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An online database and software for bridge-specific fragility analysis of as-built and retrofitted bridges

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Abstract

Bridges are the most critical and often the most vulnerable structural component while bridge damage due to earthquake is related to substantial direct and indirect losses. Therefore, the development of a tool for rapid evaluation of bridge seismic performance for different levels of earthquake intensity is valuable in the frame of resilience assessment of road networks and retrofit prioritization. The key requirements for an effective assessment tool are the broad application range and acceptable accuracy in the estimation of structure-specific parameters. To this end, an online database was developed for fragility analysis of as-built and retrofitted bridges organised in two 'tracks': Fragility curves for a specific bridge can either be calculated online based on literature recommendations and data available in the database, or according to a recently proposed, component-based, structure-specific methodology, using the software developed and available online. In the component-based methodology fragility curves for bridge piers, bearings, and abutments, are developed and combined to derive system fragility. The estimation of component capacity and demand, along with the fragility framework and uncertainty treatment are incorporated into the software developed which is available online. The first software module refers to bridge pier capacity estimation and limit state threshold quantification and is based on analysis results of a fully parameterised pier model, accounting for inelastic behaviour and different failure modes. Furthermore, experimental data are collected, classified and uploaded to the online database, and can be used for deriving user-defined limit state thresholds. The second software module refers to the development of bridge-specific fragility curves, based on dynamic analysis results of a fully parameterised OpenSees model and the application of the probabilistic framework taking account of all pertinent uncertainty sources. Both software modules are extended for application to fragility assessment of retrofitted/upgraded bridge components and systems. The platform developed and the features available are presented and discussed in detail herein.

Keywords: Online Platform, Bridges, Fragility, Retrofit.

1. Introduction

Damage due to earthquake is commonly related to substantial direct and indirect losses, highlighting the need for damage detection and retrofit prioritization based on the results of the seismic risk assessment of the road network. In this context, numerous methodologies have been developed for the seismic vulnerability assessment of bridges for different levels of seismic hazard using fragility curves.

The most comprehensive way to assess bridge seismic behaviour is to plot vulnerability curves and calculate the likelihood of damage occurring at different seismic intensity levels. Probabilistic fragility curves are plotted for different levels of damage and constitute an estimator of the degree of damage for a particular seismic event, highlighting the potential need for pre-earthquake reinforcement. Therefore, over the last 40 years, international scientific interest has focused on the development of methodologies for the definition of limit states and the calculation of seismic vulnerability. Many research groups around the world have proposed and implemented methodologies for the assessment of seismic vulnerability of bridges divided into empirical, based on expert judgment or recorded earthquake damage, analytical based on the results of computational model analyses, and hybrid, which combine the results of analyses and empirical data. In addition, the last decade, analytical fragility curves have been extended to retrofitted bridges for retrofit prioritization and evaluation of retrofit measures and techniques. Analytical methods may be classified to those focusing on the derivation of generic fragility curves, applicable to specific typological bridge classes [1, 2], and those focusing on bridge-specific fragility curves [3]. It should be noted that in most cases, the limit state (LS) threshold values of the engineering demand parameters are defined based on qualitative criteria and experimental data [4, 5] rather than being based on numerical analysis of the capacity of critical components [6]. Likewise, the uncertainty values considered in fragility analysis (uncertainty in capacity and LS definition) are usually selected based on literature recommendations [4], while uncertainty in seismic demand is usually quantified based on parametric analyses. Recently, analytical methodologies have been extended to retrofitted bridges to assess the seismic behavior of bridge systems retrofitted with various retrofit techniques and strategies and evaluate their effectiveness [7, 8, 9, 10].

Attempts to develop platforms and databases of bridge fragility curves are so far limited; they include online platforms and fragility function "manager tools". The online database created within the GEM project (see [11]) is arguably the most systematic and holistic attempt to collect and organise fragility curves of (as-built) bridges; the database also includes RC and masonry buildings. In the frame of the research project SYNER-G, [12] developed a fragility function manager tool, an interface that includes bridge fragility function lists, allowing the user to add fragility functions not included in the database. However, the database cannot be used online; the tool is available for download and should be locally installed. It should be also noted that comprehensive literature review on fragility curves have been carried out in the frame of research projects (e.g., [13,14] which include data regarding LS definition and threshold values for bridge system and components.

This paper presents an online 'database and software for fragility analysis of as-built and retrofitted bridges (www.thebridgedatabase.com). For the first time, a 'two-track' platform is provided online, including ad-hoc software for online bridge-specific fragility curve derivation using a database of bridge components, as well as the option to select an appropriate set of generic fragility curves (functions) from an extending catalogue, based on the bridge class selected. The software is based on a recently proposed, component-based, structure-specific methodology [3] tailored to bridge portfolio fragility analysis and was developed in Python [15] using OpenSeesPy [16] for multiple bridge analyses. A fully parameterised bridge model was developed, allowing for input of user-defined geometry, component parameters and seismic excitation; it includes a probabilistic framework that considers all pertinent uncertainty sources. Moreover, a database and a software module for estimating LS thresholds for as-built and retrofitted bridge piers are available on the online platform. Specifically, based on experimental studies and other information available in the literature, the LS thresholds for different as-built and retrofitted bridge pier types (namely circular, hollow circular rectangular, hollow rectangular and wall type), bearings and abutments are embedded in the platform. The toolkit also includes the closed-form relationships described in [6], allowing a component-specific (online) estimation of LS thresholds, additionally providing an ad-hoc software for their analytical

estimation based on pushover analysis results of the fully parameterised inelastic model, considering multiple failure modes. It is pointed out that the online toolkit is fully interactive, allowing input from users/contributors, with a view to not only receiving feedback but also enriching the platform.

