Methodologies for the Seismic Performance Assessment of Bridges – Application to bridges in Portugal

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ABSTRACT:
On the last two decades seismic behaviour assessment turned from force based analysis to displacement based criteria. The purpose of this work is to provide some practical support in order to incorporate the new performance based methodologies in the bridge design. These methodologies are mainly nonlinear static analysis, where structure deformation levels were imposed through the application of an increasing lateral horizontal load. There are different procedures supported by nonlinear static analysis. In this paper, only the Capacity Spectrum Method is mentioned. The presented examples include some current reinforced concrete bridges of small to medium dimension and allowed the analysis of the influence of some characteristics like the skewness, structures irregularities and the type of connection between the deck and the piers.

Keywords: seismic performance, bridges, analysis methodologies, nonlinear static analysis

1. INTRODUCTION

The structure's performance assessment is a common practice on the design process. Supporting each decision there are hypothesis and concepts determining the structure expected behaviour. According to the traditional procedures those hypothesis are restricted to common design situations. With the latest technological advances and the growing social, economical and aesthetic needs, new engineering challenges rise and lead to a better understanding of the nonlinear phenomena. In parallel, the formal performance assessment of the structures is gaining strength on the recent codes and in the design process.

2. STATE OF THE ART

2.1 Introduction

The design of a structure and the behaviour assessment has the same basis, the main differences rises from the problem's approach and from the distinctive goals. In common practice of designing structures the main goals focus on the determination of element characteristics based on behaviour assumptions, the models rely on the elastic effects of the seismic action and there is a safety philosophy behind the process. In the assessment process it is mandatory a correct quantification of the structure's response. A methodology for the bridge seismic behaviour assessment is the Capacity Spectrum Method (CSM), a nonlinear static analysis methodology.

2.2 Capacity Spectrum Method - CSM

The procedure known as the Capacity Spectrum Method is one of the most common methodologies and it is considered in a large number of studies. The formulation is described in ATC-40 Seismic Evaluation and Retrofit of Concrete Buildings (ATC-40, 1996). The method is divided into two parts, one of them is related to capacity curve definition and its transformation into the Acceleration-Displacement Response Spectra (ADRS) format related to the Single Degree of Freedom (SDOF) system. The conversion principles from a Multiple Degree of Freedom (MDOF) system to a SDOF system and consequently from the capacity curve (F-d) to the capacity spectrum, described as a function of the spectral displacements and acceleration, are described ahead. It must be noted that the formulation, as it is in ATC-40, is focused on the application of the method on buildings.

$$S_{ai} = \frac{V_i}{W\alpha_1} \tag{1}$$

$$S_{di} = \frac{\Delta_{roof}}{PF_1 \times \phi_{1,roof}} \tag{2}$$

$$\alpha_1 = \frac{\left[\sum_{j=1}^{N} \left(w_j \phi_{j1}\right)/g\right]^2}{\sum_{j=1}^{N} w_j/g \times \sum_{j=1}^{N} \left(w_j \phi_{j1}^2\right)/g} \tag{3}$$

$$PF_1 = \frac{\sum_{j=1}^{N} \left(w_j \phi_{j1}\right)/g}{\sum_{j=1}^{N} \left(w_j \phi_{j1}^2\right)/g} \tag{4}$$

S_{ai} – spectral acceleration of point i on the capacity spectrum (m/s^2);
S_{di} – spectral displacement of point i on the capacity spectrum (m);
V_i – base force of point i on the capacity curve (kN);
W – Structure weight associated with the action combination in question (kN)
N – Structure level;
w_j – weight associated to level j (kN);
g – Gravity acceleration (g = 9,8 m/s^2);
ϕ_{j1} – amplitude of the 1st mode on level j;
Δ_{roof} – displacement on the top of the building (m);

The second part of the methodology concerns the way how, from the capacity spectrum defined for the SDOF on the ADRS format, we can get a solution for a specific seismic demand.

In order to simplify the procedure, ATC-40 proposes the capacity spectrum bilinearization. There are several proposals to make this approach and they must be adjusted to each situation. The ATC-40 propose the maintenance of spectrum's initial stiffness and the evaluation of the best post yielding slope so that the areas above and under the simplified spectrum are the same (dissipated energy maintenance).

