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N2 building design method

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Subject review

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N2 building design method

The N2 method is a fast nonlinear static method for the seismic design of buildings. This paper presents main properties and limitations of the method, its development over time, and possibilities of its application for different types of buildings. Differences between the traditional N2 method and its extensions are highlighted. Comparison of the N2 method with similar design approaches is also provided. The results obtained by calculations based on the N2 method are found to be in good agreement with the results obtained by much more complex methods. Guidelines for further research are given in the final part of the paper.

Key words:
N2 method, pushover method, nonlinear static method, regular building, irregular building

Pregledni rad

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Metoda N2 za projektiranje zgrada

N2 je brza nelinearna statička metoda za projektiranje zgrada otpornih na potres. Rad predstavlja značajke i ograničenja metode, njezin razvoj te mogućnosti primjene na različitim tipovima zgrada. Istaknute su razlike između klasične N2 metode i njezinih proširenja. Također, dana je usporedba N2 metode i sličnih proračunskih pristupa. Ustanovljeno je da se rezultati dobiveni proračunima uz primjenu N2 metode dobro slažu s rezultatima dobivenim uz primjenu znatno složenijih metoda. Na kraju su dane smjernice za daljnje istraživanje.

Ključne riječi:
N2 metoda, metoda postupnog guranja, nelinearna statička metoda, pravilna zgrada, nepravilna zgrada

Übersichtsarbeit

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Methode N2 für die Gebäudeplanung

N2 ist eine schnelle nicht lineare statische Methode für die Planung von erbebensicheren Gebäuden. Die Abhandlung stellt die Merkmale und die Grenzen der Methode, deren Entwicklung sowie die Möglichkeiten der Anwendung an verschiedenen Gebäudetypen vor. Hervorgehoben werden die Unterschiede zwischen der klassischen N2 Methode und deren Erweiterungen. Des Weiteren wird ein Vergleich der N2 Methode und ähnlicher Berechnungsansätze dargelegt. Es wurde festgestellt, dass die Ergebnisse, die durch die Berechnung durch Anwendung der N2 Methode erhalten wurden, gut zu den Ergebnissen passen, die man durch die Anwendung wesentlich komplexerer Methoden erhalten hat. Am Ende werden Richtlinien für weitere Untersuchungen gegeben.

Schlüsselwörter:
N2 Methode, Methode der inelastischen statischen Untersuchung, nicht lineare statische Methode, rechteckiges Gebäude, nicht rechteckiges Gebäude

1. Introduction

With fast advancements in computational technology, increasingly powerful computers are now used in the engineering practice, fostering development of new concepts and tools that will enable a more reliable study of seismic behaviour of structures. Sound theoretical background on seismic design based on nonlinear static method for buildings can be found in books published by Čaušević [1-3]. The nonlinear static N2 method, developed by researchers from the University of Ljubljana in the late 1980s [4, 5] is a simple method that provides the engineering practice with reliable design results. The objective of this study is to thoroughly investigate and provide better understanding of the nonlinear static method, and to point to potential areas for further research. It was recognized in the late 1990s [5] that nonlinear analysis needs to be used within the seismic design of structures to enable better control of damage due to earthquakes. The idea was to combine steps from two distinct approaches to achieve desired results [4-6]. The algorithm of capacity spectrum method appeared to be a good step-by-step approach that was later used in the N2 method. At an early stage, the N2 method relied on the nonlinear dynamic analysis, which was later replaced by the pushover analysis to simplify the method [4, 7]. The two approaches, namely the capacity spectrum method and the pushover analysis, were well accepted by practising engineers and researchers alike, and so they were finally combined to form a simple and fast method that provides results very similar to other methods, such as the time history analysis. Although it can reasonably be argued that the most accurate results are provided by the time history analysis, it is time-consuming and requires an extensive data input. Therefore, it is not frequently used in everyday design, especially in engineering practice.

- Eurocode 8 [8] proposes several different approaches for the analysis of earthquake-resistant structures, starting with the simplest approach:
- lateral force method of analysis, for structures in which the first mode of vibration is dominant
- modal response spectrum analysis, valid even for structures with higher mode effects
- nonlinear static (pushover) analysis, and iv) nonlinear dynamic analysis.

