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Attention Classes and Seismic Vulnerability of Highway Bridges

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Abstract

This study compares different methodologies for assessing the seismic vulnerability of viaducts, focusing on the contrast between the 2003 Ordinance procedure (OPCM 3274/2003), in particular on modal pushover analysis, and the more recent 2022 National Guidelines (CSLLPP (2020) D.M. 204/2022) for existing bridges. Results, expressed in terms of return periods, are evaluated against the 949-year benchmark for the life-safety limit state (Chopra & Goel, 2002, 2004; Paraskeva & Kappos, 2008). The analysis also examines the multi-level structure of the Guidelines, particularly Level 2 and the attribution of Attention Classes (MIT–CSLLPP, 2020). A case study and a statistical evaluation of 382 viaducts reveal weak correlation between the qualitative classifications of the Guidelines and the quantitative seismic assessments derived from the Ordinance methodology. Findings highlight the importance of adequately capturing pier behavior and show that several bridges has not been assigned a HIGH overall Attention Class nonetheless they fail seismic checks. The results indicate that quantitative seismic analyses can effectively serve as an equivalent to Level 4 of the Guidelines, revealing that many structures currently exempt from verification are not seismically compliant, an insight crucial for informed prioritization of interventions.

Keywords: Seismic vulnerability; Modal pushover; Attention Class; Highway bridges

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1. Introduction

This work presents a critical comparison of the different approaches used to assess the seismic vulnerability of viaducts, contrasting historically adopted methodologies with the most recent regulatory guidelines. The seismic vulnerability analyses originally carried out according to Ordinance PCM 3274/2003 were re-examined, with particular focus on the modal pushover approach adopted by SINA (OPCM 3274/2003; Freeman et al., 1975; Chopra & Goel, 2002, 2004). The main outputs, especially the return period, were compared with the reference value of 949 years, corresponding to a 10% probability of exceedance in 100 years and associated with the Life Safety Limit State (NTC 2018; EN 1998-2:2005).

The study also considers the multi-level methodology proposed by the national Guidelines for the Classification and Management of Risk, Safety Assessment and Monitoring of Existing Bridges, focusing on Level 2 for the identification of the various Attention Classes and the definition of the overall class (MIT–CSLLPP, 2020; D.M. 204/2022). A representative case study is presented to highlight the substantial methodological differences between the two assessment approaches.

Finally, a statistical analysis of 382 viaducts across two motorway sections in Northern Italy shows a generally weak correlation between the two methods, one quantitative and the other qualitative, supporting the need for further targeted investigations (Di Prisco, 2019; Bazzucchi et al., 2018). Regulatory references such as Ordinance PCM 3274/2003, NTC 2018, and the 2020 Guidelines frame the comparison between analytical procedures and risk-based approaches, forming the foundation of this work and its exploration of their consistency and potential synergies (OPCM 3274/2003; MIT–CSLLPP, 2020; NTC 2018).

2. Analysis methodology and employed tools

The study was developed in collaboration with SINA S.p.A., a company specialized in the design, management, and maintenance of motorway infrastructures. Several bridges belonging to the Northern Italy motorway network were analyzed, for which seismic vulnerability data were available according to Ordinance 3274/2003 (OPCM 3274/2003). Finite element models were developed using MIDAS Civil, and nonlinear static (pushover) analyses were performed to check the main collapse mechanisms, including pier plastic rotation, shear failure of the pier, and unseating of the deck (EN 1998-2:2005; ATC, 1996).

The results of the pushover analyses were used as input for a Matlab-based Modal Pushover Analysis (MPA) tool, which considers the most significant vibration modes and iteratively computes seismic risk indices and intervention period until convergence (Sasaki et al., 1998; Chopra & Goel, 2002; Chopra & Goel, 2004). The MPA procedure combines modal responses and automates the verification process, performing checks for ultimate rotation, shear, and bearing capacity consistently with MIDAS Civil analyses (Kappos et al., 2005; Paraskeva & Kappos, 2008). In parallel, the seismic Attention Class of the same bridges was assessed according to the 2020 Guidelines, based on seismic hazard, vulnerability, and exposure parameters (MIT–CSLLPP, 2020; Protezione Civile, 2021).