2. Generic Fragility Curve Database

The first module of the online database (www.thebridgedatabase.com) is the estimation of generic fragility curves based on the provided fragility curve catalogue. The catalogue is interactive allowing the users to contribute and upload their fragility curves using the template available online. The bridges included in the database are classified according to a classification scheme that is an extended version of that suggested in [17]. A catalogue of existing generic fragility curves for various typological classes is included in the database, derived from numerical analysis in studies carried out in the last two decades. The database includes links to each pertinent publication, mentioning material and structural characteristics of the bridge and the bridge typology according to the classification scheme. Additional parameters that affect the fragility curve development are also included, namely, the critical components considered for bridge fragility estimation, the engineering demand parameters and the threshold values selected for each component or at system level, as well as modelling and analysis method issues. Details regarding the seismic input motion are also included, along with issues related to the 'format' of the fragility curve, i.e. the considered parameter of seismic intensity and the uncertainty values.

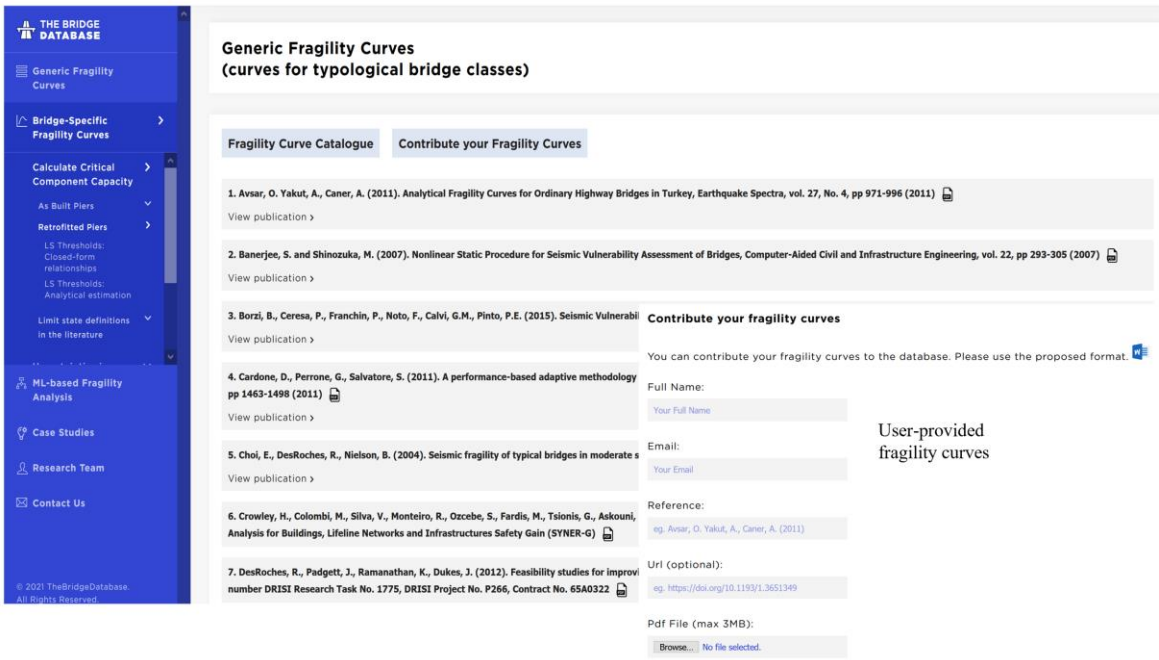

Figure 1. Online catalogue of generic fragility curves for typological bridge classes

3. Bridge-Specific Fragility Curves

The second (and most important) module of the platform is the online, real-time, structure-specific calculation of bridge fragility curves. In the frame of the component-based methodology for the estimation of fragility curves [3], capacity and demand for all critical components should be considered, and all sources of uncertainty have to be quantified. Several features are provided within the platform, including the *calculation of component-specific capacity and LS thresholds* (either analytical, based on closed-form relationships, or adopted from the literature) and the *estimation of uncertainties in capacity and LS definition.* For a large number of bridge classes, the uncertainty in seismic demand was estimated for every component based on inelastic response history analysis, by Stefanidou & Kappos, 2019 [6], and these values

are included in the database (in addition to those from the literature, see Section 3). The user can either *calculate bridge-specific fragility curves online or just extract from the databases LS thresholds* (quantifying damage for different limit states) and uncertainties, to be used in alternative methodologies for fragility curve development.

The features provided online, i.e. the calculation of component-specific capacity and LS thresholds using the three alternatives described above, the quantification of uncertainty (in seismic capacity and LS definition) and the online estimation of bridge-specific fragility curves in both directions (longitudinal and transverse) using the wizard and the component-specific input parameters for the bridge studied are described in §3.1 to §3.3.