The first two methods are based on the linear elastic structural behaviour, while the third and the fourth methods can provide insight into nonlinear behaviour of structures. However, the two latter methods are more time and resource consuming. The 2004 edition of Eurocode [8] mentions the N2 method as one of the possibilities for building design. This method became widely known through education of civil engineers, but was rarely used in practice. The N2 method has been used to this day for almost every type of building (eg. [5, 9-12]). However, some limitations still exist, as will be shown later on in this paper. Due to paper length restrictions, this work concentrates on reinforced-concrete (RC) buildings only. Nonetheless, the N2 method has also been applied to multi-storey cross-lam buildings [13], steel structures [12, 14] and bridges [11, 15]. Krolo, Čaušević and Bulić [12, 16] researched joint stiffness contribution in steel structures using the N2 method.

The following sections present development of the N2 method over the last two decades, including its limitations and application, while also providing a brief overview of extensions of the method.

2. Development of N2 method

As far as current records reveal, early developments of the N2 method can be traced back to the late 1980s [4]. At that time, the N2 method was promoted as a relatively simple method for regular buildings oscillating predominantly in a single mode. The method comprises two different mathematical models and three basic steps of non-linear analysis:

- the structure is modelled as a multi-degree-of-freedom (MDOF) system undergoing non-linear static analysis
- MDOF system is further converted to an equivalent single-degree-of-freedom (SDOF) system, based on presumption that the deflections shape is unchanged during strong shaking
- maximum displacements are determined from non-linear dynamic analysis on an equivalent SDOF system.

However, the use of inelastic response spectra is recommended as an alternative to the nonlinear dynamic analysis, Validity of the method was tested in the late 1980s [4] using results:

- obtained from nonlinear dynamic analysis conducted on MDOF model
- experiments conducted in Japan. Comparisons have revealed a good agreement of results, which is why the method is considered reliable for practical application.

In 2000 [5], the simplest version of the N2 method was presented, detailed information on its limitations was provided, and possible extensions and modifications were listed. By that time the use of the method was restricted to planar frame structures only. In the early 1990s the N2 method was extended to include the effects of damage caused by the post-elastic earthquake-induced cycles [6]. The third step of the extended method included the input energy incorporated in the SDOF system. This structural parameter was chosen to complement the N2 method since it is independent of the structural system and, once obtained from the SDOF system, it can be used as a good estimate for the input energy of the MDOF system, but only if higher mode effects are negligible. The extended method was tested on two numerical models following differing concepts:

- strong column-weak beam concept
- the concept of week storey subjected to inverted triangular load pattern.

The results obtained from the early 1990s version of the N2 method were compared with the counterparts obtained from the nonlinear time-history analysis. This study suggested that:

- the extended method provides good results for the design of week-storey buildings

- the higher mode effects need to be observed if the predominant period of oscillation of a structure is noticeably higher than the predominant period of ground motion.

However, the predominant period of ground motion can only be known after the earthquake, and after recording and analysis of ground motion. When discussing a predominant period of ground motion, it should be noted that there is no unique or error-proof method for its estimation. Predominant period of ground motion can only be predicted based on previous earthquake events at a location of interest, or based on fundamental period of foundation soil. Indeed, the soil can be observed as a medium for amplification of energy at frequencies close to the fundamental frequency of soil [17]. The results obtained from the 1990s version of the N2 method were considered in the light of predominant period and duration of ground motion. However, these parameters are fickle. Predominant period of ground motion is difficult to predict even based on natural periods of foundation soil [17]. What is more, duration of an earthquake is almost unpredictable. However, information from previous earthquake events can be used to categorize seismic input load according to duration. This categorization could then be used to analyse structures for different durations.