Considering that damping calculation is defined by taking into account the bilinear representation, it is possible to directly calculate the damping value to a specific point of the capacity spectrum (Clough and Penzien, 1995).

The performance point represents the intersection of the capacity curve, in the ADRS format, with the response spectrum for the seismic action in analysis and damping compatible with the dissipated energy.

3. SEISMIC PERFORMANCE ASSESSMENT OF COMMON BRIDGES IN PORTUGAL

3.1 Work characterization

The structures used in the study (Serra, 2008) comprises overpasses, underpasses and viaducts already built and with some years of service. The choice of these works was mainly due to the fact that they are located in the Portuguese region with higher seismicity. This paper presents some results obtained in the study (Serra, 2008). On figures 1 to 3 are represented two of the studied structures: an underpass (PI12B1) and a viaduct (Messejana Viaduct).

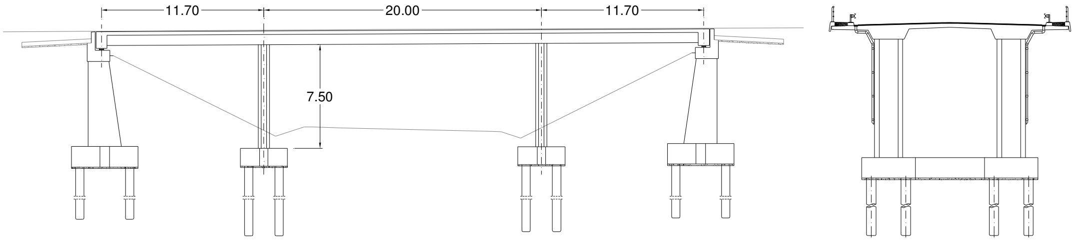

Figure 1. Longitudinal and transverse section of PI12B1

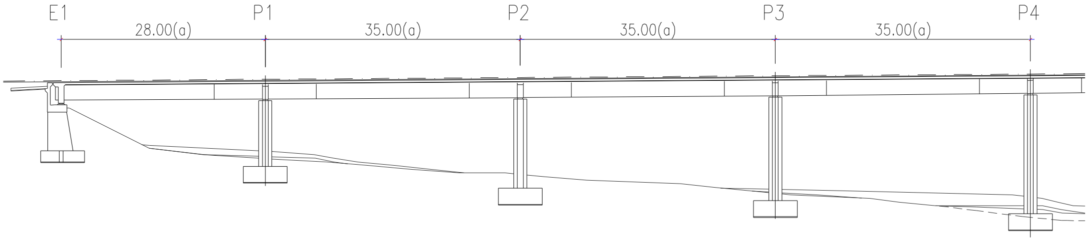

Figure 2. Longitudinal section of Messejana Viaduct (Part 1)

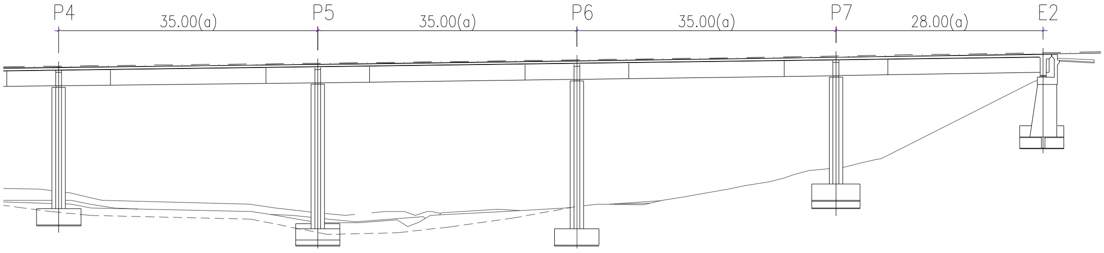

Figure 3. Longitudinal section of Messejana Viaduct (Part 2)

3.2 Seismic demand characterization

One of the goals of the performed study was to compare the results of the behaviour assessment through the CSM method with the results of a Nonlinear Dynamic Analysis (NDA). Since in the NDA the use of base acceleration time series is mandatory, and in order to allow a comparison between the two methodologies, it was decided to use not the smoothed response spectra but the response spectra directly evaluated from the time series. This option allowed the validation of the results of the pushover analysis through the analysis over time, since both use the same seismic action, in different representations. In figure 4 is presented the used time series and the evaluated response spectra. It is also represented the original EC8 (ECS, 2003) response spectra that was the basis for the artificial time series generation.