3.1 Capacity and LS thresholds for as-built and retrofitted piers

(a) Closed-form relationships for the estimation of LS thresholds

Closed-form relationships are provided within the platform for the estimation of limit state thresholds for RC as-built and retrofitted piers. Extensive parametric inelastic (pushover) analyses were performed, considering different failure modes (flexural and shear), and regression analysis of the results was performed for the derivation of closed-form relationships. Different relationships are included for the quantitative definition of minor to major damage thresholds of various pier types, namely cylindrical, hollow cylindrical, rectangular, hollow rectangular and wall-type piers. Critical parameters affecting the seismic capacity of bridge piers were considered as variables (pier type, dimension, material properties, reinforcement ratio, etc.); a value range for each parameter was selected and multiple models were set up and analysed. Details regarding the distinct steps for the derivation of the closed-form relationships can be found in [6] and [10] for as-built and retrofitted piers, respectively, along with details of modelling issues and the qualitative and quantitative definition of damage in local (section curvature) and global (pier displacement) terms. Damage thresholds in terms of curvature (and strain) are initially defined at section (local) level and are subsequently mapped onto displacement of the control point (global level) using inelastic pushover analysis results. So long as the results in terms of moment-curvature are available, regression of section analysis results is performed and closed-form relationships for yield and ultimate moment and curvature are derived and also included in the database. The LS thresholds for as-built and retrofitted bridge piers in displacement terms (d_1~ d_4), estimated according to the closed-form relationships described previously, are included as default within the software for the online estimation of bridge-specific fragility curves and are illustrated in Fig. 2 for the case of cylindrical piers. Similar relationships are available for all limit states (LS1 to LS4, i.e., minor damage to collapse) and all different pier section types (cylindrical, hollow cylindrical, rectangular, hollow rectangular, and wall-type) and for retrofitted piers, namely cylindrical and hollow cylindrical piers retrofitted with RC and FRP jackets. Details regarding the assumptions and parameters of retrofitted pier sections (confined concrete, retrofit parameters, etc.) are available in [10].

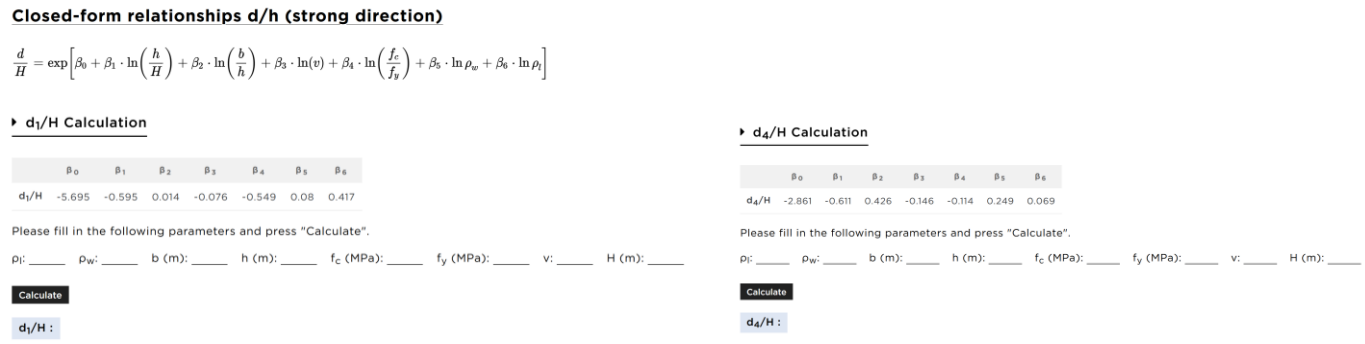

Figure 2. Online form for the estimation of LS thresholds for cylindrical piers in terms of displacement (example for d1&d4)

It should be noted that the proposed relationships are based on regression analysis of results for cantilever pier models. However, depending on the structural system and the deck stiffness (in monolithic joints), or bearing stiffness (in non-monolithic deck to pier connections), the moment at the pier top may be non-zero.

Then the threshold values estimated from the closed-form relationships in the platform, should be modified according to Eq.1 (from [3]), feature included in the online software)

$$d_{(L)} = \left(\frac{6x-2}{4 \cdot x^3} \right) \cdot d_{(L_o)} \qquad (1)$$

(b) Analytical estimation of LS thresholds

An alternative for the online estimation of LS threshold values in displacement terms for RC as-built and retrofitted piers is available in the database, based on inelastic (pushover) analysis carried out *on the platform*. A detailed, fully parameterised inelastic model has been developed in OpenSees.py [16] supplemented by an ad-hoc software in Python [15] to estimate all key parameters (i.e. confined concrete properties, section aggregator properties, etc.) and process the analysis results. Inelastic pushover analysis using the OpenSees.py model is performed and the pushover curve is provided, along with LS threshold values in displacement terms, i.e., displacement of the control point (d_1 to d_4), quantitatively defining minor damage to collapse for the as-built or retrofitted (with RC or FRP jacket) cylindrical and rectangular piers.

