OpenSeesPy-based Web Application for Pushover Curve Computation of RC Bridge Piers Subject to Arbitrarily Non-uniform Corrosion Patterns

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Abstract. Existing reinforced concrete (RC) bridge piers are often subject to complex spatially non-uniform steel corrosion patterns typically due to water percolation and exposition to environmental agents. This produces degradation of strength and ductility of the pier, which may significantly influence the seismic performances of bridges. The computation of pushover curves of corroded RC piers can be carried out by fiber-beam-column elements combined with suitable degradation laws for the uniaxial materials. For this purpose, a multi-level fiber-based modeling procedure is proposed based on a partition of the pier into *zones* characterized by different cross-sections with fiber discretizations reproducing the sectional deterioration pattern.
A web application based on OpenSeesPy is defined to implement this procedure. This includes an interface developed by React JS and Boostrap V5 and an APIs layer based on the Flask framework. Through the interface, users can insert the parameters needed for the structural response simulation, which is, then, performed by employing the numerical procedure developed in Python. At the end of the computation, users can visualize and download the results or vary the input parameters to perform new simulations. The web application runs in a Docker container, making it easy to deploy on cloud platforms or on-premises solutions. Numerical simulations of real specimens affected by material deterioration are performed.

Keywords: Bridge Piers, Material Deterioration, Pushover Analysis, Web Services, User Interfaces, Web Application.

1 Introduction

Many of the existing reinforced concrete (RC) bridges show important degradation phenomena due to their old construction period often combined with bad maintenance [1]. Indeed, over time, steel corrosion caused by water percolation produces concrete cracking and spalling and affects the strength and ductility of the bridge to both static and dynamic loads.

This issue is particularly relevant for piers, where rebars corrosion significantly reduces the element capacity to horizontal actions [2]. Therefore, along with efficient solutions for monitoring of existing structures [3], particular attention must be paid to the development of reliable approaches for the structural analysis of RC elements subject to degradation effects [4].
Beam finite element (FE) models with fiber discretization of the cross-sections are frequently adopted to this purpose [5,6] since they allow the accurate evaluation of the bridge response under seismic actions with reasonable computational effort [7]. Moreover, the use of fiber beam model allows to include the degradation effects simply by modifying the constitutive response of the fibers. In other words, the structural behavior of materials altered by the corrosion is described by means of proper calibrations of the constitutive model parameters with respect to the case of plain material [8].
However, even with this approach, the structural analysis of RC piers often presents important difficulties, as material deterioration can evolve according to significantly non-uniform patterns, depending on the specific environmental exposure [9]. Hence, detailed modeling of the corrosion distribution is often required.
In this work, the multi-level modeling approach proposed in [8] is considered to compute the pushover force-displacement response curve of RC piers subject to non-uniform deterioration. The approach, implemented in OpenSeesPy [10], is based on the partitioning of the pier into *pieces*. These are represented by distinct beam-column FEs, each considering a proper definition of the fiber-based cross-section. This is further dived into *zones* and *regions*, to accurately represent the geometric variation of the corrosion.
A web application is developed and presented in this work to easily apply the approach to real bridge piers with complex deterioration scenarios. The web application guides the user in modeling bridge piers following a bottom-up approach. The user starts by defining essential elements, such as the concrete, to then use them as a building block to progressively represent more complex elements (e.g., *zones* and cross-sections) and finally model the whole pier. Each time a new element is created, the web application verifies that all the required parameters to perform the computation are included and that the inserted values are valid. Moreover, for more complex elements, it is possible to visualize them, allowing the user to visually inspects their correctness.
This approach allows for easy re-use of already generated data, avoiding unexpected output and consequentially speeding up the whole modeling process and analysis.

2 Material degradation modeling

In numerical simulations, the mechanical behavior of the materials is described with properly defined constitutive models. These usually depend on specific parameters that govern the evolutionary laws and, thus, drive the response of the entire structure. As the proposed modeling procedure is based on the adoption of beam FEs with fiber cross-section discretization, the assumption of the constitutive behavior and mechanical parameters pertains to the definition of the element fibers, i.e., each fiber composing the beam assumes a specific constitutive law that describes the nonlinear evolution of either concrete or steel behavior.