RC structures actually directed or provided orientation to early developments of the N2 method [4-6, 18]. Structures used in the mentioned studies were all planar. The method was at that time validated by experiment and more advanced nonlinear dynamic method, which provided non-conservative and reliable results that can be used for design. The N2 method was also applied to buildings following the strong-column-weak-beam concept and the weak-storey concept [18]. The results obtained from this study were compared with the results obtained by a nonlinear dynamic analysis showing that the N2 method predicts seismic response better on the global level than on the local level. However, even then it was quite clear that certain limitations and deficiencies do exist within the method. That was clearly highlighted by its creators, and so the development continued with the focus on the same type of structures [9, 18-20]. Fajfar et al. [5, 11, 18, 19] presented a detailed step-by-step algorithm of the N2 method along with the improvements and simplifications. Undoubtedly, this made the method more user-friendly to students, researchers and practicing engineers, while also simplifying and accelerating further development. The algorithm is presented in the following section. After approximately 16 years of practical use, and after it has been tested by practice and academia, the N2 method has deservedly earned its place in European standards for the design of earthquake resistant structures [8].

A leap forward from regular to irregular structures was made in the early years of the 21st century, and the possibility of applying the pushover method to asymmetrical-plan buildings was demonstrated [19-21]. It was shown how to incorporate higher mode effects into the N2 method [22, 23]. The application of the N2 method was extended to bridges [11] and base-isolated structures [24-26]. In addition, the extended N2 method for asymmetric buildings was rigorously tested on a set of existing real-life buildings [10, 27]. Key results obtained in these studies are summarized in later sections of this paper.

3. N2 method procedure

The method is driven by structural and soil data, which are used to define the capacity of a structure and seismic demand, respectively. The inelastic spectra need to be defined to include the dissipation of energy, using for that nonlinear SDOF system based on the bilinear force-deformation relationship. The following relationship is used to relate the spectral displacement S_d to the spectral acceleration S_a:

$$S_d = \frac{\mu}{R_\mu} \cdot \frac{T^2}{4\pi^2} \cdot S_a \tag{1}$$

where:

T - the natural period of vibration of the building

μ - the ductility coefficient defined as the ratio of maximum displacement to displacement at yield

R_μ - the reduction factor due to the hysteretic dissipation of energy within ductile structures

The reduction factor can be approximated as follows:

$$R_\mu = (\mu - 1)\frac{T}{T_C} + 1 \quad \text{za } T < T_C \tag{2}$$

$$R_\mu = \mu \quad \text{za } T \geq T_C \tag{3}$$

where:

T_c - period defining the right edge of the acceleration spectra plateau.

Expressions (2) and (3) were used in most of the reviewed literature (eg. [5, 11, 19, 28, 29]). Also, the following expressions for reduction factors were found in the literature (eg. [17, 30]):

$$R_\mu = 1 \quad \text{za } T < T_B \tag{4}$$

$$R_\mu = \sqrt{2\mu - 1} \quad \text{za } T_B \leq T < T_C \tag{5}$$

$$R_\mu = \mu \quad \text{za } T \geq T_C \tag{6}$$

where:

T_B - the period defining the left edge of the acceleration spectra plateau.

For the sake of easier future referencing any μ < 4 refers to low ductility demand [5]. To learn about the capacity of a structure, nonlinear MDOF model is subjected to a monotonically increasing horizontal load, which results in progressive plasticization of structural elements. A nonlinear curve that shows the relationship between the base shear and top displacement is obtained in this step. This curve provides information about the stiffness, strength and ductility. Essentially, the force-displacement relationship can be determined for each floor of a building. The horizontal load can be added to the model using an arbitrary pattern. However, several specific patterns are recommended in literature (eg. [4-7, 9, 18, 28]). The transformation of the MDOF model to an equivalent SDOF system is based on the data obtained from bilinear approximation of the capacity curve (Figure 1).

