PERFORMANCE-BASED NONLINEAR SEISMIC METHODS OF STRUCTURES: A REVIEW OF SCIENTIFIC KNOWLEDGE IN THE LAST 20 YEARS

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Abstract*: The authors of the paper, on the basis of the analysis of several thousand scientific papers, presented their original systematization of nonlinear seismic methods for structural performance analysis, which were developed in the last twenty years. Nonlinear seismic methods are generally classified into two groups: Nonlinear Static Analyses (NSA) and Nonlinear Dynamic Analyses (NDA). The analyses of non linear seismic structural response were classified separately from the target displacement analysis which defines the relationship of the seismic demand and the seismic response. On the other hand, the classification was also conducted depending on whether a nonlinear response of the system is obtained by the implementation of incremental-iterative procedures or by the implementation of semi-iterative and/or semi-incremental procedures. Nonlinear Dynamic Analyses were classified according to the concept of mathematical formulation, i.e. whether they are based on only one dynamic analysis, several dynamic analyses or are solved in combination with other methods. By implementing the conducted systematization and classification of nonlinear seismic methods, on can very efficiently consider which type of method is optimal for structural analysis and which type of method should be taken into account in the phase of preliminary and final analyses in the course of scientific research and professional projects.*
Key words*: systematization, nonlinear seismic methods, structures, performances*

1. Introduction

In the last two decades, development of methods for analysis of structures exposed to earthquake actions saw a rapid expansion. An array of alternatives for solving of common and complex problems was formed, both in everyday engineering practice, and in scientific research. However, the expansion of a large number of these methods raised a number of questions, among which are: Which method, when and for what type of structure should be implemented? These questions are answered in part through scientific publications, but there is still a large number of questions which need to be answered through extensive research and comparative studies, in order to conduct systematization, define algorithms and provide instructions for choice of an optimal type of a method for analysis of structures exposed to earthquake actions. In EN 1998-1:2004 [17] only basic

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recommendations were given, while in the regulations ATC 40 [4], FEMA 440 [20], FEMA 750P [21], FEMA P-58-1 [22] i FEMA P-58-2 [23] far more detailed instructions were provided of how, where and which type of method for analysis of structures exposed to earthquake actions should be implemented.

Improvement of contemporary equipment, laboratories for element testing, structural parts, models and *in-situ* testing of actual structures facilitated a better quality of behaviour analysis and the safety level of newly designed structures to earthquake actions was increased. On the other hand, development of contemporary numerical methods and their implementation in the software solutions supported by hardware resources whose capacity is continuously increasing, facilitates high quality simulation of structural behaviour. In general, it can be concluded that the development of methods for analysis of structures exposed to earthquake actions is directly correlated to a number of factors, the principal ones being: development and improvement of instruments for continuous monitoring of earthquake actions in real time, archiving, digitalization and development of earthquake data bases which are accessible on the internet, development of methods for processing of seismic signals, improvement of experimental research on models and actual structures, development of computer mechanics and numerical methods, development of parallel processing techniques in highly sophisticated scientific-research centers, implementation of new methods and materials in rehabilitation of structures, improvement of the existing and development of new structural systems, development of hybrid methods of structural analysis, introduction of multidisciplinary approach in problem analysis, exchange of experiences on a global level through lectures, meetings, congresses, workshops and publications. The most complex and most extensive research is conducted in highly sophisticated scientific centers, the following centers being the leading ones: *Earthquake Engineering Research Institute* (EERI), *Mid-America Earthquake Center* (MAE), *Multidisciplinary Center for Earthquake Engineering Research* (MCEER), *Pacific Earthquake Engineering Research Center* (PEER), *The John A. Blume Earthquake Engineering Center*, *California Institute of Technology* (CALTECH), *Network for Earthquake Engineering Simulations* (NEES) etc. In these centers are developed new theoretical approaches and numerical analyses, experimental research and hybrid simulations are conducted, whereby a meticulous approach can reliably evaluate, additionally improve or reject the existing methods or even develop new methods for analysis of structures exposed to earthquake actions. Considering that in the last two decades the focus of research in the area of earthquake engineering is on the analysis of structural performance according to *Performance-Based Earthquake Engineering* (PBEE) methodology, a large number of analyses is therefore developed in the framework of this methodology.