3. Case study

The analyzed viaduct (Fig. 1, left), designed according to Italian Ministerial Circular No. 384/1962, is a three-span simply-supported deck bridge with spans of approximately 42 m and two independent carriageways (Westbound and Eastbound) (Ministero dei Lavori Pubblici, 1962). The deck consists of prestressed reinforced concrete girders with a composite slab, supported by single-column piers and reinforced concrete abutments founded on piles.

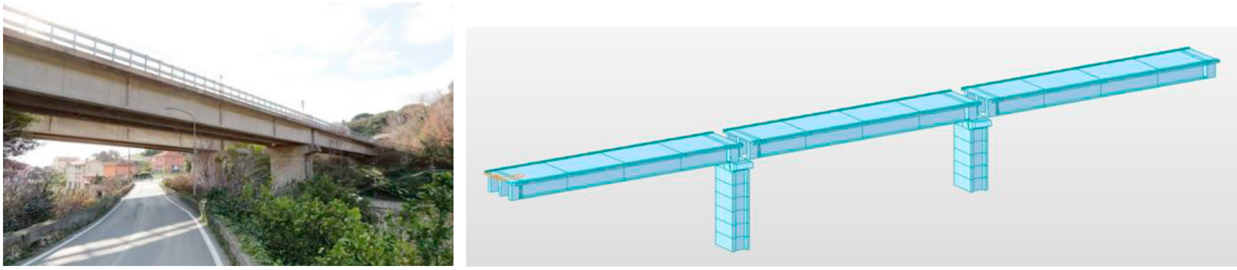

Fig. 1. Case study viaduct (left); West carriageway viaduct model on Midas Civil (right).

The seismic Attention Class was assessed in accordance with the Italian Bridge Guidelines (MIT–CSLLPP, 2020; D.M. 204/2022), based on visual inspections and seismic hazard and vulnerability parameters. For the Westbound carriageway, the seismic Attention Class resulted as medium–high, while for the Eastbound carriageway, characterized by higher vulnerability, it resulted as high. Consequently, the overall Attention Class of the viaduct was defined as medium–high for the Westbound carriageway and high for the Eastbound carriageway, indicating different priority levels for further investigations and interventions.

In parallel, the seismic vulnerability of the viaduct was evaluated according to Ordinance PCM 3274/2003 through nonlinear modal pushover analyses (OPCM 3274/2003). A three-dimensional finite element model was developed in MIDAS Civil based on original design drawings, accurately reproducing geometry and structural details (Fig. 1, right). Material nonlinearities were introduced through concentrated plastic hinges defined using Kent–Park concrete and Park steel constitutive models (Fig. 2) (Kent & Park, 1971; Thompson & Park, 1978), in accordance with Eurocode 8 and FEMA provisions (EN 1998-2:2005; ATC, 1996).