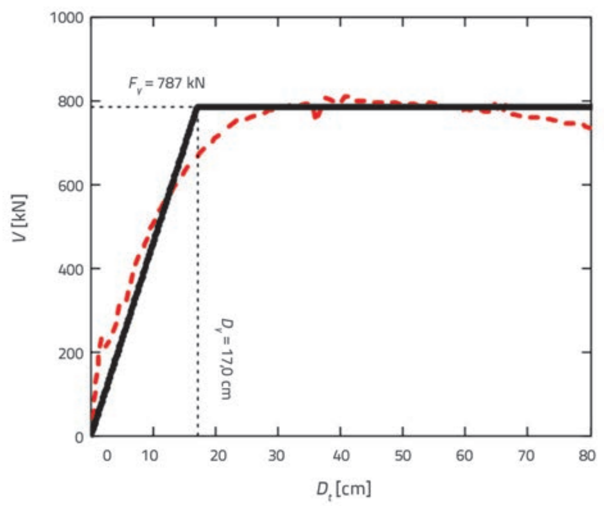

Figure 1. Capacity curve [28]: real curve in solid line and idealized curve in dashed line. *V* is base shear force and D_t is top displacement

The period of vibration of the equivalent SDOF system is determined using the following expression:

$$T^* = 2\pi\sqrt{\frac{m^* D_y^*}{F_y^*}} \tag{7}$$

where:
m^* - the mass of the equivalent SDOF system
D^*_y i F^*_y - the displacement and base shear force of the SDOF system at yield.

he mass is obtained as:

$$m^* = \sum m_i \Phi_i \tag{8}$$

where:
m_i - the mass
Φ_i - the displacement vector at the *i*-th level of the observed MDOF system.

The displacement D^* of the equivalent SDOF system is estimated using the following expression:

$$D^* = \frac{D_t}{\Gamma} \tag{9}$$

where:
D_t i Γ - the top displacement of the MDOF system and the coefficient that controls the transformation, respectively.

The base shear force F^* of the equivalent SDOF system is estimated via the following expression:

$$F^* = \frac{V}{\Gamma} \tag{10}$$

where:
V - he base shear force of the MDOF system.

The joint denominator Γ is determined through the following expression:

$$\Gamma = \frac{m^*}{\sum m_i \Phi_i^2} \tag{11}$$

Bilinear approximation of the capacity curve is usually fitted in an eyeball fashion and by using engineering judgment [5, 7, 9, 11, 19, 31]. Nevertheless, some useful guidelines on bilinear approximation can be found in [31]. However, the post-yield stiffness has to be equal to zero [5]. A procedure for the transformation of MDOF to the equivalent SDOF system was also proposed by a group of Japanese researchers [32]. They tested the procedure on a set comprising RC and steel buildings of different height. The study showed that the procedure provides good results for both RC and steel buildings not exceeding 10-storeys regardless of the type of bearing system used. The target top displacement of the MDOF system is assessed through multiplication of the spectral displacement demand for the equivalent SDOF system with the transformation coefficient Γ. Finally, the local seismic demands and damage assessment of the MDOF system are determined using the pushover method. In this step, the MDOF system is pushed until its top displacement reaches the target displacement. This provides information on local demands, storey drifts, and the sequence of formation of plastic hinges, etc.

4. On integral parts and characteristics of N2 method

This section discusses integral parts of the N2 method along with key effects that influence results and steer the design process.

4.1. Plastic hinges

Plastic hinges are usually employed at the ends of structural elements to introduce nonlinear behaviour into the model. A crucial step before conducting the pushover analysis is to define plastic hinges correctly. However, the process of defining hinging zones is usually not simple. Moreover, it is usually based on a bilinear or three-linear moment-rotation relationship [5, 11, 25, 26, 33]. Apart from [20, 26], the properties of hinges used in analyses presented in other studies are masked.

4.2. Pushover method

The pushover method is an integral part of the N2 method and one of its crucial steps. The capacity curve obtained from this step looks for engineering judgment as it needs to be approximated in bilinear (or three-linear) fashion. This can be a stumbling stone since different software programs for structural design offer differing definitions of plastic hinges. In addition, different plastic hinge definitions require different sets of parameters that are not always easy to assess. In the late 1990s [34], it was suggested that the use of the pushover method should be limited solely to structures with short and medium periods. This issue was raised once again in 2000 [5].

4.3. Lateral load pattern

The lateral load pattern imitates seismic inertial forces at the centre of mass at each floor of the structure and there is no unique way to define it. Three different load patterns are frequently used:
- triangular
- uniform
- modal.