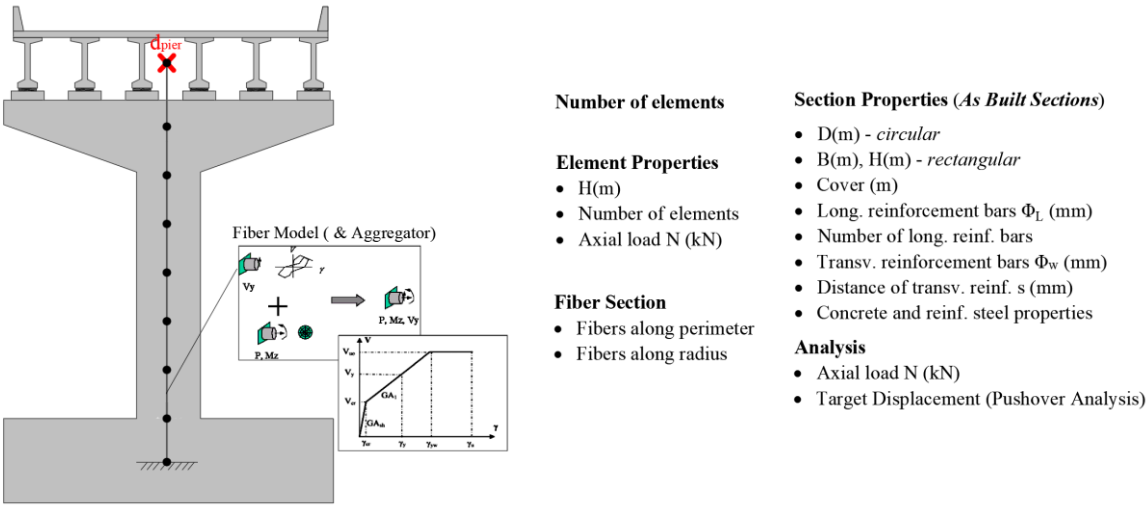

Figure 3. Input parameters for as-built and retrofitted piers and analytical estimation of LS thresholds

All critical parameters related to member and cross-section geometry, and the axial loading are considered as variables (Fig.3, are entered in online forms, and used as input to the parametrically defined inelastic model considering distributed plasticity (fiber model) at the pier base, developed in OpenSees.py. Regarding concrete material, unconfined properties are provided and used as input for the concrete cover, while confined concrete properties are used as input for the concrete core; they are estimated according to: (a) the Mander et al. (1988) model [18] for cylindrical pier sections, (b) the confined concrete model of EC2 [19] for rectangular piers, and (c) the Spoelstra & Monti (1999) model [20] for FRP-retrofitted cylindrical pier sections. It should be noted that for the RC jacketed pier sections, a 50% reduction in core confinement was applied, to avoid the 'double' core confinement effect (core and jacket transverse reinforcement), described in [10]. Shear capacity is also considered, by defining the V-γ (shear force vs shear deformation) curve according to [21], which is used as input at plastic hinge location via section aggregator. The parameters of the V-γ curve are calculated according to [22] and EC2 [19] for cylindrical and rectangular pier sections, respectively, and according to the code for Structural Interventions KANEPE (2017) [23] for RC and FRP retrofitted sections. Based on the input parameters described above, a case-specific inelastic pier model is set up, and pushover analysis is performed, calculating the displacement at the step where the local parameter threshold is exceeded is recorded; therefore all LS thresholds are estimated in displacement terms and are marked on the pushover curve (d_1~d_4 values). This software module of the platform may be used for pushover analysis of a pier and LS threshold estimation, irrespective of the methodology applied for fragility analysis. It should be, however, noted that these values refer to the equivalent cantilever, therefore Eq.1 should be applied for the estimation of LS thresholds of end-restrained piers.

(c) LS threshold definitions from the literature

Additional to the analytical estimation and closed-from equations, the platform provides extensive lists with literature recommendations for the definition of LS thresholds for cylindrical, hollow cylindrical, rectangular, and hollow rectangular piers, as well as for cylindrical piers retrofitted with RC and FRP jackets. The pertinent references are classified according to the engineering demand parameter used (drift or displacement ductility), while the qualitative and quantitative definition of LS thresholds is provided along with loading type and specimen characteristics. The qualitative definitions of damage in the literature are matched to the limit state thresholds (LS1~ LS4) described in [3] for all references listed in the database.

3.2 Capacity and LS thresholds for bearings and abutments

The methodology for bridge-specific fragility analysis is component-based; therefore, the seismic capacity of all critical (for the seismic behaviour) components should be estimated in order to calculate both component and system fragility. To this end, LS thresholds for bearings and abutments are provided in the database for different bridge bearing types, namely elastomeric, elastomeric with PTFE, lead rubber, and steel bearings, in terms of shear deformation, as well as for seat type abutments in terms of displacement, expressed as a percentage of the backwall height. The quantitative definition of damage (LS thresholds) along with the qualitative damage description and mapping onto the limit states (LS1~ LS4), defined in [3] are also available online. These values were derived by proceesing information available in previous studies, mainly experimental; all references considered are listed in the database.

3.3 Uncertainty in Seismic capacity and LS definition for critical components

The estimation of uncertainty is a crucial (and often inadequately treated) issue in fragility analysis and requires quantifying several sources of uncertainty in capacity, demand, and limit state definition. In the frame of bridge-specific fragility analysis, the seismic fragility of all critical components should be estimated; therefore, the total uncertainty associated with each component should be defined as

$$\beta_{tot,comp} = \sqrt{\beta_{C,comp}^2 + \beta_{D,comp}^2 + \beta_{LS,comp}^2} \quad (2)$$

Uncertainties in seismic capacity are calculated based on the processing of analysis results for critical components (e.g. pushover analysis results for bridge piers), while uncertainty in limit state definition is quantified based on statistical processing of limit state threshold values proposed in the literature. Uncertainty in seismic demand is quantified for all critical components based on inelastic response-history analysis results and is presented in [6] for representative bridges of several typological classes (according to the classification scheme mentioned in Section 2).