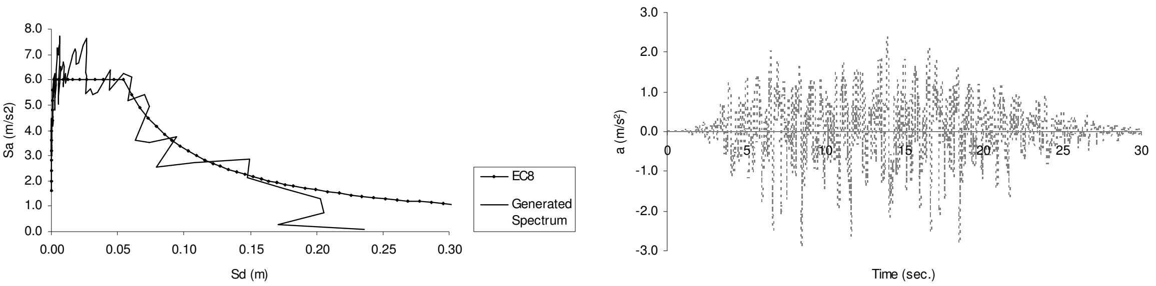

Figure 4. Example of time series and correspondent response spectra

3.3 Nonlinear Static Analysis Results

In this chapter a brief view of the results obtained in pushover analysis and in performance point determination through the Capacity Spectrum Method (CSM) is presented.

Regarding the nonlinear static analysis, the results focus on the capacity curve and the capacity spectrum analysis conducted for longitudinal and transverse directions, for two separate loading distributions, a uniform pattern and a pattern proportional to the first mode of the direction in question. In the study it was considered that the control node is located at the middle of the deck.

The performance point determination, i.e., the intersection between the reduced response spectrum and the capacity curve, is illustrated for each of the presented cases.

On each analysis, the real properties of the structures where used on the models. The mean values of the ultimate compression strength, for both steel and concrete, where considered, as well as the actual longitudinal and transverse reinforcement bars.

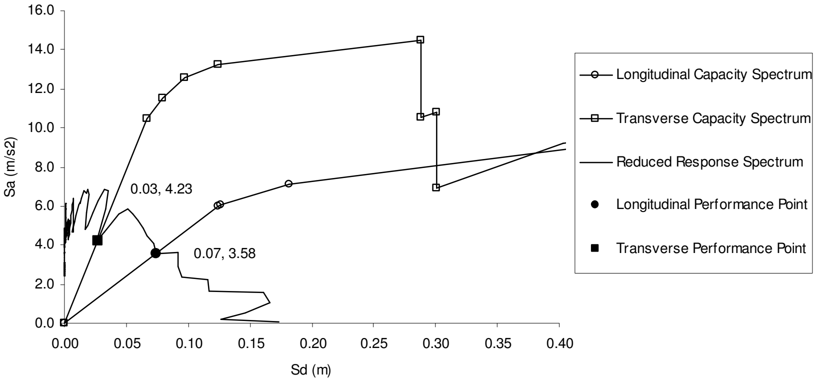

Figure 5. PI12B1 representation of the performance point (Long./Trans) – Uniform Load

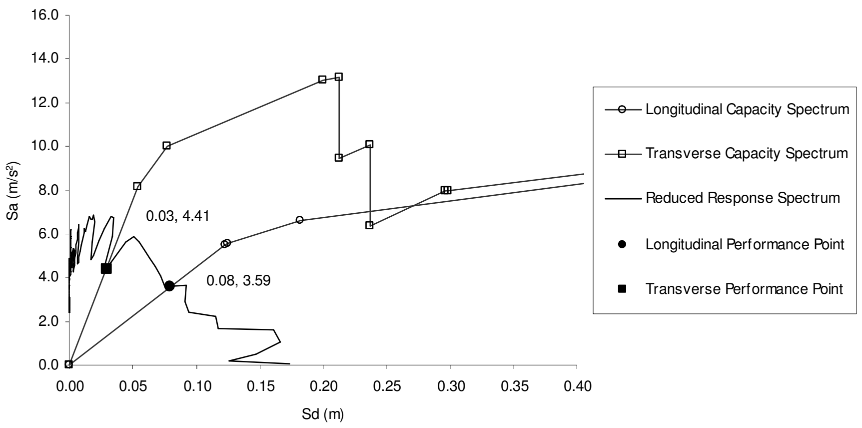

Figure 6. PI12B1 representation of the performance point (Long./Trans) – Modal Load