2. General systematization of seismic methods

In comparison to the actual physical models of structures, mathematical structural models represent idealized behaviour models with a certain extent of approximation. Analysis of wave propagation through the soil due to earthquake actions, soil-structure interaction, numerical modelling and analysis of structures exposed to earthquake action are continuously being improved along with the development of computer mechanics. In the everyday engineering practice are implemented the linear-elastic models of structural behaviour for analysis of static and dynamic actions. The analyses belonging to this group are *Linear Static Analysis* (LSA) and *Linear Dynamic Analysis* (LDA), i.e. *Equivalent Static Analysis* (ESA) and *Spectral Modal Analysis* (SMA). The usual procedure of implementation of linear calculation models for static or dynamic analysis does not provide insight in the actual behaviour of structures exposed to earthquake actions, because it does not takes into account emergence and development of nonlinear deformations in the bearing structure. Contemporary methods for analysis of structures exposed to earthquake actions are based on implementation of nonlinear behaviour, taking into consideration development and geometrical and material nonlinearities. The analysis belonging to this group are *Nonlinear Static Analysis* (NSA) and *Nonlinear Dynamic Analysis* (NDA). Previously classified static and dynamic analyses of structures are calculated by implementing some of the methods for mathematical-numerical modelling is simulation of structural behaviour. In solving the problems of *Performance-Based Seismic Design* (PBSD) the most utilized methods are *Finite Element Method* (FEM) and *Boundary Element Method* (BEM); a considerable contribution to solving of the problem of structural collapse due to earthquake actions was achieved by the development of *Discrete Element Method* (DEM), *Extended Finite Element Method* (XFEM) and *Applied Element Method* (AEM). On the other hand, there is a number of seismic methods which employ solutions of NSA or NDA and combine them with other scientific disciplines so that the problem is considered multidisciplinary in PBEE. Systematization of these methods is also presented in the paper.

3. *Nonlinear Static Analysis* (NSA)

Nonlinear Static Analysis (NSA) is conducted in capacitive domain, and it is more known as pushover analysis or *Nonlinear Static Pushover Analysis* (NSPA). On the abscise and ordinate of the capacitive domain, *engineering demand parameters* (EDP) are displayed, which are actually structural response parameters. *Target displacement analysis* is conducted as a complement of the final solution obtained by NSPA. NSPA is conducted on an actual *multi degree of freedom* (MDOF) system, while the *target displacement analysis* is conducted on a *single degree of freedom* system (SDOF) or the calculation is directly conducted based on the realized pushover curve. Development of the concept of NSPA and *target displacement analysis* of the buildings designed for seismic areas was initiate more than two decades ago, and official implementations were effected in ATC 40 [4], EN 1998-1:2004 [17], FEMA 356 [19] and FEMA 440 [20] codes. Nowadays, there is a wide range of NSPA and *target displacement analyses*. In case of certain analyses, the calculation of target displacement is directly conducted through NSPA (integrated solution), while in other analyses, this is conducted independently (successive solution). In the second case, it is possible to combine solutions of NSPA and *target displacement analyses* by implementing various approaches. Another important factor which can be taken into consideration in classification of these analyses is type of lateral seismic load. Therefore, three key factors which determine differences in these analyses stand prominent: NSPA type, *target displacement analyses* type and lateral seismic load type. Systematization of NSPA is presented without further detailed classification of these analyses, regarding that for these analyses different types of incremental-iterative algorithms are used. Analyses belonging to this group are:

- *Nonlinear Static Conventional Pushover Analysis* (NSCPA),
- *Nonlinear Static Adaptive Pushover Analysis* (NSAPA),
- *Modal Pushover Analysis* (MPA),
- *Multi-Mode Pushover Procedure* (MMPP),
- *Method of Modal Combinations* (MMC),
- *Incremental Response Spectrum Analysis* (IRSA),
- *Performance-Based Plastic Design* (PBPD),
- *Nonlinear Static Pushover Analysis - Damage Mechanisms-Based Design* (NSPA-DMBD).