(a) Uncertainties in capacity and LS definition for as-built and retrofitted bridge piers

The uncertainty in seismic capacity (β_c) of as-built and retrofitted bridge piers has been quantified in [3], based on the processing of inelastic pushover analyses results of a representative sample for each type, generated using Latin Hypercube sampling. The β_c values are calculated for all different pier types and the results are available in the platform for each limit state ($\beta_{c\text{-}LS1}$~ $\beta_{c\text{-}LS4}$). The mean value $\beta_{c,mean}$ for all limit states is also provided, ranging from 0.31 to 0.41 for each pier type. Therefore, consideration of a uniform value equal to 0.35 irrespective of pier type and LS, is a pragmatic option.

Statistical analysis of the data regarding the various definitions of LS in the literature provided estimates of the mean, standard deviation, and hence the β_{LS} values for bridge piers of all common types. The β_{LS} values were quantified for all limit states and different pier types, considering the most frequently used engineering demand parameter, namely the pier drift. The average β_{LS} values range from 0.20 to 0.43, depending on the pier type and are provided in the database for different EDPs, namely drift, displacement ductility, rotational ductility and curvature ductility. Therefore consideration of a uniform β_{LS} value equal to 0.30 irrespective of pier type, EDP, and LS, is deemed as a pragmatic optionUncertainties in capacity and LS definition for bearings and abutments.

The online platform provides extensive data from the literature for the limit state threshold values for different bearing types in terms of shear deformation, and for seat-type abutments in terms of top displacement (expressed as a percentage of the backwall height). Statistical analysis of the data collected was performed and led to the estimation of β_{LS} values for all limit (damage) states. The results are presented in Table 2 and Fig.8, indicating that consideration of a constant β_{LS} equal to 0.35 and 0.40, for elastomeric bearings and abutments, respectively, is a pragmatic option. It should be noted that the β_{LS} values presented here differ from those proposed in Stefanidou & Kappos (2017) regarding the sample size used for the statistical analysis; the data included in the database is more extensive, as the sample size is larger, and hence the resulting values are more reliable.

3.4 Online software for bridge-specific fragility analysis

(a) Methodology for analysis using the simplified 3D bridge model

For the analysis of portfolios, bridge-specific fragility curves are calculated accounting for the fragility of all critical components using a 3D simplified elastic model (including the deck, piers, bearings and abutments); response spectrum analysis is performed for the selected spectra and the results are scaled to different levels of earthquake intensity.

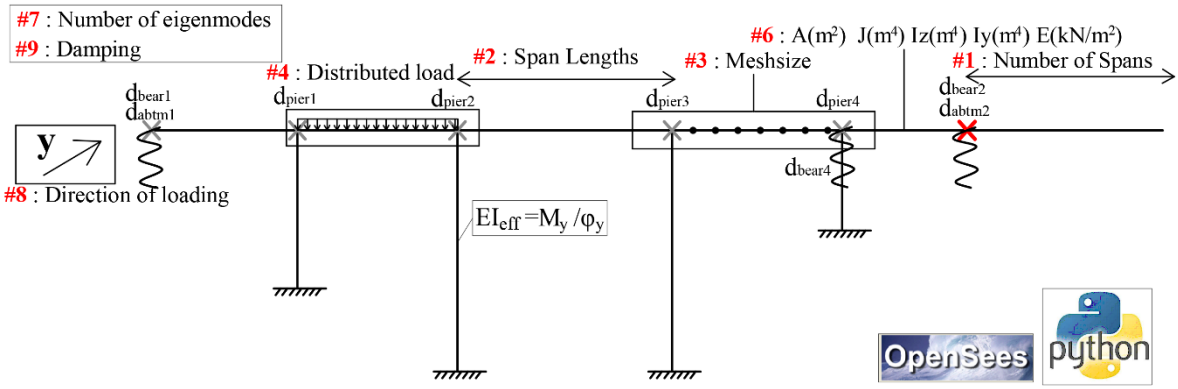

Figure 4. 3D simplified model for bridge-specific fragility analysis

The 3D elastic model set up in the platform is described in Fig. 4. Both deck and piers are modelled as elastic beam-column elements with user-defined geometry and section properties. Reduced stiffness is considered for bridge piers, estimated on the basis of section analysis which provides the secant flexural rigidity at yield $EI_{eff}=M_y/\varphi_y$. Yield moment and curvature (M_y, φ_y) may also be calculated utilizing the closed-form relationships proposed and included in the database, that account for the effect of varying geometric, material and reinforcement properties. Bearings are modelled as springs with stiffness equal to that of all bearings considered at every support, while different boundary conditions are considered at the abutment for the case of open/closed gap (Fig.5-right). The elastic model is clearly less refined than the corresponding inelastic model; however, its reliability for fragility analysis of portfolios is deemed adequate since the bridge deformation shape is accurate and the effect of multiple modes in the results is accounted for (the number of modes considered is a user-defined parameter). The often adopted assumption of a single-degree-of-freedom model for bridges may be adequate for the longitudinal direction (approximately equal displacements at the pier tops for the case of stiff decks), but this is not the case for the transverse direction, where the deformation pattern is strongly related to boundary conditions and the translational and rotational deck [24].

