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An Overview of Deterministic and Probabilistic Analytical Approaches for Non-Linear Seismic Risk Assessment of Structures

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Abstract: Performance-based earthquake engineering (PBEE) is a framework that seeks to improve decision-making for seismic risk mitigation through assessment and design methods featuring quantifiable performance metrics. The selection of seismic design analysis approach depends on several factors such as the size and layout of the structure, design objectives, seismic design category, and the value of the structure. Generally, analysis methods can be categorized into two major groups: static and dynamic analysis, both of which are possible to be conducted as linear or nonlinear analysis. This paper presents an overview of the procedures of the nonlinear analysis methods, namely the nonlinear static analysis (NL-SA) and nonlinear dynamic analysis (NL-DA), in addition to the development of fragility curves for a probabilistic seismic risk assessment.

Keywords: Non-linear analysis, incremental dynamic analysis, pushover analysis, fragility curves, ground motion records, seismic response.

1. Introduction

To evaluate the performance of structures accurately, nonlinear analyses should be utilized, since real structures yield when subjected to severe earthquakes. In most cases, seismic loads govern the behavior of structures and thus they must be included in the analysis and design procedures of these structures [1]. Static or dynamic nonlinear analysis techniques, such as the Pushover Analysis (POA) and Nonlinear Time History Analysis (NLTHA), are typically used by engineers to determine the behavior of structures efficiently and affordably as opposed to other analysis methods [2]. Numerous guidelines and code requirements include non-linear analysis and Performance-Based Earthquake Engineering (PBEE) methods, but still, some aspects are kept unguided. Many researchers still do not consider this framework as a strict science, but rather an art. Therefore, it is important to provide additional guidance to anchor nonlinear response analysis as a pillar for seismic behavior of structures.

In this study, an overview on the nonlinear seismic assessment was presented in a detailed flow. The discussion starts with a brief overview of the nonlinear performance of structures and the importance of considering it during seismic performance assessment. Then, the nonlinear analysis methods were introduced and the basic concept behind them was defined. This was followed by highlighting the construction of fragility curves in the context of PBEE framework. Finally, important considerations on selecting and scaling of ground motions were reported.

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2. Nonlinear Performance of Structures

The inelastic action of the Reinforced Concrete (RC) material is one of the factors that could result in nonlinear response in RC structural members. Material nonlinearity may be explained by using the stress-strain relationship. When performing a static pushover or an incremental dynamic analysis, the reinforced-concrete frame element of the supporting structure is strained beyond its proportional limit as shown in Fig. 1. Consequently, the structure experiences a nonlinear behavior due to the changes in stiffness matrix in the frame elements, thereby affecting the load-deflection relationship [3].

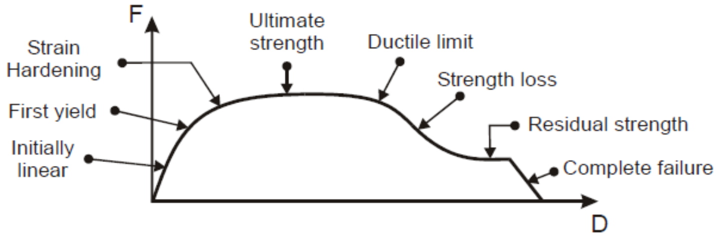

Fig. 1 - Concrete material nonlinearity

Point of nonlinearity in stress-strain behavior of the structural member is called as the plastic hinge. At this state, a reduction of strength and loss in elastic properties of the structural component is experienced, which prevents the component from returning to its initial position. A plastic hinge is assumed to form when the yielding strain of the steel reinforcing bars at the location of d/2 measured from the centerline of the orhtogonal element is exceeded [4], where d is the thickness of the orthogonal element, as illustrated in Fig. 2.