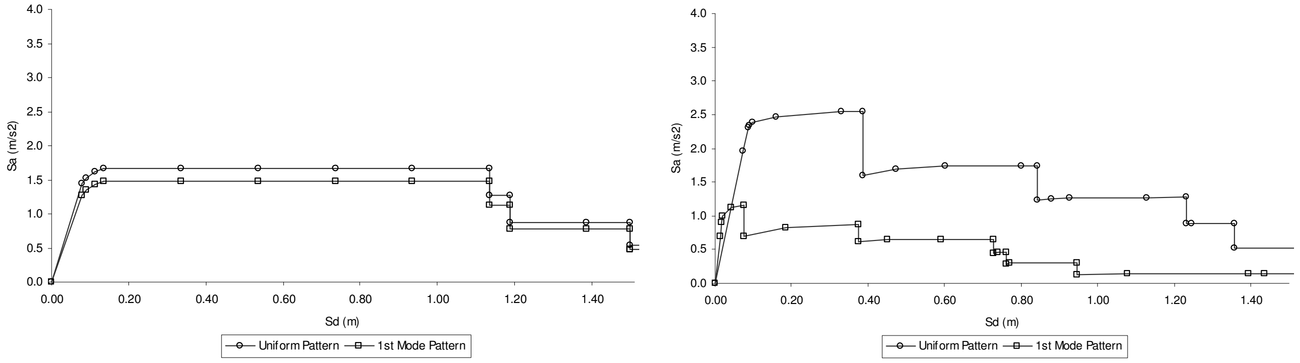

Figure 7. Messejana Viaduct longitudinal (left) and transverse (right) capacity curves

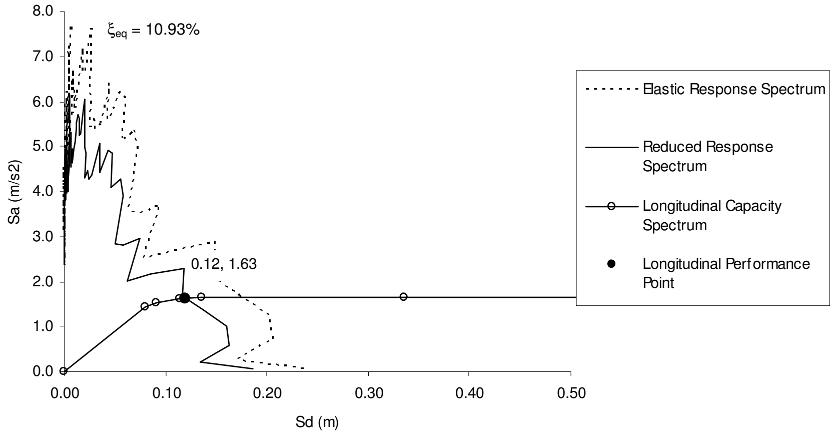

Figure 8. Messejana Viaduct representation of the performance point (Longitudinal) – Uniform Load