For the estimation of bridge-specific fragility curves in the frame of the component-based methodology, seismic capacity (i.e., LS thresholds for minor to collapse limit state), demand, and uncertainties should be quantified for every critical component. The limit state thresholds for either as-built or retrofitted bridge piers are calculated from the closed-form relationships included in the database, accounting for all component-specific properties. The ratio of the height that pier moment equals zero (equivalent cantilever height) to the total pier height should be defined ($x=L_o/L$) to apply Eq 1 and estimate limit state thresholds for

restrained piers. In order to estimate the equivalent cantilever height, an initial analysis considering a loading pattern proportional to the predominant mode shape in each direction of the bridge (longitudinal, transverse) is applied. For the estimation of demand at component control points, response spectrum analysis is performed, and the results are scaled to varying levels of earthquake intensity (typically, PGA from 0.1 to 1g); the displacements at the control point of every critical component are recorded. Based on these response spectrum analysis results, the evolution of damage (or 'primary vulnerability') curve is plotted and the $A_{g,m}$ and $A_{g,LS}$ values are estimated according to Fig. 5 (left). The total uncertainties for the bridge system are calculated according to §4.3. So long as capacity, demand and uncertainties are estimated, fragility curves are plotted for all limit states (Eq. 3).

$$P_f = \Phi\left(\frac{1}{\sqrt{\beta_{tot}^2}} \cdot \ln\left(\frac{A_{g,m}}{A_{g,LS(i)}}\right)\right) \tag{3}$$

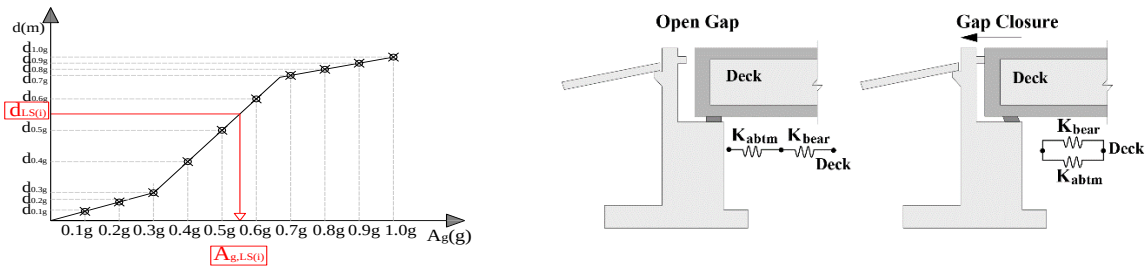

Figure 5. Different boundary conditions before and after gap closure (Right)

(b) *Development of the online software (wizard) for bridge-specific fragility analysis*

An online software (wizard) has been developed and made available online at the platform www.thebridgedatabase.com for the derivation of bridge-specific fragility curves, according to the methodology described in (a) above. The bridge geometry, and the properties of the piers, bearings and abutments are defined on online forms and used as input to the parametrically defined bridge model in OpenSees.py. An ad-hoc software (in Python) has been developed, incorporating the features of the methodology described in the previous sections (model set up, limit state threshold estimation, response spectrum analysis, development of the evolution of damage curve, fragility curve estimation, etc.). The software is applicable to practically every straight bridge (up to 50 spans), with unequal spans, various deck geometries and pier-to-deck connection type. Both single and multi-column piers can be considered, with varying height and pier type (cylindrical, hollow cylindrical, rectangular, hollow rectangular, wall type). It is noted that only seat-type abutments are considered at this stage of development. The online software enables the user to calculate in real time bridge-specific fragility curves for the longitudinal and transverse bridge direction (separately).

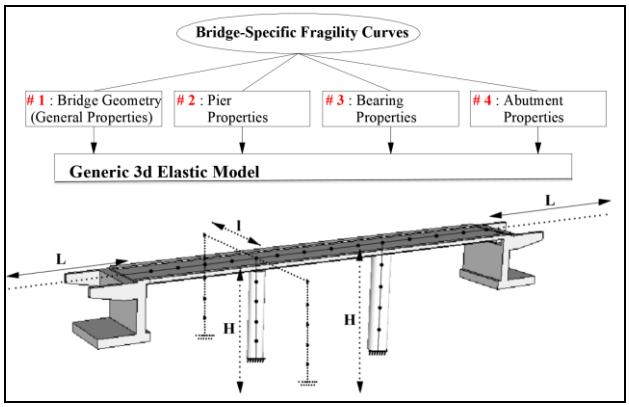

Figure 6. 3D generic bridge model and input parameters

The wizard consists of four online forms (Fig.7) that should be filled in by the user. In the first form, general properties are defined, i.e., number of spans, span lengths, pier heights and deck geometry (at span and support location), along with properties related to seismic input (response spectrum), damping, and number of modes considered. Regarding deck geometry, the properties defined for the support location are used as input for 15% of the span length (measured from piers or abutments) and the span properties in-between. It should be noted that the number of modes considered (related to the activated mass) is a critical parameter and should be defined by the user. The type of pier-to-deck connection is also defined, i.e. monolithic, through bearings, or combination thereof, along with the total uncertainty value for each fragility curve. In the second form, the (single- or multi-column) pier type and properties are defined. For the estimation of the reduced pier stiffness, the effective flexural rigidity may be calculated based on the closed-form relationships proposed for M_y and φ_y or user-defined values may be provided. Both as-built and retrofitted with RC or FRP jacket piers can be considered; both are defined using the same form. The following two forms refer to bearing and abutment properties, namely stiffness values (in either direction), bearing type and thickness, abutment stiffness (as proposed in Caltrans Guidelines, or user-defined), backwall height, embankment soil type and gap size. It is recalled that analyses considering two different boundary conditions are performed (Fig. 5, right) and the relevant results, before and after gap closure, are considered for the fragility curve estimation.