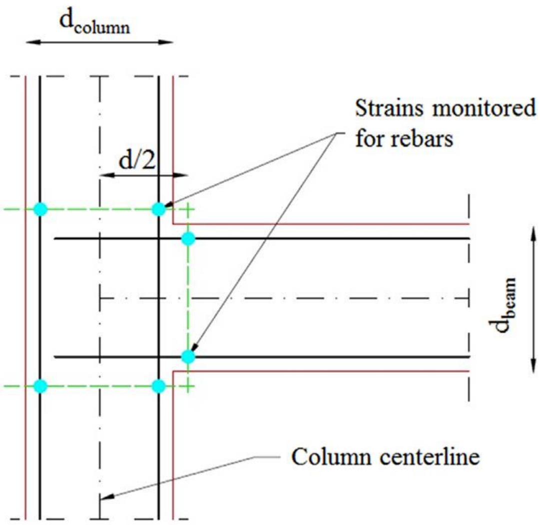

Fig. 2 - Beam–column joint showing monitored locations (marked in blue) for strains in reinforcing bars [4]

3. Nonlinear Seismic Analysis as a Performance-Based Earthquake Design Methodology

The nonlinear analysis is a commonly used method for evaluating the seismic performance of structural designs. Generally, nonlinear analysis techniques can be categorized into two major groups: static and dynamic analysis. To apply these analysis procedures, it is required to have a knowledge of the relationship between nonlinear modeling and performance. Fig. 3 shows the steps that needs to be taken to conduct a correct nonlinear analysis that satisfies the required seismic design and the expected hazard levels. However, even if the nonlinear analysis field was thoroughly investigated, necessary judicial decisions about the accepted risk of outpacing different performance limit states would still be required. Many guidelines and code requirements, such as Vision-2000, ATC-40, FEMA-273, FEMA-440, Eurocode-8, etc., have included nonlinear analysis in assessment methodologies within the frameworks of performance based seismic design [5]-[9]. In this framework, the structure must be able to withstand multiple seismic loading scenarios in a tangible manner and to endure possible losses corresponding to acceptable levels of performance [10].

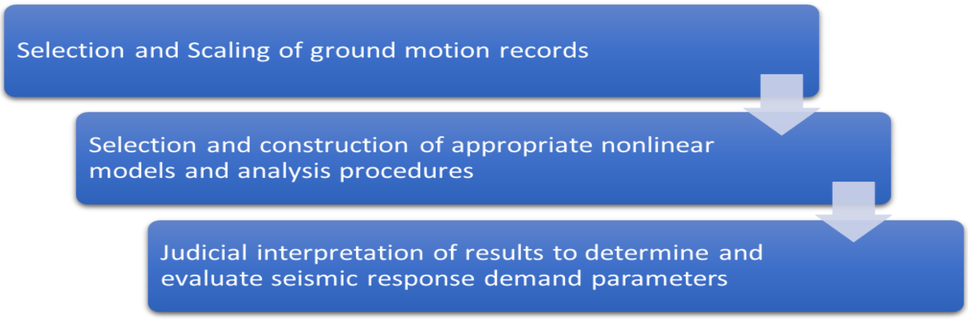

Fig. 3 - Steps to conduct a nonlinear seismic analysis

3.1 Nonlinear Static Analysis (NL-SA)

The push-over analysis (POA), also named as the nonlinear static analysis, is being used widely for the seismic analysis of structures [11]. The popularity of this method has risen due to the fact that it offers means of highlihgting weak links and potential damage in a structure [12], while reducing complexity and computational effort relative to the nonlinear dynamic analysis. Furthermore, numerous standards and guidelines are recommending the use of POA procedures in seismic design of new structures [5], [6].

Habibullah & Pyle [13] provided the procedure used to carry out a POA of the basic three-dimensional structure using SAP2000 program [14], from creating of the model, running of the analysis, to reviewing of the pushover results. In the procedure, the structure is subjected to lateral load with an increasing magnitude and a predefined load distribution such as triangular and uniform pattern as prescribed within Eurocode [6]. As the magnitude of the loading increases during the analysis, the stiffness matrix gets updated at each increment to account for the nonlinear behavior such as local yielding of frame elements of the structure. Consequently, soft links and failure modes of the structure are defined, and the corresponding pushover curve is obtained by plotting base shear versus control top lateral displacement values as shown in Fig. 4.