However, under the effects of corrosion, the constitutive response differs from that of the plain material. Hence, the numerical model parameters need to be properly set to correctly account for the degradation-induced loss of strength and ductility [11]. To this end, degradation laws are used to convert the parameters governing the response of the plain materials into those representing the behavior of the deteriorated ones.
The general framework adopted in this work considers, for each material parameter X, an empirical relationship, f, that relates the value, X_P, assumed for the plain state and that, X_D, assumed for the deteriorated state:

$$X_D = f\,(X_P;\, \Omega) \tag{1}$$

Quantity Ω represents a Damage Intensity Measure (DIM) that is properly chosen as an independent variable ruling the degradation law. The technical literature provides several empirical proposals for such expressions, usually based on statistical analyses, and differently calibrated for each type of material. Once these laws are selected, parameters for plain materials can be converted into those of deteriorated materials and assigned to the fibers.
The degradation laws for the unconfined concrete compressive peak strength, f_{cp}, and for steel yielding and ultimate stress and ultimate strain, f_{sy}, f_{su}, and ε_{su}, are the main expressions considered in this work. Their definition follows the models proposed by Coronelli et al. [12], for concrete, and Imperatore et al. [13], for steel. The other relevant model parameters are converted based on these quantities.

3 Multilevel modeling approach for the pier structural response

The main goal of the proposed numerical modeling procedure is the evaluation of the nonlinear pushover response of the single RC bridge pier under seismic equivalent horizontal loads. To this end, the pier is modeled in the OpenSeesPy FE analysis framework [10] through nonlinear force-based beam-column elements, i.e. the `forceBeamColumn` model, endowed with a `Fiber` cross-section description [5]. Although many of the available `uniaxialMaterial` formulations can be generally adopted, either the `Steel02` (Giuffrè-Menegotto-Pinto [14]) or `ReinforcingSteel` [15,16] model is used in this work to reproduce the behavior of the steel fibers, whereas either the `Concrete02` (Kent-Scott-Park [17,18]) or `Concrete07` (Chang-Mander [15]) formulation is used for concrete.
To account for the non-uniform distribution of the corrosion effects over the pier volume, a multi-level approach is adopted, so that any deterioration pattern is correctly described. This approach divides the pier into several portions, namely *pieces*, *zones*, and *regions*, as depicted in Fig. 1. A *piece* is a whole vertical segment of the pier where the transverse cross-sections have the same geometric and mechanical characteristics, i.e. same shape, dimensions, steel reinforcements and, most importantly, same deterioration distribution. Hence, each *piece* of the pier is modeled with a single beam FE having a uniform cross-section. This is modeled according to the *zones*. Each *zone* is an area of the structure characterized by the same level of overall degradation and contains different *regions*. A *region* is a portion of the cross-section with uniform material behavior and deterioration. Hence, each cross-section is composed of several *regions*,

modeled with independent fiber `patches`, for concrete portions, or `layers`, for steel. *Regions* are, thus, defined to describe various portions of the concrete cover, confined concrete core, and longitudinal steel reinforcements. The constitutive law associated with each *region* is assigned according to the deterioration level of the belonging *zone*, as detailed in the following, and employing the chosen degradation laws (Sec. 2).

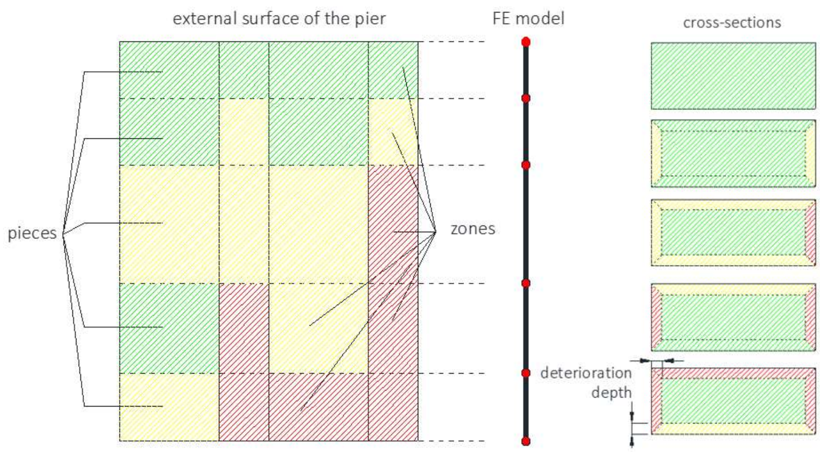


Fig. 1. Example of non-uniform corrosion pattern and corresponding numerical discretization model for a rectangular pier.

Table 1. Region Deterioration Index employed for each level of *zone* deterioration.