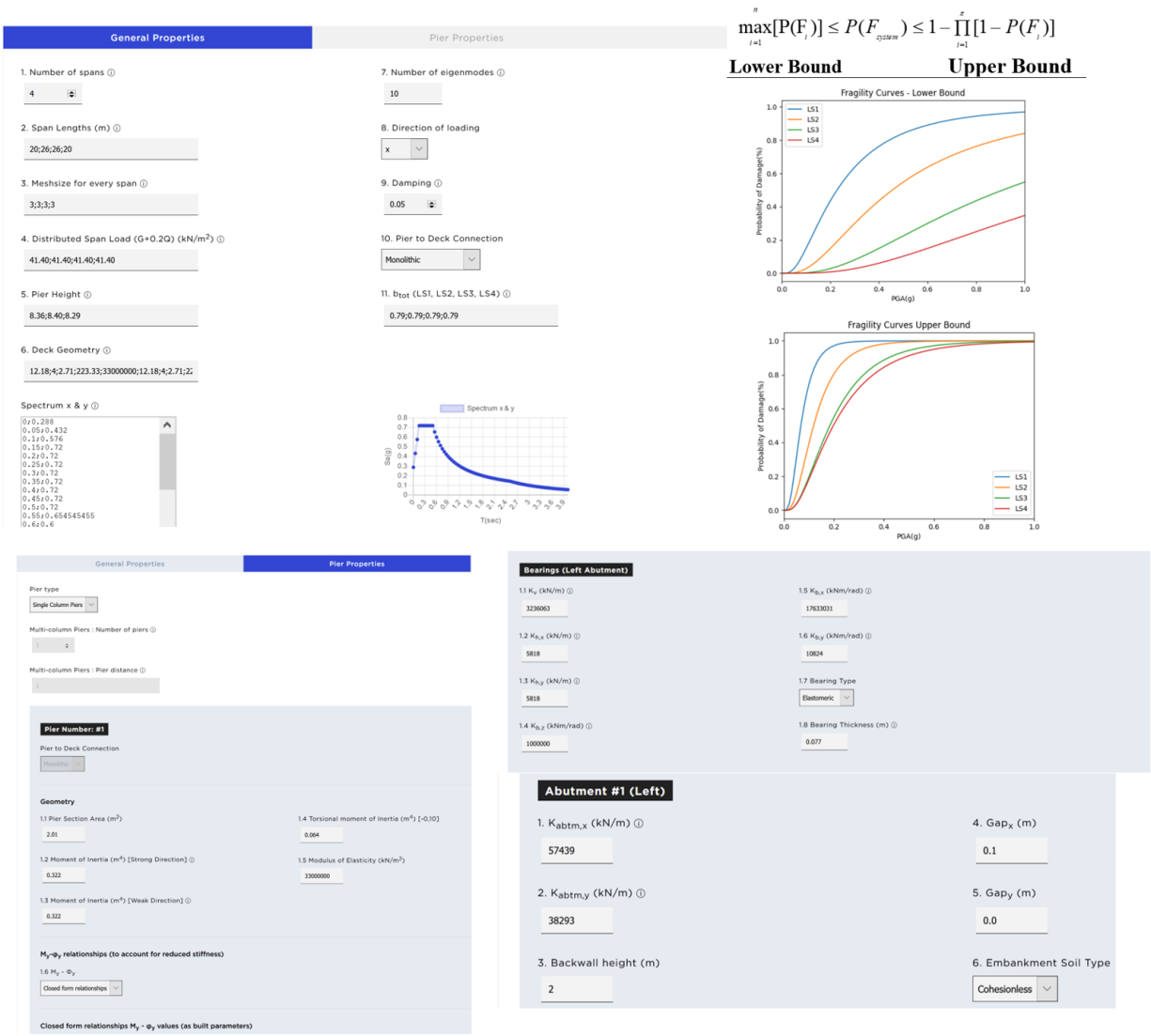

Figure 7. The online software for bridge-specific fragility analysis (online forms and fragility curves)

Based on the parameters defined in the online forms, the 3D model is set up, and response spectrum analysis for various PGA levels is performed for the derivation of bridge-specific fragility curves in the longitudinal and transverse direction (spectrum applied separately in each direction). Series connection between components is assumed for the derivation of bridge fragility curves, according to Eq. 4 (upper and lower bound, [9]):

$$\max_{i=1}^{n}[\mathrm{P}(\mathrm{F}_i)] \le P(F_{system}) \le 1-\prod_{i=1}^{\pi}[1-P(F_i)] \quad (4)$$

The lower bound corresponds to completely correlated components, while the upper bound assumes no correlation between components. Bridge fragility lies within these two bounds and the exact value is dependent on the correlation of the component response. Both upper and lower bound bridge-specific fragility curves for all limit states are calculated by the online software and are displayed on the platform (Fig. 7).