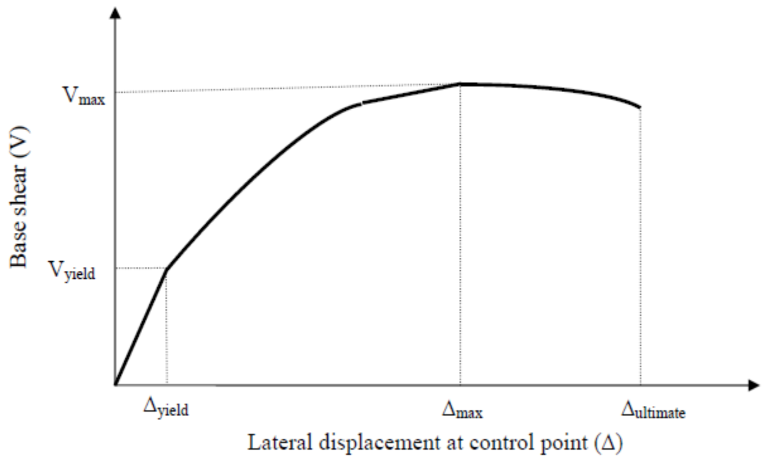

Fig. 4 - A typical pushover curve for a given structure [15]

Static pushover analysis is practical tool for Performance-Based Earthquake Design (PBED) methodology [16]. It provides valuable information regarding seismic response and allows for the evaluation of the resilience of the structure during seismic excitations. Modeling and analysis procedures for POA were developed based on ATC-40 [7] and FEMA-273 [8] documents. Firstly, the force-deflection criteria for hinges used in POA are defined. In order to define the force deformation behavior of the hinge, five points are labeled on the pushover curve (A, B, C, D, and E) as shown in Fig. 5. Then, to define the acceptance criteria for the hinge, three points (IO, LS and CP which represent "Immediate Occupancy", "Life Safety" and "Collapse Prevention" respectively) are defined between point B and C.

Maximum developed base shear (V_{max}), ductility of the structure (μ) and maximum lateral deformation prior to onset of stiffness reduction (Δ_{max}) are among the most useful response characteristics that might be derived from a pushover curve [17], such as the one illustrated in Fig. 4. Using pushover curves to find specific points such as distinct yielding point and maximum displacement could be difficult due to the nonlinearity of concrete material. Park [18] evaluated ductility using analytical procedures and suggested different strategies to estimate the yield deformation (Δ_{yield}) and maximum displacement (Δ_{max}) based on pushover curves. In the simplest method, the first yielding point is considered to be the global yielding point of structure and the maximum displacement can be traced on pushover curve by plotting the point of highest displacement prior to onset of stiffness reduction in a structure that has suffered severe yielding and cracking.

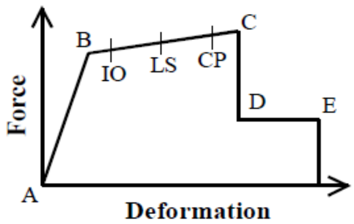

Fig. 3 - Force-Deformation curve for pushover hinge [13]

In the literature, There are countless research articles on the topic of the POA. Fragiadakis et al. [19] tested the applicability of nonlinear static analysis approaches to estimate seismic demands for standard RC-MRFs. When comparing different methods of pushover analysis such as single mode and multi-modal techniques, the former shows reliable performance for low-rise buildings, while the latter extends the range of applicability at an increased computational cost.

3.2 Nonlinear Dynamic Analysis (NL-DA)

Incremental Dynamic Analysis (IDA) is conducted by subjecting a single structure to a suite of ground motion records, each scaled to increased intensity levels to force the structure to shift out from the elastic to inelastic range and eventually causing the failure of the structure. IDA output generates response curves showing the relationship between damage measure and the ground motion intensity [20]. It is often named as dynamic pushover analysis, which is mainly owing to the procedural similarities it possesses to the static pushover approach, with the exception that it is performed by gradually increasing the intensity of seismic force instead of increasing static loads.

Bertero [21] was the first to introduced the concept of IDA, before it was refined and expanded with by researchers such as Nassar & Krawinkler [22]. The IDA procedure is extremely time-consuming and requires a large amount of computing power which did not exist until the last few decades. The recent advances in computing power, processing speed, and enhancements in the simulation procedure are among the contributing factors which gave rise to the popularity of IDA method.