Uniform and inverted triangular patterns are most frequently used [4, 6, 7, 18, 35]. A recent study [26] used distribution proportional to mass. According to two extensive studies [5, 34], the selection of lateral load pattern is more important than the selection of target displacement. The same studies revealed that the lateral load pattern issue is one of the weakest points of the pushover method and, hence, of the N2 method. Mitrović and Čaušević [28] used three different displacement shapes for the distribution of horizontal forces: uniform, triangular, and modal, and showed that they all provide similar results (Figure 2).

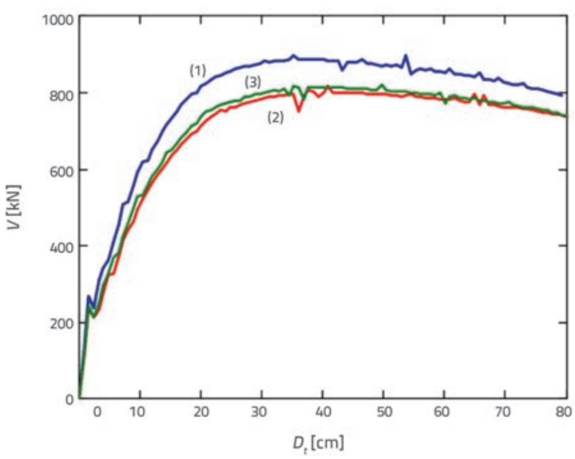

Figure 2. Capacity curve comparison obtained for the same MDOF system using three different load distributions [28]: (1) uniform, (2) triangular, and (3) modal

Krawinkler [34] and Fajfar [5] recommend using at least two different load patterns during the design process. In fact, none of the load patterns can account for a redistribution of forces within the building. Moreover, different local mechanisms can be discovered using different load patterns.

4.4. Target displacement

The issue of target displacement was addressed in the late 1990s as one of the problems related to the N2 method. Krawinkler [34] noted that target displacement depends on the preselected shape vector but also that target displacement is not known beforehand. Thus, the iteration process is imminent. In the early days of development of the N2 method, it was clear that structural damage caused by earthquakes is not controlled purely by the maximum top displacement [4]. A study proposed in the late 1990s [7] assumed that target displacement is equal to 1 % of the building height. The target displacement can inter alia be affected by torsional effects, numerous post-elastic cycles, and foundation uplift. This has also been confirmed by other researchers (eg. [6, 31, 34]).

4.5. Reduction factor

The reduction factor, usually defined in bilinear fashion (eg. [7, 11]), is expressed as the ratio of the required elastic strength to yield strength. Definition of this factor requires knowing the period of the structure under study, but also the period designating the right corner of the acceleration response spectrum plateau. However, the corner period only exists in coded response spectra, which are derived based on experience and using smoothing techniques [30, 36]. On the other hand, there is no unique method for estimating the period of oscillation of a structure, eg. [37-41].

4.6. P-delta effects

The P-delta effects were not taken into account in early studies on the N2 method (eg. [4, 6]). Not much attention has been paid to the P-delta effects in newer studies either. However, it is important to stress that the P-delta effects can increase ductility demand and amplify storey drifts [34]. It is also known that the P-delta effects are most pronounced in the lower storeys of structures where the largest vertical forces occur [34]. Moreover, the P-delta effects can increase natural period of oscillation of structures, and cause additional overturning moments [33, 42].

4.7. Foundation medium

Apart from assessing capacity and potential hinging zones, the N2 method could also be used for assessing performance of the entire soil-structure system. According to [5], the influence of soil conditions can be neglected when average shear velocities are greater than 180 m/s. However, it is clear that foundation systems need to be modelled if it is expected that they will yield, or if it is suspected that uplift might occur. This has also been confirmed by Krawinkler [34]. If we exclude the studies with base-isolation systems, and apart from [17, 43, 44], all other studies listed at the end of this paper consider buildings rigidly attached to an undeformable medium. However, to make the N2 method applicable to soil-structure systems, the inelastic demand spectra need to be additionally researched for soft soil sites and near-fault earthquakes [5]. It is known that low-rise buildings on soft soils are the most susceptible to seismic soil-structure interaction effects [17]. However, the equal displacement rule embedded in the N2 method suggests that the method is less accurate for short-period structures founded on soft soil sites [5]. It is therefore clear that this leaves ample room for further research.