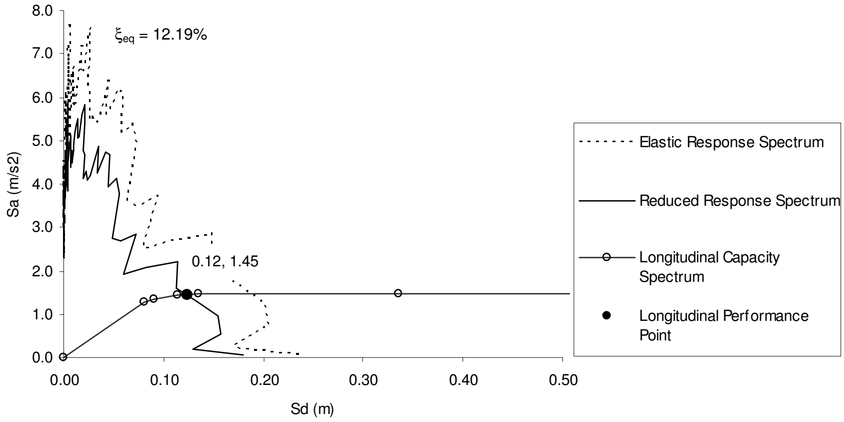

Figure 9. Messejana Viaduct representation of the performance point (Longitudinal) – Modal Load

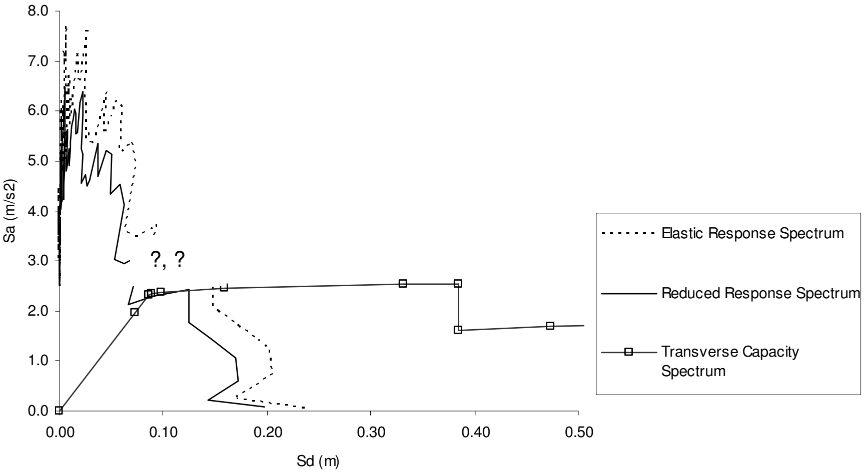

Figure 10. Messejana Viaduct representation of the performance point (Transverse) – Uniform Load

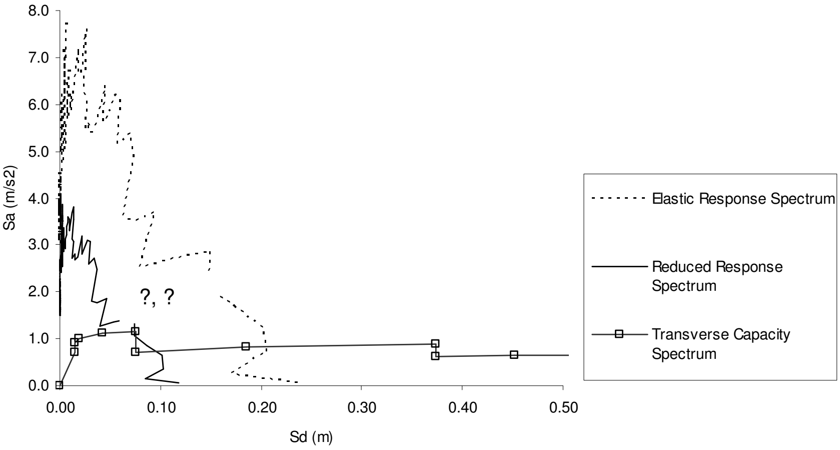

Figure 11. Messejana Viaduct representation of the performance point (Transverse) – Modal Load

The results presented on figures 5 to 9 show that, in the longitudinal direction, the results are almost independent of the load pattern. In these cases, since the structure is similar to a SDOF in the longitudinal direction, the load patterns are similar. In the transverse direction the situation is completely different, with important differences between the results with the two load patterns. In the case of Messejana Viaduct the differences between the two load pattern results are more important due to the bridge configuration. A long viaduct with piers with different heights present a rather complex transverse modal behaviour with a configuration significantly different from the one imposed by a uniform load (figures 10 and 11).