IDA is a powerful non-linear dynamic analysis method which is widely used [23]-[29]. This method may be used to compare the response of a structure to a suite of ground motions or to assess the effect of a design change (or uncertainty) on the response of a structure to a particular ground motion. The result of IDA is a curve which plots a damage measure (i.e. drift as a percentage) versus the intensity measures (i.e. Peak Ground Acceleration (PGA)) at which structural damage occurred as shown in Fig. 4. In order to reflect the structure's condition after performing IDA, a damage measure must be defined. This could be a local or global measure. Selection of damage measures relies primarily on the goals of the study which may involve variables such as base shear, story drift, joint rotations, or the highest deformation of the top level. On the other hand, intensity measures typically include peak ground motion (e.g. PGA, PGV) and spectral acceleration at structure's first mode period (Sa).

Use of IDA shows the extreme sensitivity of damage to ground motion intensity, as well as the extreme sensitivity of damage to the chosen ground motion. As shown in Fig. 6, A structure's response to a certain seismic record may be different to the response to another record. Due to this inconsistency in behavior, it is advised to use multiple of ground motion records when carrying out an IDA to cover all possible responses and behaviors in the structure.

4. Fragility Curves

The fragility curve is an effective tool, which is used in PBED, for quantifying seismic vulnerability of a structure in the context of a probabilistic seismic risk evaluation [30]. A short historical background of fragility analysis is presented in the following studies [31]-[39]. Fragility curve is a statistical tool defined as the probability of reaching the failure level or exceeding a specific damage state for a given structure as function of a specific Engineering Demand Parameter (EDP), which represents the structural response, e.g. inter-story drift, displacement, floor acceleration etc. EDP is further conditioned on Intensity Measure (IM) that defines the ground motion, such as PGA, Peak Ground Velocity (PGV), Spectral Displacement (Sd), and Spectral Acceleration (Sa) [40]-[47].

Fragility functions are typically represented through a set of curves. Each curve is characterized by a particular probability value to indicate ambiguity in the fragility estimation. This probability value correlates to a specified degree of performance. Various documents [7]-[9] promote the same concepts but differ in details and specify different performance levels .

Several methods have been employed to establish fragility curves, such as judgmental methods, numerical, empirical, hybrid, and analytical methods which involve many equations. Analytical approach is the most widely used method. Unlike other methods, the analytical approach derives fragility curves from statistical elaboration of outcomes from dynamic analysis performed on structural models [20], [48]-[50].

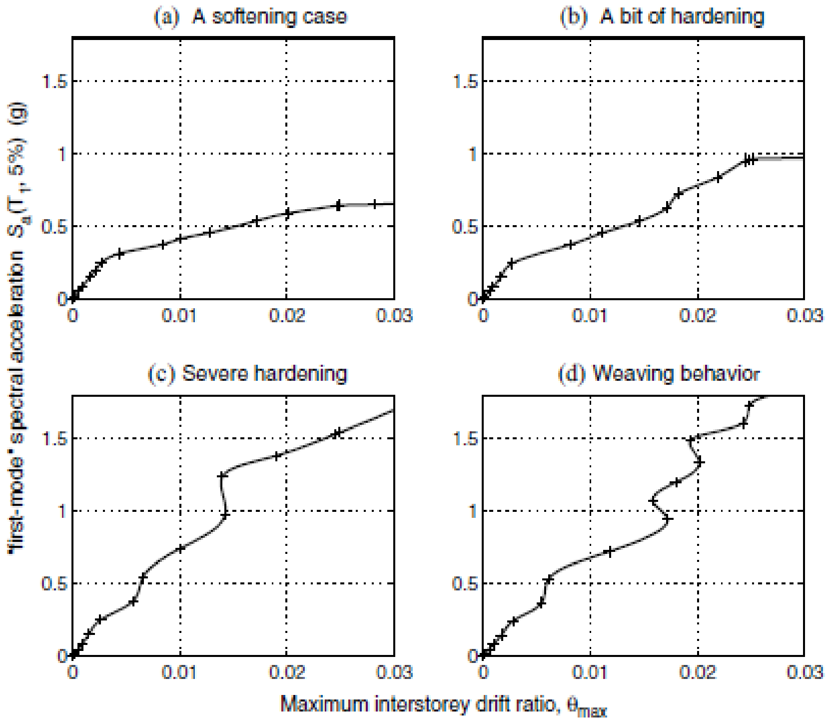

Fig. 4 - Typical IDA curves for a multistory steel frame subjected to four different earthquake records [20]