5. Comparison of N2 method with other similar methods

Apart from the N2 method, there are other methods that use similar principles: the capacity spectrum method defined in ATC-40 and its improved version provided in FEMA 440; the coefficient method and the nonlinear static procedure provided in FEMA 273 and its improved versions in FEMA 356. A Croatian research group led by Prof. Čaušević carried out studies [9], [28] and compared the N2 method with the methods defined in FEMA and ATC. They demonstrated that:

- all three methods use the pushover procedure, although different procedure are used for defining target displacement
- it is necessary to idealize the pushover curve into bilinear curve in all three methods
- the ATC method does not always converge when real response spectrums are used, although multiple solutions are possible
- the ATC method can provide results differing by up to 50 % compared to the nonlinear time-history method
- all three observed methods provide similar maximum top displacement if the inverted triangular lateral load pattern is used
- the uniform pattern results in maximum top displacements that can differ by up to 60 % depending on the method used
- the ATC and FEMA methods do not link lateral load distribution with displacement shape, while in the N2 method the lateral force distribution is affected by displacement shape.

An Italian group of authors [29] also made a comparison between the N2 method and the capacity spectrum method. They pointed out the following:

- the N2 method is ductility based while the capacity spectrum method is related to the energy dissipated in the structure
- the N2 method uses the tangent fundamental period of oscillation, while the capacity spectrum method uses the secant fundamental period of oscillation
- the capacity spectrum method underestimates displacement values for highly dissipative systems.

Lagaros and Fragiadakis [45] reviewed and compared the following methods on a set comprising low- and medium-rise RC buildings of regular and irregular plan:

- the displacement coefficient method of ASCE-41
- the ATC-40 capacity spectrum method
- the N2 method.

They discovered the following:

- the ATC method overestimates the seismic demand, while the differences between the N2 method and the ASCE method are small
- the ATC results in larger demands for low-rise regular buildings when compared to the N2 method and the ASCE method.

Unlike the nonlinear static procedure, the N2 method and the capacity spectrum method allow graphical representation of results, [9, 18, 28]. For instance, the demand spectra and capacity diagram can be shown on the same graph (Figure 3). To create an envelope of the most severe seismic demands on a structure, the FEMA and Eurocode recommend that the target displacement be increased by 150 %, [5, 8, 9].

6. N2 method for irregular buildings and base isolated buildings

It is known that:

- torsional effects can increase displacements but also
- that torsional rotations can turn from a clockwise direction to counter-clockwise direction and vice versa, with hinging of structural elements [7].

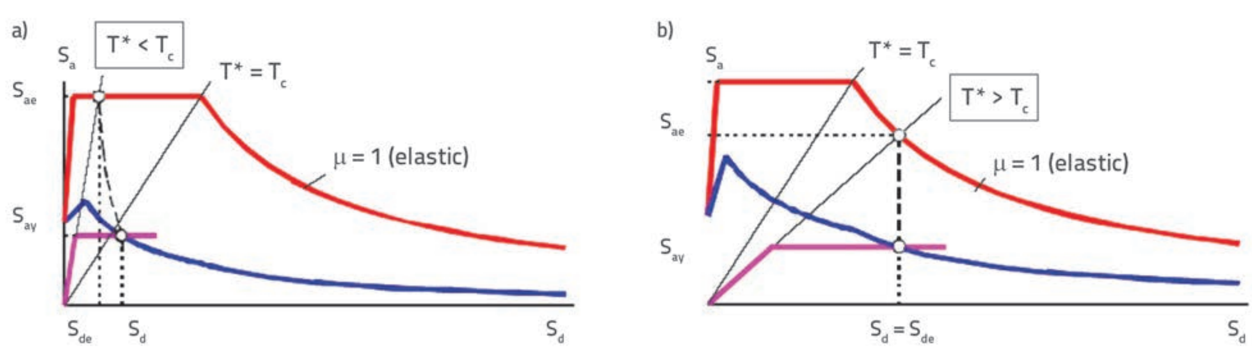

Figure 3. Elastic (red) and inelastic (blue) demand spectra with respect to capacity diagram (fuchsia) for [9]: a) short-period buildings; b) medium- and high-period buildings