	RDI		
ZDI	Unconfined concrete [w_{cr}]	Longitudinal steel [ψ_L]	Transverse steel (confined concrete) [ψ_T]
0	**0** [0 mm]	**0** [0.00]	**0** [0.00]
1	**1** [1 mm]	**1** [0.05]	**1** [0.05]
2	**2** [3 mm]	**2** [0.15]	**2** [0.15]
3	**3** [5 mm]	**3** [0.30]	**3** [0.30]
4	**3** [5 mm]	**4** [0.60]	**3** [0.60]

From a numerical modeling point of view, the definition of the deterioration level and, thus, of the constitutive response of the single *region* is independent from that of the rest of the pier. However, in real structures, pier degradation is usually caused by transverse and longitudinal steel corrosion, which induces the cracking of concrete [8,12]. Hence, the deterioration levels of adjacent *regions* are related to each other and must be consistently assigned. To this end, the proposed modeling procedure introduces, for each *zone*, a numerical index, namely the Zone Deterioration Index (ZDI), and a Zone Deterioration Depth (ZDP), indicating the overall level and depth from the pier external

surface, respectively, of the deterioration affecting the zone. These can be achieved either by targeted survey, involving visual inspections and in-situ measurements or by indirect evaluation. Thus, from the ZDI and ZDP, a related index is derived for each composing *region*, namely the Region Deterioration Index (RDI). An example of a possible mapping from the ZDI to the RDIs is reported in Table 1. Of course, any other definition of the ZDIs can be implemented to model different types of deterioration.
Once the RDIs are given, the corresponding DIMs, i.e., the Ω, to be used in the deterioration laws are defined and, thus, the constitutive laws of all *regions* are defined and assigned to the fibers. In this work, the cracking width, w_{cr}, is used as DIM for the concrete, whereas mass losses, ψ_L and ψ_T, are used as DIM for the longitudinal and transverse reinforcements, respectively. The values associated with each deterioration level are indicated in brackets in Table 1.

4 Web application

The proposed modeling procedure is implemented in a web application that automatically performs all the required tasks. The web application consists of two components: the front end and the back end.
The front end is the graphical interface of the web application, and it is developed with the React Framework and the Boostrap [19], HTML/CSS library. Thanks to the responsiveness guaranteed by Boostrap, the web interface gracefully scales to different screen sizes, resolutions (e.g., HD, FHD, 4K), and aspect ratios (e.g., 4:3, 16:9). The back end is the core element of the web application. Indeed, it is the component that performs the analysis, processing, and modeling of the data through the OpeenSeesPy framework. Moreover, the backend is made of a communication and an authentication layer. The communication layer developed with the Flask framework exposes web services to retrieve and provide data to the front end. Web services are designed to follow the RestFul principles [20] and use the JSON data format to encode the exchanged data. The authentication layer provides the possibility to sign up using the personal email for the web application and ensures that only authorized users can interact with it. Since the authentication layers have been developed using the Firebase API [21], it is easy to extend the possibility to sign up for the web application also using social network accounts such as Facebook or Google accounts.
The whole web application runs in a Docker [22] container, making it easy to deploy on cloud platforms or on-premises solutions. The web application is designed to guide the users in modeling the pier following a bottom-up approach. The user can first define the basic elements and step by step combining these elements into more complex ones, ending with the modeling of the entire pier. In the following, the web application and its flow of navigation are described. After the authentication phase, the user lands on the actual web application and can start interacting with it. Each web application page is characterized by two parts: on the left, there is a side navigation menu that contains the links to navigate through the different pages of the application, whereas at the center of the screen, there is the main content of the actual page.