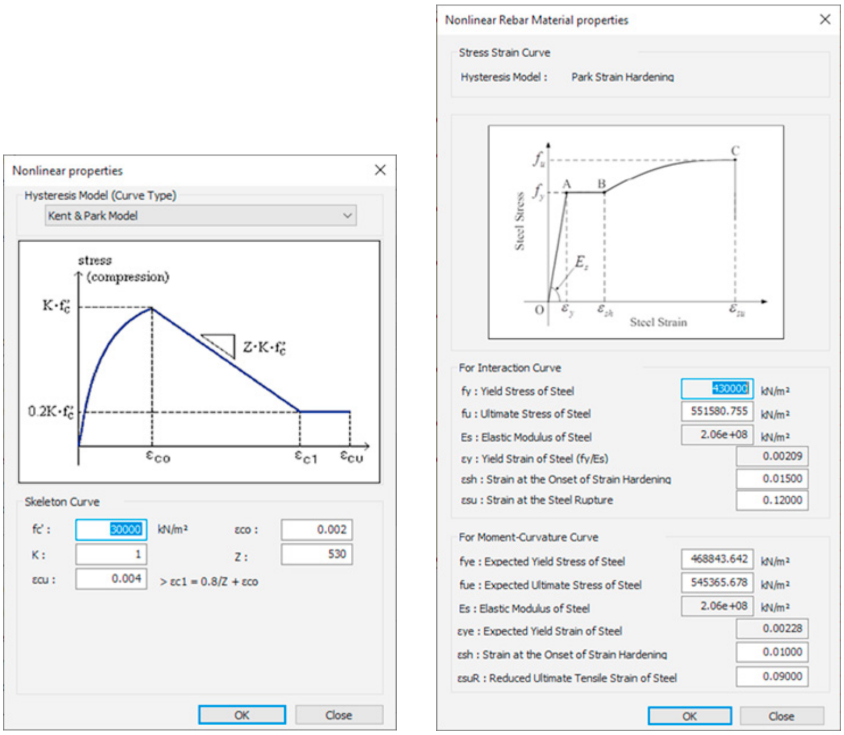

Fig. 2. Kent and Park constitutive model for concrete(left); Park constitutive model for steel (right).

Three collapse mechanisms were investigated: pier ultimate rotation, shear failure of the pier, and unseating of the deck (bearing failure) (Paraskeva et al., 2008). Modal pushover analyses were performed along the principal directions (longitudinal and transverse with respect to the viaduct axis) to identify performance points of the structure in the ADRS plane (Fig. 3) (Fajfar, 1999). Afterwords, the CQC modal combination rule was used to evaluate to capacity of the viaduct against increasing peak ground accelerations with the aim to evaluate the seismic risk indices and return periods (Chopra & Goel, 2002; Aydinoglu, 2003).

For the Westbound carriageway, the governing mechanism was pier shear failure in the longitudinal direction, with an estimated return period of approximately 835 years, slightly lower than the reference value of 949 years. A similar result was obtained for the Eastbound carriageway, with a minimum return period of about 759 years, again governed by shear failure, mainly due to differences in pier geometry.

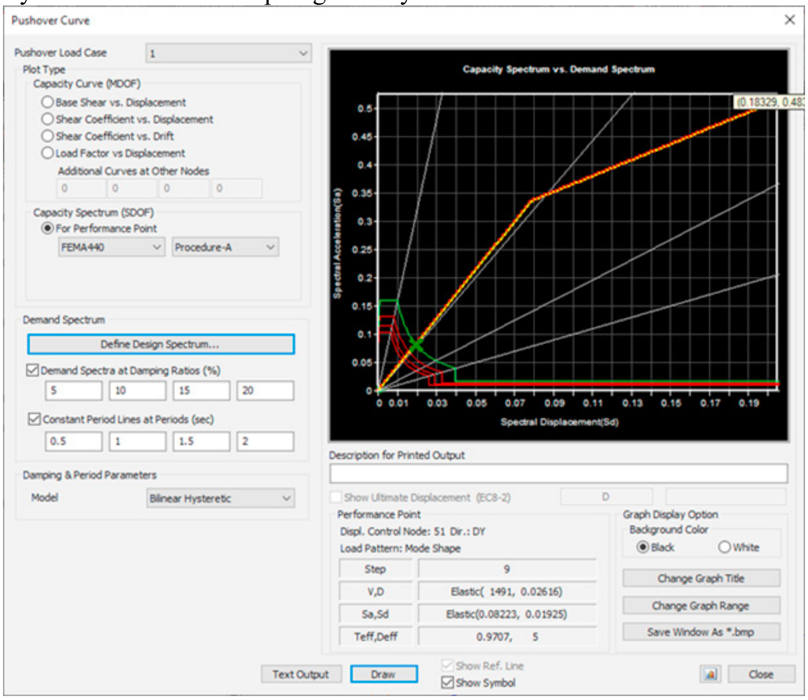

Fig. 3. Pushover analysis and identification of the performance point in Midas Civil