NSCPA is based on the continuous retention of distribution of lateral seismic load through all the phases of incremental-iterative analysis, i.e. from initial linear to final collapse state of the structure [2]. NSAPA is based on the correction of lateral seismic load by increments, taking into consideration variation of periods of structural vibrations and spectral amplification of seismic forces according to the acceleration response spectrum or correction of displacement according to the displacement response spectrum [1]. Control of incremental concept for NSCPA and NSAPA is possible via forces as *Force-Based Analysis* (FBA) or via displacements as *Displacement-Based Analysis* (DBA). Depending on how correction of lateral applied forces is conducted, the following options are possible: total (TU), incremental (IU) and hybrid (HU) correction. Depending on the applied control and correction, results with various degree of accuracy are obtained, where application of incremental displacement concept is especially emphasized. In MPA, pushover curves can be evolved according to eigenforms or they can be combined and final solutions for a large number of eigenforms can be obtained by transformation into bilinear curves of the SDOF, for the purpose of calculation of targed displacement and response parameters [10]. MMPP [31] and MMC [26], too, utilize different principles for combinations of actions of eigenforms in the total response of the system, expressed via pushover, where, in addition to the standard ones, combinations of direct superpositions, effective modal superposition and similar stand prominent. IRSA basically uses SMA and the rule of equivalent displacement, whereby the total response of the system is obtained through implementation of the pushover curve [6]. In the mathematical sense, this analysis can be considered as adaptive multimodal pushover analysis, in which modal pushover analyses are simultaneously performed for each eigenform for corresponding scaled modal displacement followed by the corresponding rule for combining of eigenforms. According to PBPD method, for performance states at the level of the entire building, a drift of target displacement chosen in advance, and yield plastic mechanism are used [29]. Design total shearing force at the ground level of the structure, for the chosen level of seismic hazard, is obtained from the calculation of the amount of total work required to bring the structure to the target displacement level and corresponding required energy of equivalent SDOF system. NSPA-DMBD method came into being by bringing together NSPA, *Capacity Design Method* (CDM) and *Damage Mechanisms-Based Design* (DMBD) [13]. NSPA-DMBD method belongs to the group of *Iterative-Interactive Design* (IID) methods, regarding that the procedure of analysis of system failure mechanism is conducted iteratively, and dimensioning is verified after ultimate strains has been reached.

NSA analyses based on the non-iterative and/or non-incremental procedures or implementing semi-iterative and/or semi-incremental procedures are:

- *Force-Based Design* (FBD),
- *Displacement-Based Design* (DBD),
- *Direct Displacement-Based Design* (DDBD),
- *Secant Modes Superposition* (SMS).

These analyses utilize expressions formulated from a large number of numerical tests, experimental research and statistic data processing, through implementation of regression analyses, so that in literature there is lots of ready-made solutions, algorithm and analytical procedures. By implementing these analyses, it is possible as early as in the phase of conceptual design of structures to include its nonlinear behaviour, without venturing into the more detailed aspects of numerical modelling and complex numerical calculations. Fundamental difference between FBD and DBD analyses is because in the former ones, the solution is obtained using forces as an initial parameter, and in latter ones use the displacement parameter. DDBD analyses use a direct approach for obtaining the final solution, whereby, through analytical procedures, the response of the system is obtained via elastoplastic behaviour models, by establishing a relation between the damping - ductility and displacement - period of vibrations [35]. SMS method is developed with the purpose of obtaining a rapid and sufficiently reliable nonlinear response of the system to earthquake actions, without directly taking into account NSPA and NDA, but basing itself on the secant stiffness and indices of system response [34]. Solution is obtained directly in contrast to the methods where the solution is obtained *step by step.*

4. *Target displacement analysis* for *Nonlinear Static Analysis* (NSA)

It was presented in the previous section that *target displacement analysis* represents a second part of NSA analysis. Until now, a large number of these analyses were developed for the purposes of scientific research and professional designs, among which the following are the most common ones:

- *Capacity Spectrum Method* (CSM),
- *Non-Iterative Capacity Spectrum Method* (NICSM),
- *Improved Capacity Spectrum Method* (ICSM),
- *Adaptive Capacity Spectrum Method* (ACSM),
- *Displacement Coefficient Method* (DCM),
- *Iterative Displacement Coefficient Method* (IDCM),
- *Equivalent Linearization Method* (ELM),
- *Displacement Modification Method* (DMM),
- N2 *Method* (N2),
- *Incremental* N2 *Method* (IN2),
- *Yield Point Spectra* (YPS).