4. Conclusions

- A 'two-track' online, open access platform is developed, including ad-hoc software for online bridge-specific fragility curve derivation, as well as the option to select an appropriate set of generic fragility curves from a database including a variety of bridge classes. The platform is fully interactive, allowing input from users/contributors with a view to enriching the database and receiving feedback.
- Detailed approach for the estimation of component-specific limit state thresholds is provided, including three alternatives, namely extensive lists with thresholds for all critical components (from experimental studies) as well as closed-form relationships and a parametrically defined pier model for capacity assessment and estimation of limit state thresholds for as-built and retrofitted piers.
- The software for bridge-specific fragility assessment performs analysis of a fully parameterised model bridge model developed in OpenSees.py, set up according to user-defined (through user-friendly online forms) geometry, component parameters and seismic excitation input. The probabilistic framework for fragility analysis and all relevant features were also included in the software, enabling the online, real-time estimation of bridge-specific fragility curves for each direction of the bridge.
- The software developed is open access, and it can be claimed that it makes feasible (for the first time) the derivation of bridge-specific fragility curves for entire portfolios; hence, it can be used (free of charge) by professionals and researchers for decision-making or in the frame of bridge/roadway network resilience analysis.

5. Acknowledgements

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6. References

[1] DesRoches, R., Padgett, J., Ramanathan, K., & Dukes, J. (2012). Feasibility Studies for Improving Caltrans Bridge Fragility Relationships (Vol. 0003, Issue 2).

[2] Tsionis, G., & Fardis, M. N. (2012). Seismic Fragility of Concrete Bridges with Deck Monolithically Connected to the Piers or Supported on Elastomeric Bearings. 15th World Conference of Earthquake Engineering.

[3] Stefanidou, Sotiria P, & Kappos, A. J. (2017). Methodology for the development of bridge-specific fragility curves. Earthquake Engineering & Structural Dynamics, 46, 73–93.

[4] Hazus-Multi-hazard Loss Estimation Methodology. (2015).

[5] Berry, M., & Eberhard, M. (2003). Performance Models for Flexural Damage in Reinforced Concrete Columns (Issue August).

[6] Stefanidou, S.P., & Kappos, A. J. (2019). Bridge Specific Fragility Analysis: When is it really necessary? Bulletin of Earthquake Engineering, 17(4), 2245–2280.

[7] Bisadi, V., Head, M., & Gardoni, P. (2011). Seismic Fragility Estimates and Optimization of Retrofitting Strategies for Reinforced Concrete Bridges: Case Study of the Fabela Bridge in Toluca, Mexico. Structures Congress 2011, ASCE, 13–22.

[8] Mohammadi, K., & Lahijanian, H. (2010). Fragility Curves of Bridges Before and after Retrofitting by FRP. 5th Civil Engineering Conference in the Asian Region and Australasian Structural Engineering Conference.

[9] Zhang, J., & Huo, Y. (2009). Evaluating effectiveness and optimum design of isolation devices for highway bridges using the fragility function method. Engineering Structures, 31(8), 1648–1660.

[10] Stefanidou, Sotiria P., & Kappos, A. J. (2021). Fragility-informed selection of bridge retrofit scheme based on performance criteria, Engineering Structures, 234, 111976.

[11] Yepes-Estrada, C., Silva, V., Rossetto, T., D'Ayala, D., Ioannou, I., Meslem, A., & Crowley, H. (2016). The global earthquake model physical vulnerability database. Earthquake Spectra, 32(4), 2567–2585.

[12] Silva, V., Crowley, H., & Colombi, M. (2014). Fragility function manager tool. In SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk (Vol. 27, Issue September).

[13] Crowley, H., Colombi, M., Silva, V., Monteiro, R., Ozcebe, S., Fardis, M., Tsionis, G., & Askouni, P. (2011). SYNER-G : Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain.

[14] D'Ayala, D., Gehl, P., & et al. (2015). INFRARISK: Novel Indicators for identifying critical Infrastructure at Risk from Natural Hazards - Deliverable D3.2 - Fragility Functions Matrix.

[15] Van Rossum, G., & Drake, F. L. (2009). Python 3 Reference Manual. Scotts Valley, CA: CreateSpace.

[16] Zhu, M., McKenna, F., & Scott, M. H. (2018). OpenSeesPy: Python library for the OpenSees finite element framework. *SoftwareX*, *7*, 6–11.

[17] Moschonas, I. F., Kappos, A. J., Panetsos, P., Papadopoulos, V., Makarios, T., & Thanopoulos, P. (2008). Seismic fragility curves for greek bridges: methodology and case studies. Bulletin of Earthquake Engineering, 7(2), 439–468.

[18] Mander, J. B., Priestley, M. J. N., & Park, R. (1988). Theoretical Stress-Strain Model for Confined Concrete. Journal Of Structural Engineering, 114(8), 1804–1826.

[19] EN1992-1-1, Eurocode 2: design of concrete structures – Part 1-1: General rules and rules for buildings, European Committee for Standardization, 2004.

[20] Spoelstra, B. M. R., & Monti, G. (1999). FRP-Confined Concrete Model. Journal of Composites for Construction, 3(3), 143–150.

[21] Mergos, P. E., & Kappos, A. J. (2009). Seismic damage analysis including inelastic shear–flexure interaction. Bulletin of Earthquake Engineering, 8(1), 27–46.

[22] Kowalsky, M. J., & Priestley, M. J. N. (2001). Improved Analytical Model for Shear Strength of Circular Reinforced Concrete Columns in Seismic Regions. 97, 388–396.

[23] KANEPE. Greek Retrofitting Code. Athens, Greece: Greek Ministry for Environmental Planning and Public Works. 2017.

[24] Kappos, A.J., Gkatzogias, K.I., and Gidaris, I. "Extension of direct displacement-based design methodology for bridges to account for higher mode effects", Earthquake Engineering & Structural Dynamics, V. 42, no.4, Apr. 2013, 581–602.