The results revealed that the underpass PI12B1 should remain elastic if submitted to seismic action compatible with the EC8 code definition. This behaviour is a consequence of the differences between the actual analysis models and the models used in the year when the bridge was designed. The major difference between models is related to the elastic stiffness of the piers. The bridge was designed assuming that the pier's stiffness was the stiffness of the uncracked section and, in the pushover model, a reduced stiffness was assumed.

3.4 Nonlinear Dynamic Analysis Results

An example of the results for nonlinear dynamic analysis (Direct Integration) is presented in figure 12, where a direct comparison with the pushover analysis for an underpass is shown.

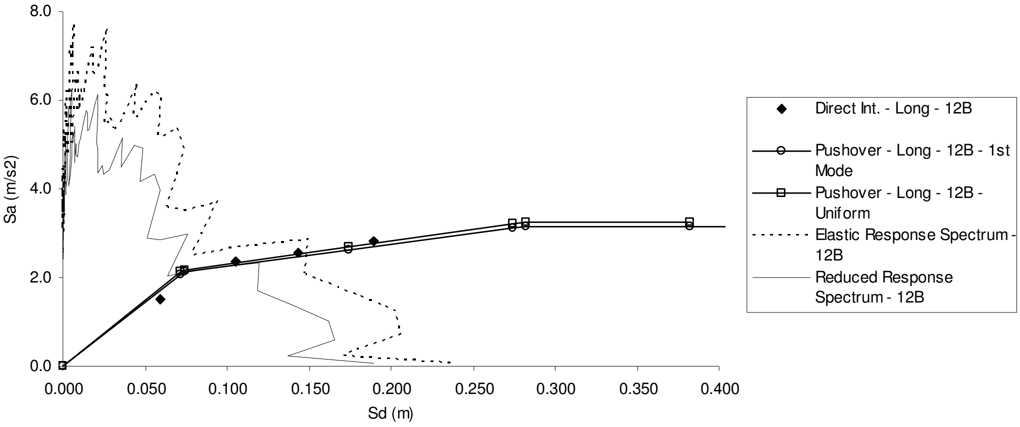

Figure 12. Comparison between Longitudinal Pushover Analysis and Nonlinear Dynamic Analysis

In general, the results of the dynamic analysis showed good agreement with the pushover analysis results obtained with the uniform load pattern.

4. CONCLUSIONS

The nonlinear dynamic analysis continues to be the validating procedure for the results of nonlinear static analysis and the performance point determination methodologies. In this work the results showed that the uniform pattern of loads used in pushover analysis (transverse direction) gave a better estimate of the seismic behaviour. The yielding evolution of the different sections reduces the rotation effects and the displacement distribution along the analysis turns to uniform throughout the deck.

The Sa-Sd pair of values defined as the performance point, obtained in each bridge, corresponds to the structures response for the seismic demand level. However, the assumed models don't have in consideration the nonlinear behaviour of some structural and non-structural elements, which may compromise the position of the performance point. Examples of aspects that are not enclosed in calculation models are the nonlinear behaviour of foundations, the sudden unseating of the deck, the total or partial deck failure or the fragile rupture by transverse forces.

In the observed bridges it was only used models where piers nonlinear bending behaviour was defined. This fact leads to a limitation of the structure's behaviour analysis as a whole. Despite that it is possible to assess some specific situations regarding the capacity curves analysis.

In the case of the analysed examples, which are a representative collection of the common bridge scenario in Portugal, the required ductility value will hardly reach the available ductility value, because, in general, the ultimate displacement values don't correspond to the structures limit. The mean values of material properties provide great levels of deformation capacity and lead us to conclude that there are other structural and non-structural elements that wouldn't support these displacements.

For example, the elastomeric bearings are designed to a much lower displacement limit as the one matching the ultimate displacement. The loss of support in the abutments is also a question that numeric model doesn't simulate and can be of great importance in performance evaluation. On the other hand, for this level of displacements, the P-Δ effects begin to have an importance that can not be neglected.

Therefore we can conclude that there is a mismatch between the ductility and resistance demands imposed by the seismic action and the ductility levels available and also, in a great number of cases, the effective resistance of the structure. In terms of strength, this difference comes mainly from the safety philosophy with the objective of reducing the collapse probability. A more careful evaluation of the ductility in the design process could enhance the structure potential, suiting the required behaviour to the demanded levels.

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