CSM belongs to a group of analyses which conduct only *target displacement analysis* from the relations of capacity curve, seismic demand curve and response spectrum [4], [24]. Several types of CSM methods were developed, which use response spectrum in the format *spectral acceleration - spectral displacement* (ADRS), whereby the procedure of determining target displacement level is iterative. This method is implemented in ATC 40 codes [4]. NICSM directly determines the level of target displacement, without iterations, basing on the solutions of equivalent linear methods [39]. This group also includes ICSM [38], [25] and ACSM [9], [8] which are actually improved versions of the existing CSM and which implement statistically optimized linearized parameters and adaptive algorithms for determination of target displacement level. By implementing DCM only *target displacement analysis* is conducted, employing the principle of multiplication of a group of coefficients which takes into account influence of various factors of structural behaviour. This method is implemented in FEMA 356 codes [19]. In IDCM, successively conducted double iterative algorithm is implemented and the solution of target displacement level is, among other things, searched for using a pushover curve [12]. IDCM basically used a mathematical formulation of DCM, whereby, through an iterative algorithm, the solution of target displacement is considerably improved. ELM is actually a new generation of CSM implemented in FEMA 440 codes [20], where instead of a response spectrum in ADRS format, modified response spectrum is utilized in the format *spectral acceleration - spectral displacement* (MADRS). DMM is je, also, a newer generation of DCM, where certain coefficients participating in the calculation were eliminated, while parts of the calculation related to the hysteretic models of structural behaviour were additionally improved. This method was implemented in FEMA 440 codes [20]. *Target displacement analysis* according to N2 method, implemented in EN 1998-1:2004 [17] code is determined by taking into consideration the inelastic response spectrum in function of ductility coefficient [18]. Extension of N2 method is presented in the form of IN2 method, where, except of presentation of EDP parameters on abscissa and ordinate, it is possible to use *intensity measure* (IM) on ordinate [16]. In this way IN2 method can directly compare solutions with *Incremental Dynamic Analysis* (IDA). New spectral presentation of seismic demand is presented by YPS method, in which the basis of CSM and NSPA was retained [3]. YPS method can be used for designing of new and strengthening of existing structures for the required levels of stiffness and bearing capacity, with the additional limitation of global ductility and drift.

5. *Nonlinear Dynamic Analysis* (NDA)

In comparison to the solutions obtained in the capacitive domain using NSA, in NDA solutions are obtained in time domain. Nonlinear response calculation is conducted by implementing numerical integration, whereby the most frequently implemented is *Newmark Average Acceleration Method* (AAM) or *Linear Acceleration Method* (LAM), and also implemented are procedures by *Wilson*, *Hilber-Hughes-Taylor* and *Chung-Hulbert*. The most accurate methods for analysis of seismic response are NDA, if into account is taken full development of material nonlinearity through plastic hinges or by propagation of inelastic deformations by using fibers, and geometrical nonlinearities when the analysis takes into account large deformations and displacements. These analyses include:

- *Nonlinear Dynamic Analysis* (NDA) (modal and numeric integration),
- *Endurance Time Method* (ETM).

By implementing NDA, as already said, a system response in time domain is obtained, but only for one level of seismic demand. On the other hand, implementation of ETM provides system response in time domain with continuous increase of nonlinear deformations, from initially elastic to collapse state [5]. The specific of this method reflects in implementation of specially designed excitation function (accelerogram) which is, among other things, additionally compatible with the response spectrum and optimized for nonlinear system response.