4. Statistical evaluation of the results from the two analyses

The statistical analysis is based on a database of 382 bridges located along two motorway sections in Northern Italy, for which both seismic vulnerability assessment results (Return Period) and Seismic Attention Classes are available. The study highlights the fundamentally different nature of the two indicators: the Return Period is a purely probabilistic parameter, independent of site-specific characteristics (OPCM 3274/2003), while the Seismic Attention Class represents a qualitative risk assessment integrating hazard, vulnerability, and exposure (MIT–CSLLPP, 2020).

The results show that most structures with a Return Period lower than the threshold value of 949 years fall within Medium, Medium-High, or High Seismic Attention Classe levels, although no direct correlation between Attention Class and Return Period is observed. Structures belonging to the same attention class may exhibit significantly different Return Period values (Bazzucchi et al., 2018).

From a structural typology perspective, simply supported girder bridges account for approximately 85% of the sample. For these structures, the percentage of bridges satisfying vulnerability checks is generally higher than that of non-verified ones, regardless of pier configuration. Low and Medium-Low attention classes are almost absent.

A key aspect concerns the influence of pier height, which is explicitly considered in Return Period calculations but not in the Attention Class definition. The results indicate that structural slenderness plays a crucial role in seismic performance, with short and stocky piers being more prone to shear failure (Bracci et al., 1997; Elnashai, 2001).

The comparison based on peak ground acceleration (PGA) confirms a coherent trend: as seismic hazard increases, so does the percentage of non-verified structures (INGV, MPS04-S1). Nevertheless, a non-negligible number of non-verified bridges is also found in medium-low hazard classes.

Finally, the analysis of structural classifications adopted by the Guidelines demonstrates that general parameters such as static scheme, span length, and material are insufficient to fully capture actual structural capacity (MIT–CSLLPP, 2020). This highlights the need to complement qualitative classifications with detailed vulnerability analyses. The Seismic Attention Class and the Return Period should therefore be considered complementary tools, to be jointly applied for a comprehensive seismic safety assessment of existing bridges.

5. Overall Attention Class vs. Seismic Attention Class

This section investigates the relationship between the Overall Attention Class (global CdA) and the Seismic Attention Class, with the aim of assessing the consistency between the indications provided by the Guidelines and the results of structural safety verifications (MIT–CSLLPP, 2020). The analysis is intended to evaluate whether the criterion requiring safety checks exclusively for structures classified as High Overall Attention Class is always appropriate, or whether it would be advisable to extend such investigations to other classes as well.

In the first phase, structures classified as High Overall Attention Class are examined, for which the Guidelines mandatorily require Level 4 safety verifications (VdS). The results show that within this category structures with markedly different seismic performance coexist, including both verified and non-verified structures with respect to code requirements (OPCM 3274/2003). This confirms that, although the Overall Attention Class represents an effective prioritization tool, it does not allow for a precise discrimination of the actual seismic safety level of individual structures.

Subsequently, attention is focused on structures characterized by an Overall Attention Class lower than High, but by a High Seismic Attention Class. The analysis of this subset of bridges highlights a critical issue: in this case as well, the distribution of Return Periods includes both verified and non-verified structures with respect to the reference threshold of 949 years, with no clear dependence on the overall class. This evidence suggests that the automatic exclusion of these structures from safety assessments may be non-conservative (Di Prisco, 2019), especially in the presence of a high level of seismic attention. For these structures, a couple of histogram representations for a set of viaducts in two motorway sections are provided in Figs. 4 and 5, with the Return Periods reported on the vertical axis.

In light of these results, it is appropriate to consider extending safety verifications to structures with a High Seismic Attention Class, regardless of their Overall Attention Class, making use of the data already available from seismic vulnerability analyses. Such an approach would enhance risk management by avoiding potential underestimations arising from a predominantly qualitative classification.