In order to develop fragility curves, various equations were derived from previous research [33], [40], [51]-[72], all of which are based on a general equation which is expressed by Billah and Alam [73] as shown in Eq. **Error! Reference source not found.**. The development of the fragility curves consists of two steps. The first step is to compute the mean and the standard deviation of the collapse capacity. The second step is to develop the fragility curve from the obtained values of mean and standard deviation using the lognormal Cumulative Distribution Function (CDF). Fig. 6 presents the general flow for the development of fragility curves.

$$\text{Fragility} = P[LS \mid IM = y] \tag{1}$$

in which LS is the limit state or damage state (DS), IM is the intensity measure (ground motion), and y is the realized condition of ground motion IM.

5. Ground Motion Records for Nonlinear Analysis

The selection criteria of ground motion records play a key role when performing seismic analysis, IDA, and in performing seismic fragility assessment. Choosing inappropriate input ground motions contributes to difficulties in reflecting the actual variation of the ground motions and leads to inaccuracies in the required structural demand parameters of the considered structure, which are obtained through NLTHA. The selection of ground motions has been discussed in details in literature [41], [42], [74]-[77] and is documented in various guidelines [78]-[80].

The selected seismic records must come from real earthquake events, taking into consideration important parameters, such as magnitude, site condition, and fault distance. Ground motion records are widely available and can be selected from different online libraries, such as Pacific Earthquake Engineering Research PEER [81] NGA database website (https://ngawest2.berkeley.edu/). Another type of obtained seismic records are the simulated ground motions. However, the latter is not a widely used method which is attributed to the lack of suitable recordings, such as large seismic magnitude at short site-to-source distances [43].

Several parameters should be considered in the process of selecting ground motion records for a desired site, such as the number of ground motions, local site effect, and the properties of the ground motion including the event magnitude, seismic source, path attenuation effects, and the PGA [82]. Additionally, ground motion characteristics (i.e. ground motion intensity, spectral shape, duration, frequency content, near fault, amplitude, and number of cycle) must be considered to obtain accurate prediction of the behavior of the structure [66], [75], [83]. Moreover, the selected ground motions should be scaled to the anticipated seismic intensity of the site. Random scaling of ground motions up to a specific spectral acceleration may result in overconservative structural response [84].

