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Multidirectional pushover analysis for seismic assessment of irregular-in-plan bridges

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ABSTRACT

Nonlinear static procedures are becoming, evermore, popular tools for the seismic assessment of structures. Despite the considerable number of studies that have already addressed the improvement of pushover analysis, its limitations are still widely recognized by the scientific community, namely the inherent inability to accurately predict the behaviour of irregular structures. On the other hand, 3D structures exhibit a complex dynamic behaviour, in which the most critical direction of the ground motion input is many times not readily clear. In such cases, a multi-directional seismic analysis must be performed in order to capture the vulnerable earthquake demand direction of the structure. The study presented herein aims to assess the accuracy of pushover analysis in predicting the behaviour of irregular-in-plan RC curved bridges and to ascertain its effectiveness in multi-directional analysis. Particular attention is paid to the definition of the force distribution patterns, the direction of analysis and the determination of the target displacements, as well as to the modelling of the biaxial behaviour of the columns. The structural response of the bridges is assessed in terms of global and local behaviour. A comparative evaluation of the response of the bridges, estimated using nonlinear static (*pushover*) and dynamic analysis, illustrates the applicability of the pushover analysis technique as well as the influence of the directions of analysis, in the local and global structural demand of irregular-in-plan bridges.

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1. Introduction

Since the early 1960s, irregular-in-plan curved bridges have gained high popularity, particularly in highway interchanges and urban expressways, as a result of geometrical constraints, limitations of space and high density of urban traffic. Due to the particularity of its shape, curved bridges reveal a different dynamic response when compared to common straight bridges, which naturally affects its seismic behaviour. Following the collapse of some curved bridges during the 1971 San Fernando earthquake, Williams and Godden [1] conducted a shaking table test study on a reduced scaled model of a microconcrete curved bridge with the aim of evaluating the effects of linear and nonlinear dynamic responses and the influence of expansion joints on the capacity of the structure. Tseng and Penzien [2] also studied the nonlinear seismic response of long, multiple-span, RC curved and straight bridges, concluding, similarly to [1], that the ductility requirements at the base of the columns of curved bridges are not as critical as it would be expected when compared to the levels observed in long straight bridges. Similarly, Burdette and Elnashai [3] observed that, in the transverse direction, curved decks provide greater stiffness to the structure through arch or catenary action, while straight decks resist transverse forces in flexure, which allows pseudo-static displacements to be absorbed by the bridge deck. In the longitudinal direction, the opposite phenomenon was observed, i.e. curved bridges resist inertial forces by a combination of flexural and axial stiffness of the deck while the straight bridges deck resists these forces efficiently in pure tension and compression, providing the structure with higher longitudinal stiffness. As a result, unlike straight bridges, for which seismic response is usually governed by its transverse direction of analysis, the seismic direction that produces the maximum demands in a particular member or a specific point of a certain curved bridge is not evident. Several seismic action input directions must be considered in order to ensure that all modes are excited and the critical response direction is conveniently identified. Indeed, a number of past studies [4–7] have outlined the key role played by the planar irregularity and consequent biaxial bending of the piers in the maximum values of the seismic response of curved bridges.

Nonlinear time-history analysis (THA) is, by far, the most reliable method to estimate the seismic response of structures, especially in the case of irregular ones however, in addition to the complexity associated to the formulation of the mathematical

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model, major issues arise, regarding the definition of the seismic action, which can lead to different levels of uncertainty in terms of both local and global structural responses. Pushover-based nonlinear static analysis (PA) appears therefore as an interesting alternative approach, less time consuming and lying on simple principles, yet ensuring fairly accurate results.

The applicability of PA to seismic assessment of bridges has been extensively scrutinized in the recent past and numerous variants of nonlinear static procedures, with different levels of accuracy and complexity, are available today [8–11]. On the other hand, a limited number of studies focused on the application of PA to curved bridges have been conducted up to date [11–14]. The seismic assessment of bridges using PA is not straightforward and not only an accurate model of the inelastic behaviour of the structural frames is required, but also a correct definition of the force distribution patterns, analysis directions, reference nodes and target displacements that best represent their seismic structural performance is needed. The listed issues increase when irregular-in-plan bridges are considered, given that the piers are expected to exhibit biaxial behaviour and the critical input angle of the seismic action will vary with the type and curvature of the structure.

This paper attempts to address the limitations mentioned above, by assessing the seismic response of a set of bridges with varying curvature in plan using the PA-based procedure prescribed in Eurocode 8 (EC8) [15,16]. A practical framework that takes into account different directions of analysis is proposed herein, appraising the adequacy and accuracy of pushover analysis in matching THA predictions.