If a set of NDA is implemented while successively increasing scaling factor of the accelerogram, then the final solution can be obtained in capacitive domain. In this sense, it is very favourable to conduct comparison of solutions obtained by NSA and IDA. In fact, solution obtained from a set of NDA in time domain is transformed into capacitive domain. This is performed by singling out extreme and corresponding discrete values which are then interpolated by spline functions. Analyses belonging to this group are:

- *Incremental Dynamic Analysis* (IDA),
- *Incremental Nonlinear Dynamic Analysis* (INDA),
- *Adaptive Incremental Dynamic Analysis* (AIDA),
- *Extended Incremental Dynamic Analysis* (EIDA),
- *Progressive Incremental Dynamic Analysis* (PIDA),
- *Multicomponent Incremental Dynamic Analysis* (MIDA),
- *Stochastic Incremental Dynamic Analysis* (SIDA).

The term IDA is already well-established in scientific research [37], while the term INDA was for the first time introduced in [14] and these analyses refer to a set of NDA in which an accelerogram is successively scaled, whereby the structure is modeled so as to provide the best possible actual physical model of a structure and in which development of complete material and geometric nonlinearity was introduced. AIDA is based on the adaptive variation of selection of ground motion records at different intensities of ground motion [30], while EIDA introduces into the calculation epistemic (depending on the structure model) and aleatoric (depending on the seismic hazard and selection of ground motion records) uncertainties [15]. Epistemic uncertainty is determined by implementing *Latin Hypercube Sampling* (LHS) method. PIDA was developed with an aim of shortening the time necessary for performing of extensive IDA, while retaining the quality level of the solution. [7]. Also, similar to PIDA, MIDA and SIDA were developed, whereby the former analysis can analyze a nonlinear system response for different angles of earthquake actions [28], and the latter analysis, through stochastic modelling among other things, by implementing *Point Estimation Method* (PEM) a solution in capacitive domain is obtained [40].

Special types of NDA which obtain solutions in combination with other methods are:

- *Static Pushover to Incremental Dynamic Analysis* (SPO2IDA),
- *Modal Pushover Analysis based on Incremental Dynamic Analysis* (MPA-IDA),
- *Hybrid Incremental Nonlinear Static-Dynamic Analysis* (HINSDA).

SPO2IDA method is developed in the framework of research [36], and it is based on implementation of NSPA and a number of regression analyses which simulate IDA system response. The obtained system response is located in a capacitive domain, whereby EDP parameters are used on abscissa and IM parameters on ordinate. In case of IDA-MPA, seismic system response is determined from NDA of SDOF system, which is equivalent to MDOF system [33]. In order to obtain a more rapid and sufficiently reliable solution, in comparison to INDA, a completely new procedure called *Hybrid Nonlinear Static-Dynamic Analysis* (HNSDA) was developed [14]. In HNSDA is used nonlinear response to MDOF system from NSPA intended for calculation on the corrected SDOF system by implementing NDA. If nonlinear system response is considered in a capacitive domain, then this analysis becomes *Hybrid Incremental Nonlinear Static-Dynamic Analysis* (HINSDA).

6. *Target displacement analysis* for *Nonlinear Dynamic Analysis* (NDA)