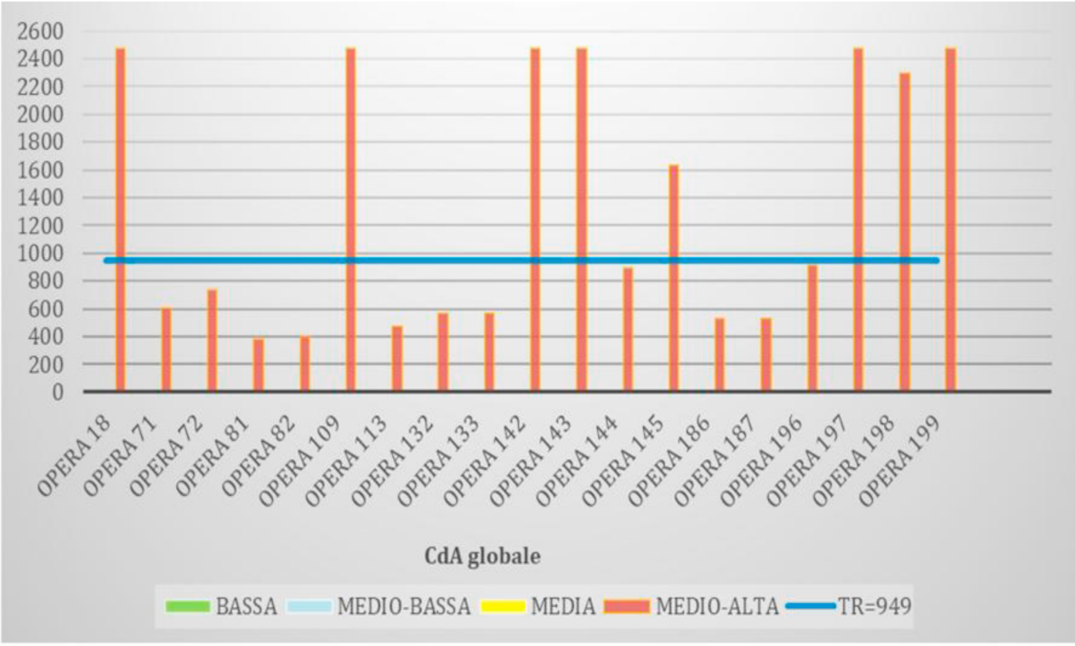

Fig. 4. Structures with High Seismic Attention Class and Overall Attention Class different from High – Motorway Section 1