2. Extension of pushover analysis to irregular-in-plan bridges

The PA-based method proposed in Eurocode 8 is based on the well-known N2 method firstly developed by Fajfar and Gaspersic [17] to assess the seismic behaviour of regular buildings. Eurocode 8 presents its general pushover analysis specifications for bridges in both parts 1 [15] and 2 [16], introducing, in the former, the methodology to determine the target displacement and, in the latter, the general parameters for the derivation of the pushover curve, such as the directions of analysis, reference points and load distribution patterns. The pushover analysis recommended by most guidelines and codes [16] simply accounts for two directions of analysis in the assessment of bridge structures, regardless of their radii of curvature. On the other hand, the Caltrans seismic design criteria [18] recommend that the application of the seismic action should be performed for various angles of incidence so as to include the maximum deformation of all critical components. The application of this alternative PA approach is not completely clear and may raise many questions regarding the definition of the lateral force patterns and the determination of the performance point. A practical procedure that focuses on the inclusion of the latter aspects in standard PA is thus proposed herein. The Eurocode 8 provisions on the characterization of the reference points, analysis directions and load distribution patterns were taken into account, as well as the strategies for the equivalent SDOF transformation and determination of the target displacement. The steps of the proposed PA procedure are summarized as follows:

Step 1: Once the structural model of the curved bridge under analysis is defined, the first step of the procedure is to select the lateral load pattern, $F_n = m_n\,\Phi_n$, where m_n refers to the nth nodal mass of the structure and Φ_n to the mode shape. According to Eurocode 8, pushover analysis of bridges is to be performed by pushing the entire structure with two load distribution patterns (Fig. 1a and b): one uniform along the deck pattern (PAc), with $\Phi_n = \{1\}$, and the other proportional to the first mode shape pattern (PAm), with Φ_n referring to the fundamental mode. As the importance of the longitudinal response of curved bridges increases with the radius of curvature, an additional load pattern (Fig. 1c) proportional to the mode shape with higher modal mass participation ratio in the longitudinal direction has been proposed by some researchers [11,12] (PAxm). Similarly, a load pattern uniform along the deck, analogous to Pac, should be adopted in the longitudinal direction (PAcx). Finally, a set of patterns uniform along the deck, corresponding to various axes orientations (PAvoc), is proposed in this study, in a way that there would be as much pushover analysis as the number of different axes considered (Fig. 1d). It is noted that PAc is a particular case of PAvoc, still they will be considered separately for comparison purposes. Furthermore, several authors [11–13,19] recommend that pushover analysis should be carried out in both positive and negative directions when irregular-in-plan structures are not symmetric.

Step 2: A critical aspect regarding the procedure herein proposed is related to the definition of the directions of analysis. According to Eurocode 8 only two horizontal directions of analysis should be considered: a longitudinal X-direction, defined by the centres of the two end-sections of the deck; and a transverse Y-direction, orthogonal to the first. In addition to these directions of analysis, version 1.6 of the Caltrans seismic design criteria [18], one of the few guidelines that specifically address this issue, recommends that the ground motions should be applied along the various principal axes of each individual component. In other words, the ground motion should be applied at a sufficient number of angles so as to capture the maximum deformation of all critical components and to ensure that all significant modes are excited. In the present work, five different input angles of the seismic action were considered, corresponding to each individual component (abutments and piers) of the bridges under analysis, as presented in Fig. 2. The directions of analysis in Eurocode 8 are treated as global axes directions, while the various individual component axes are denoted as local axes, named as ENC1, P1, P2, P3 and ENC2 from the left abutment to the right abutment of the bridges (Fig. 2).

Step 3: The third step concerns the definition of the pushover curves (total base shear versus displacement of the reference point) for the various directions of analysis, which is also a rather important part of the proposed procedure, as it requires a conversion technique that allows for the derivation of the pushover curve for a certain direction of analysis. Irregular-in-plan structures exhibit a 3D response characterized by multicomponent displacements and forces, as it can be seen, for instance, in Fig. 1a, being the first mode shape defined by X–Y component displacements in the global axes system. Differently oriented quantities of the response can be easily obtained by converting the structural analysis response results, fixed in both Y and X directions, through the relationships in Eq. (1).

$$\begin{cases} E_{y'} = E_{Yy'} - E_{Xy'} = E_Y\cos(\alpha) - E_X\sin(\alpha) \\ E_{x'} = E_{Yx'} - E_{Xx'} = E_Y\sin(\alpha) - E_X\cos(\alpha) \end{cases} \tag{1}$$

E_Y and E_X are the components of the structural response (e.g. displacements or forces) defined in the X–Y global system of axes; $E_{y'}$ and $E_{x'}$ are the components of the response obtained for a certain x'–y' local system of axes; and α is the global to local axes rotation angle. The definition of the pushover curve for a specific direction of analysis may thus be performed by simply combining the displacements and total base shear forces converted to the considered analysis direction. Fig. 2 also schematically depicts the set of pushover curves obtained for each transverse direction of analysis of the various local axes systems. Another issue related with the computation of the pushover curves concerns the selection of the monitoring node. According to Eurocode 8, the reference node should be defined as the centre of mass of the deformed deck, although several other selection proposals may be found in literature [11],

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