheless, the results provided by pushover analyses allow the identification, in a relatively accurate manner, of the internal distribution of forces, possible failure mechanisms and the way the structure is progressively deformed till it reaches a near collapse stage. Moreover, despite being the most reliable seismic simulation, the results provided by dynamic analysis exhibit a large variability reflecting the structures sensitiveness to the records frequency content. Thus, the seismic assessment of irregular RC buildings should comprise the performance of static analysis to estimate both global and local quantities and identify the overall building response, complemented with a set of more precise dynamic analyses to validate the results previously measured.

The work described herein is currently being complemented by the consideration of additional NSPs, which will hopefully lead to the withdrawal of wider ranging and more representative conclusions. A future publication will include a much more complete set of results, as well as a more comprehensive review of the current state-of-the-art on this topic.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support provided by the Italian Ministry of Foreign Affairs, through the financial program of foreign nationals, and the European Commission, through the financing of the FP7 SYNER-G and NERA research programs, under the framework of which this work has been partially funded. The authors are also very grateful to Dr. Ihsan Bal, for the kind provision of the building models and assistance regarding the interpretation of their structural and non-structural characteristics.

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