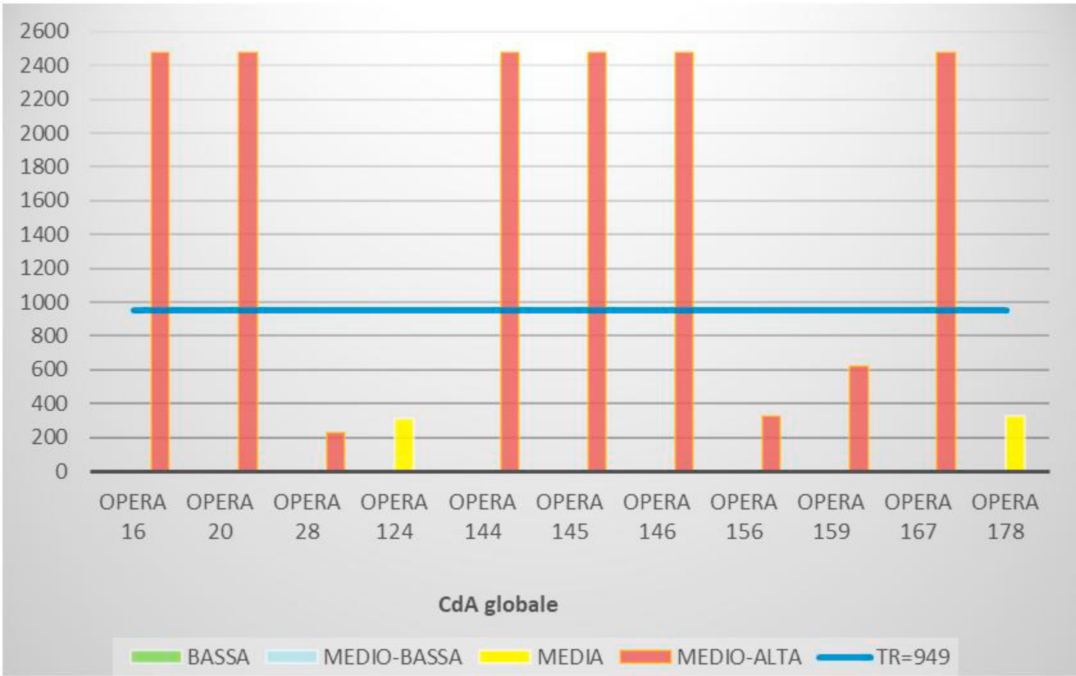

Fig. 5. Structures with High Seismic Attention Class and Overall Attention Class different from High – Motorway Section 2

6. Linking and comparing static and seismic assessments – Reliability Index Estimation for existing viaducts

This section highlights the integration between static structural checks (related to traffic loads) and seismic assessments, with the goal of defining a unified approach for evaluating the safety of existing bridges. This integration is particularly relevant in infrastructure management, where establishing a single intervention priority requires considering different sources of risk.

Existing bridges have often been designed to outdated codes (Ministero dei Lavori Pubblici, 1945; 1962), leading to two distinct analyses during current assessments: static analyses and seismic analyses *NTC 2018*. In practice, these aspects are typically handled separately, making it difficult to develop a coherent long-term maintenance strategy.

Introducing a reliability index, a synthetic parameter representing the probability of failure regardless of the load type, may help overcome the separation between static and seismic checks. A unified indicator could incorporate safety factors and uncertainties of the adopted analytical models.

Currently, no established normative methodology exists to provide a unified structural reliability assessment combining both static and seismic effects. However, this topic represents a highly relevant research area, especially in relation to the development of Bridge Management Systems (BMS).

Integrating static and seismic assessment results would enable more effective maintenance and retrofit planning, support more efficient resource allocation, and foster a more comprehensive risk-informed management process.

7. Conclusions

A critical analysis of seismic vulnerability assessment methods for bridges was conducted using an extensive infrastructure database provided by SINA S.p.A. The study compared the quantitative, code-based seismic vulnerability approach, centered on the Return Period of the critical earthquake, with the qualitative, multi-level approach of the Italian Guidelines, based on the definition of the Attention Class (CdA) (MIT–CSLLPP, 2020).

An initial case study highlighted the methodological gap between the two approaches: detailed finite element and probabilistic capacity assessments versus a risk classification system combining hazard, vulnerability, and exposure with a necessarily simplified level of detail. A statistical analysis on 382 viaducts from two motorway sections in Northern Italy confirmed the weak correlation between Return Period and Seismic CdA.

Further comparison within homogeneous structural families showed a consistent trend: higher Seismic CdA generally aligns with a larger percentage of structures not satisfying the normative Return Period. However, some inconsistencies emerged, such as bridges with Return Periods below the normative threshold but classified in CdA categories other than “High”, for which no mandatory in-depth analyses are required.

The relationship between Overall CdA and Seismic CdA also showed that relying solely on the Overall CdA may not always be conservative. In particular,bridges with a high seismic CdA should be considered more carefully, even when the overall classification is lower, leveraging available seismic vulnerability results.

Ultimately, the study underscores the importance of an integrated structural safety assessment, combining both static and seismic conditions. Although a unified reliability index is not yet defined, this represents a promising future direction, capable of significantly improving maintenance planning, risk management, and resource allocation within Bridge Management Systems.

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