In the late 1980s it was stressed that higher mode effects are more important for base shear force than for the top displacement and base overturning moment [4]. Later on, it was emphasized [5] that higher mode effects can be taken into account by the envelope of the results obtained by using different horizontal load patterns. Before the year 2000, the N2 method was used only for assessing seismic performance of planar and symmetric structures. Subsequent research extended the use of the N2 method so as to include irregular fixed-base buildings and base isolated buildings. This section provides more details about these systems.

6.1. In-plan asymmetry

In the late 1990s [34], it became clear that the possibilities of incorporating torsional effects in the pushover method have to be explored. A leap forward was made by a group of Slovenian researchers in 2005 [19] when the N2 method was extended to asymmetric structures. A detailed step-by-step algorithm, provided in [19], complements the algorithm described in an earlier section of this paper. In brief, the extended N2 method uses the same procedure of transformation from MDOF to SDOF system for planar-symmetric and -asymmetric buildings. The extended N2 method uses correction factors that are applied to the results obtained by pushover analysis. The correction factors are defined as the ratio of normalized top displacements obtained using elastic modal analysis and using pushover analysis, independently for two horizontal directions, in both plus and minus directions. The extended N2 method for plan-asymmetric buildings was checked against results obtained from the nonlinear dynamic analysis. An experimentally tested three-storey RC frame building with eccentricities amounting to approximately 12 % was used in the study. The comparison of results showed that the extended N2 method is on the safe side and that it produces conservative results. It was stressed by the Slovenian group that the torsion occurring in plan-asymmetric structures is characterized by large uncertainties and randomness. Also, they noted that the results are affected by the pushover and linear dynamic analysis. Fajfar, Marušić and Peruš [19] explained that the conservatism is due to difficulties in determining target displacement at the mass centre and the influence of torsional effects. Bhatt and Bento [10] rigorously tested the extended N2 method for plan-asymmetric buildings using real RC buildings with three, five, and eight storeys. They compared the results obtained using both the extended and the standard N2 method with the results from the nonlinear dynamic analysis, and confirmed good accuracy of the extended method in predicting torsional behaviour of plan-asymmetric buildings. A group of Italian researchers [20] introduced accidental eccentricity in the extended version of the N2 method. They conducted a study on a three-storey RC frame building and developed three different methods that allow introduction of the accidental eccentricity in the N2 method. However, the developed methods are not really user-friendly, which has also been stressed by the developers of the method. Finally, Kilar and Koren [25] presented the application of the N2 method on plan-asymmetric buildings founded on isolators. The most important results of this study are provided in the final subsection of this section.

6.2. Incorporation of higher mode effects

In an earlier study [6], the mass-proportional damping was used to simulate higher mode effects. After the N2 method was successfully applied to buildings asymmetric in plan, an extension to buildings irregular in elevation was developed to incorporate higher mode effects [22, 23]. A similar correction-factors-based approach, applied to extend the N2 method to plan-asymmetric buildings, was used to incorporate higher mode effects. This approach assumes that the higher mode effects are the same in the inelastic and elastic ranges. The contribution of higher modes is obtained from the elastic modal analysis. This is later used for the correction of results obtained using the pushover method. The proposed procedure can be described as follows:

- conduct standard N2 method
- perform the elastic modal analysis in order to determine relevant modes and storey drifts
- define the envelope of the results from previous two steps, define correction factors and storey drifts for each storey and, finally
- determine local quantities.

Correction factors are defined as the ratio between the normalized roof displacement obtained by elastic modal analysis and the results obtained by pushover analysis. The correction factor value is used only if it is greater than 1. Final results of the calculation are obtained through multiplication of results from the N2 method by the corresponding correction factors. The largest contribution of higher modes is evident for upper storeys.