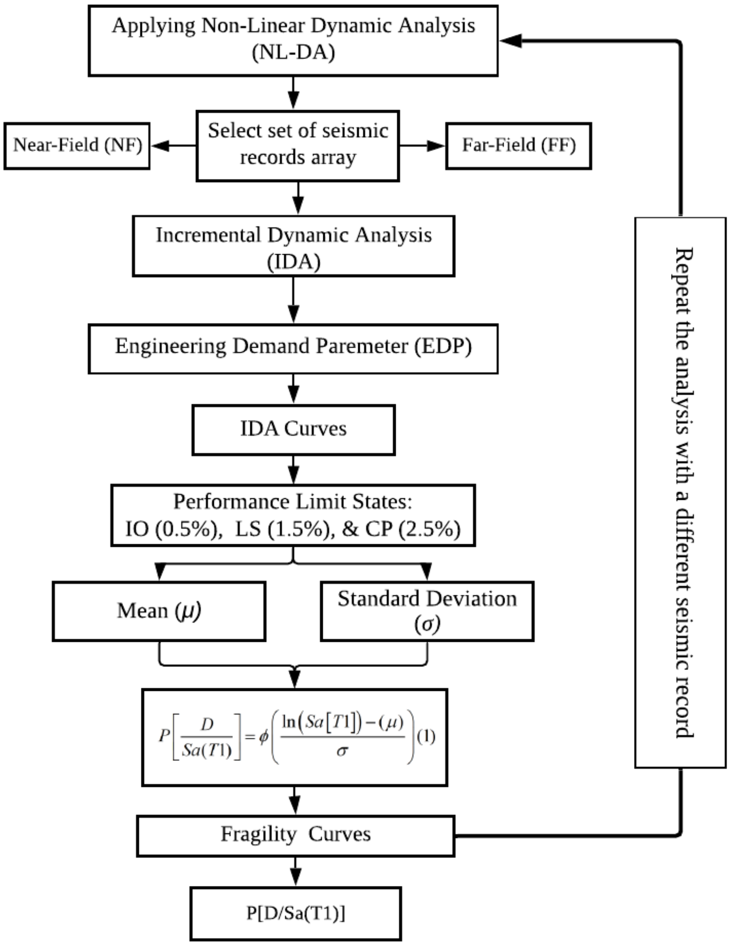

Fig. 5 - General steps for the development of the fragility curves

5.1 Near-Field and Far-Field Ground Motions

Dynamic analysis is a computationally taxing process, and therefore it is essential to select the optimum number of ground motions. The proper number of ground motions relies on the implementation and the prediction of structural response. Two types of ground motion can be considered: near-field (NF) and far-field (FF). The criteria used to categorize NF and FF are based on Joyner-Boore distance (Rjb). The NF record has Rjb distance of less than 20 km [85], whereas the FF is more than 20 km [86]. Najafi & Tehranizadeh [44] discussed a few main considerations when selecting ground motion records and scaling to a target spectrum.

For a NF site, the important factors include spectral shape and the velocity pulses if present. Whereas, for a far field site, the significant factors include spectral shape over the period range of interest, magnitude, distance, site-to-source, and hazard curve at period T. The analysis of variable site-source-distance ground motions demonstrates different impact on the seismic response of structures [87]. FF ground motions carry direct waves which are generally weaker due to near-surface attenuation [88]. The FEMA P695 [89] specifies that only the FF record set is required for the purpose of collapse probability evaluation. Moreover, Selecting records based on their design spectral acceleration and spectral shape proved to increase the efficiency and accuracy of the procedure [90].

5.2 Selection of Ground Motions

Nonlinear analysis should be conducted using several ground motion records. Single ground motions are typically characterized with peaks and valleys in their response spectrum. Using more than one earthquake record is an effective way to avoid the structural response from being predominantly affected by those peaks. The number of ground motions to be used for structural analysis is still a key problem until now and researchers have not found any consensus on a particular number. Further work is therefore required to test the impact of the number of ground motions on the structure's behavior [44]. Bazzurro & Cornell [91] recommended selecting five to seven ground motions to quantify the damage for an uncoupled analysis. Dymiotis et al. [92] selected and scaled three ground motions to study the seismic capacity of RC frames, while Shome [93] specified that ground motions, between ten and twenty, are sufficient to do proper seismic assessment for RC frames. Other studies such as that conducted by Erberik & Elnashai [94], used ten recorded ground motion records to study the behavior of structures, while Kirçil & Polat [40] chose twelve artificial ground motions to perform fragility analysis for mid-rise RC frame buildings. Moreover, many codes prescribe a number that can be used for selection of ground motions, although it is not fixed among all the codes. Najafi & Tehranizadeh [44] recommended the number of selected ground motions according to ASCE05-7 and ATC recommendations to be seven and eleven respectively. Meanwhile, codes such as UBC [95], IBC [96], FEMA-356 [97], EC8 [80], ASCE [78] recommend a minimum of three or seven ground motions and to use the mean value of the demand parameter in analyzing the structure. If the number of ground motions used is less than this recommended number, then consideration should be given to the maximum value of the demand parameter for the structural analysis.

6. Conclusion

Nonlinear analysis methods are being increasingly used to verify seismic performance of structures, especially those with high significance. Despite the existence of many guidelines and code requirements, many aspects remain undefined for which further guidance would be fruitful. Commercially available software, ongoing research studies, and acquired experience through analysis and design of real buildings are paving the way towards a better understanding of the requirements for nonlinear analysis in support of performance-based earthquake engineering. In this context, Fragility curve is an effective modern tool for quantifying seismic vulnerability of a structure in the context of a probabilistic seismic risk evaluation. Effective implementation of nonlinear analysis procedures must include important considerations, namely defining the performance objectives, constructing a suitable nonlinear analysis model, selecting appropriate ground motion records, and careful interpretation of the analysis results followed by proper judgement.

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