The key aspect for *target displacement analysis*, for NDA, is processing of an accelerogram according to signal processing theory. The accelerogram processing procedure includes analysis, interpretation and presentation of accelerogram through the phases: selection, formatting, conversion, sampling, scaling, calculation, processing, spectral matching, normalization, filtering, generating and transformation [11]. These procedures are executed in time, frequency, frequency-time and capacitive domain. Selection is a procedure of choosing of a certain type of earthquakes or group of earthquakes according to the criteria set in advance, such as the selection according to the criteria whether earthquakes are *far field ground motion* (FFGM) or *near field ground motion* (NFGM), impulse or nonimpulse ones, according to their magnitude, type of mechanism, distance from the location of initiation of propagation of seismic waves, velocity of shear waves in the ground in the top 30m of depth, hypocentral distance or according to some other criteria. Formatting is the procedure of transformation of accelerogram record from the earthquake database and adaptation for the software for structural analysis, while conversion is the procedure of transformation of one measurement units into others. Scaling is a set of procedures which directly or indirectly multiply values of acceleration of the accelerogram according to certain criteria. Scaling of accelerograms is performed by implementing several procedures, the following ones standing prominent: scaling of accelerograms in time domain, scaling of accelerograms in frequency domain, scaling through response spectrum implementing *Least Square Method* (LSM), scaling through the response spectrum by implementing genetic algorithm, spectral matching and similar procedures. Calculation is a set of procedures which determine basic parameters of accelerogram, such as *intensity measures* (IM), while processing is a set of procedures which can have different character such as *Base Line Correction* (BLC), structure of elastic and inelastic response spectrum and similar procedures. Spectral matching is a procedure of creation of representative (compatible) accelerogram on the basis of one real or group of accelerograms according to the given design response spectrum. Normalization is the procedure of balancing of two earthquake components when accelerograms for bidirectional seismic action are used, while filtering is the procedure of implementation of certain filters with the purpose of elimination of unimportant frequency range and retaining of important frequency range. Most often used are *highpass* (HPF) and *bandpass* (BPF), and also *lowpass* (LPF) and *bandstop* (BSF) filters. Generation is the procedure of creation of new accelerograms such as *artificial* or *synthetic* accelerograms, based on the defined procedures in frequency domain. These accelerograms are generated as incompletely non-stationary or completely non-stationary accelerograms. Transformation is the procedure used for determining the frequency content of an accelerogram, i.e. values of amplitudes by frequencies in a frequency domain via implementing *Fourier* transforms.

7. Seismic analyses according to *Performance-Based Earthquake Engineering* (PBEE)

Performance-Based Earthquake Engineering (PBEE) methodology was initiated in the recent twenty years, firstly on a deterministic and then on a probabilistic level. PBEE methodology is based on multidisciplinary approach through computer mechanics, numerical methods, structural dynamics, nonlinear analyses, theory of reinforced concrete structures, theory of plasticity, failure mechanics, soil-structure interaction, earthquake engineering, engineering seismology, implementation of contemporary regulations for structural design, engineering statistics and probability. Development of contemporary PBEE methodology facilitates a more complete and complex analysis and treatment of the problem through *hazard analysis*, *structural analysis*, *damage analysis* and *loss analysis* [27], [32]. *Hazard analysis* is represented by the variable *intensity measure* (IM), which quantifies ground displacement, while *structural analysis* is represented by implementation of *engineering demand parameter* (EDP). *Damage analysis* is represented by the variable *damage measure* (DM), and *loss analysis* by the variable *decision variables* (DV). Relation is established between IM and EDP through *seismic demand model*, which is determined by implementation of *Probabilistic Seismic Demand Analysis* (PSDA) and INDA. However, prior to establishing relation EDP-IM it is necessary to consider IM variable by implementing *Probabilistic Seismic Hazard Analysis* (PSHA). Based on the IM determined from PSHA and on EDP from PSDA, NDA or even via NSPA, a correlation EDP-IM is established, most often via the spectral acceleration for IM and global or interstorey drift for EDP. Model of seismic demand in PSDA analysis can be represented via *fragility curves*. Establishment of correlation between EDP and DM is conducted via *damage model*, which is determined by implementation of *Probabilistic Seismic Damage Analysis* (PSDamA), INDA or NSPA, while establishment of correlation between DM and DV is conducted using *loss model*, and which is determined by implementation of *Probabilistic Seismic Loss Analysis* (PSLA), INDA or NSPA.

8. Conclusion remarks

By implementing the conducted systematization of nonlinear seismic methods, one can efficiently analyze which type of analysis can be implemented in the phases of preliminary and final analyses for scientific research and professional projects. The authors created their own systematization and classification of analyses, with a reserve that certain nonlinear seismic analysis can belong to transitional categories of analyses. It is particularly the case in those analyses which employ multidisciplinary problem formulation, thus a more in-detail consideration of mathematical formulations of all individual nonlinear seismic analyses remains to be performed.

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