6.3. Base isolation

Buildings founded on soft medium predominately oscillate in a single mode. Kilar and Koren [24-26, 46] first proposed the idea of applying the N2 method to buildings on isolators in order to, inter alia, facilitate the process of selecting isolation systems. The base isolated structures predominantly oscillate in a single mode, which essentially remains unchanged under different shaking intensities, and hence properly fulfils principal requirements of the N2 method. In such a case the entire structure above the isolators can be observed as the lumped mass above the SDOF system's column. By using the N2 method, the target base displacement can be obtained using the same principle defined for fixed-base structures. Apart from bearing isolation systems, Kilar and Koren studied behaviour of structures founded on an XPS layer [47]. One of the first studies they conducted [26] showed that stiffer and highly damped isolators result in smaller base displacements, when compared to softer and low damped isolators. The plasticization of superstructure elements was observed only for isolators with

hard rubber, and for isolators with normal rubber and very low damping. The coefficient Γ controlling the transformation was equal to 1. An extended study [24] introduced a new three-linear approximation of the capacity curve instead of using the bilinear approximation. A constant reduction factor was assumed, which comprises:
- nonlinear behaviour and damping of superstructure
- strength reduction due to higher damping of isolators.

The newly proposed method was tested on a realistic four-storey regular plan building, using three different types of isolators and three different lateral load distributions. In this study, the values of the coefficient Γ varied from 1.04 to 1.41, depending on the isolator type and the lateral load distribution used. The study showed:
- good agreement between results obtained using the adapted N2 method and the nonlinear dynamic analysis
- underestimation of demand displacements when triangular lateral load distribution is used. Kilar and Koren [24] recommended using the mass proportional lateral load distribution for base isolated systems.

Their next study was conducted on an asymmetric base-isolated building [25] using the same three-linear approximation of the capacity curve, the upgraded version of the reduction factor, but also the torsional correction factor. The study showed good agreement of the results obtained using the N2 method and the nonlinear dynamic analysis, if the eccentricity does not exceed 20 % of the larger floor plan dimension. Otherwise, the N2 method produces underestimated displacements. The later study confirmed that the mass proportional lateral load distribution is more suitable than the triangular distribution for base-isolated buildings.

7. Conclusion

The N2 method is simple and fast nonlinear method for the seismic design of regular and irregular buildings. The early beginning of the N2 method started at the University of Ljubljana, where a group of researchers proposed an algorithm for a method that offers simple and fast insight into the seismic behaviour of buildings. The method has ever since been rigorously tested and improved by introducing the nonlinear static pushover analysis, different correction factors to account for higher mode effects and plan-asymmetry, and also procedures for assessing behaviour of base isolated buildings. The method was compared with other similar methods specified in American guidelines and standards: FEMA 273, FEMA 356, and FEMA 440, ATC-40, and ASCE-41. Relevant studies showed that the results of the N2 method and the American methods are essentially similar although, in some steps, they are based on different assumptions and approaches. The N2 method has been in the focus of interest of many researchers due to its simplicity and ability to provide reasonably accurate results when compared to more advanced and time-consuming methods, eg. the nonlinear dynamic method. Moreover, the N2 method enables graphical representation of results, which is not the case in methods provided in American guidelines and standards. Although the N2 method has many advantages, it has still not been fully explored in the light of, for instance, timber and masonry structures. Although masonry buildings represent the largest share of the world's building's stock [48], it can reasonably be argued that, in most cases, the masonry infill has actually been neglected in calculations made in engineering practice. All studies considered in this paper use the presumption of rigid diaphragms. However, it should be noted that many old masonry and stone buildings have semi-rigid horizontal diaphragms. Kilar and Koren [49] recently conducted a case study and examined applicability of the N2 method on a masonry structure. In addition, further attention within the framework of the N2 method must be paid to the effects of soil compliance, soil-structure interaction effects, and additional P-delta effects that can increase overturning moments, as these effects can play an important role in structures founded on soft soils. Furthermore, modelling of plastic hinges, and approximation of capacity curve, have been found to be the Achilles' heel of the N2 method for engineering practice, especially in the design of new buildings. Nonetheless, the N2 method has the potential of becoming a workaday and cutting-edge tool in engineering practice for the seismic structural design of new buildings and seismic evaluation of the existing buildings.

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