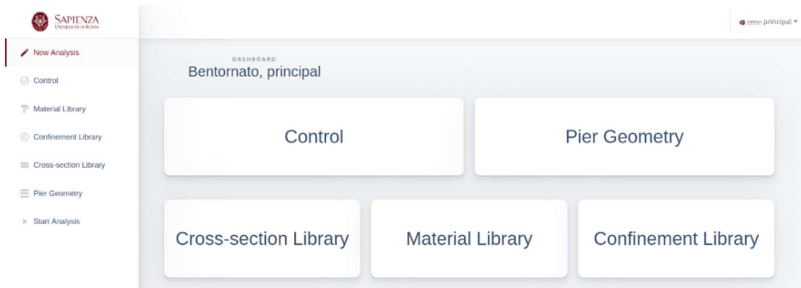
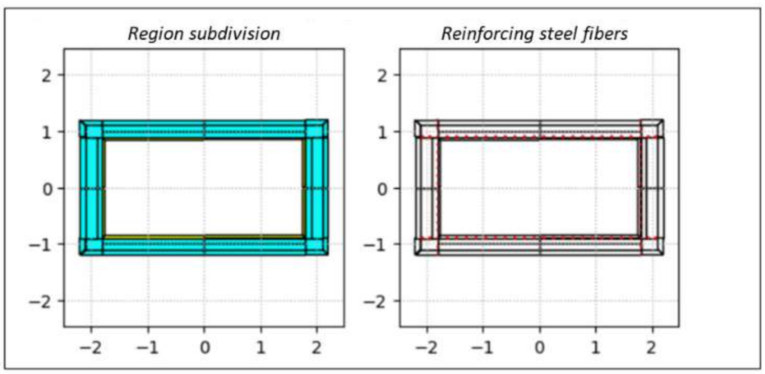
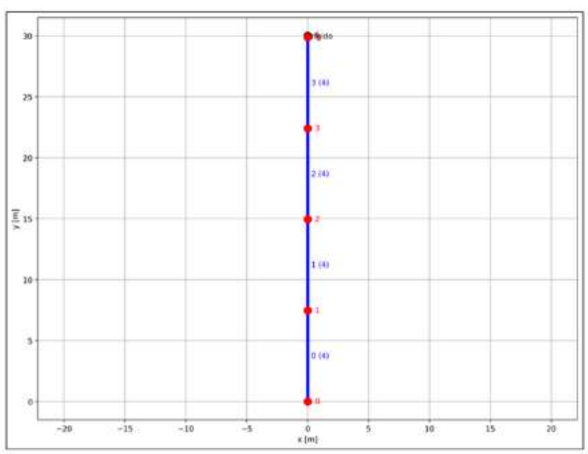


Fig. 2. The "New analysis" page of the web application.



(a)



(b)

Fig. 3. Example of rectangular hollow pier (a) cross-section and (b) FE mesh generated by the web application through the preview functionalities.

The navigation of the web application begins from the “New Analysis” page. This page has twofold functionality. The first is to clear the status of the web application if the user has previously performed analysis, and the second is the possibility to upload a file in Excel format containing the data needed for subsequent analysis. Once the file is uploaded, the web application firstly clears its status, then parses the file and automatically fills the parameters with the provided data for the new analysis. At this point, the user can navigate through the different pages of the web application to insert, modify, or start the analysis (Fig. 2). Of course, if the user does not have a pre-compiled file, he can skip this page and go directly to the next ones that are the "Material Library" and the "Confinement Library" pages.
In the "Material Library", it is possible to define one or more uniaxial material models (`Concrete02` or `Concrete07` and `ReinforcingSteel` or `Steel02`), as described in Sect. 3. Instead, in the "Confinement Library" page, the user can describe the features (e.g.) of different types of confinement. The elements created in these two pages can be used as building blocks to model different cross-sections into the "Cross-section Library" page. Here, the user can define the cross-section's various *zones* and indicate the corresponding deterioration level. An interesting feature of this page is that the user can graphically inspect the cross-section while modeling it using the preview functionality (Fig. 3a).

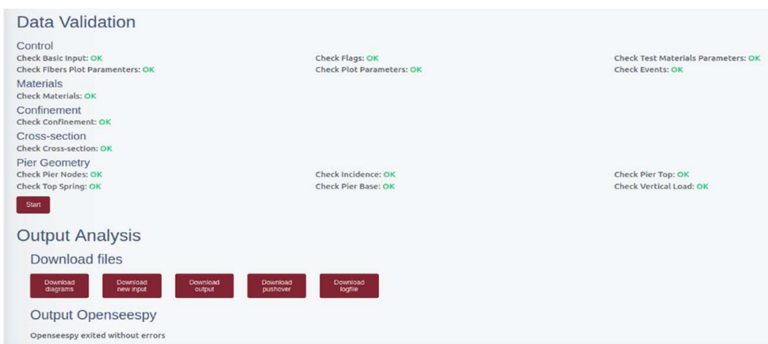


Fig. 4: Interface showing the results of the analysis

After modeling all the needed cross-sections, the user can move into the "Pier Geometry" page of the web application. Here, he can model the pier using the previously defined cross-sections. To this end, the web application presents a form to specify each *piece*'s height and associate it with one of the previously defined cross-sections. Also, in this case, the web application offers the opportunity to visualize the preview, i.e., the resulting FE model of the pier (Fig. 3b). Once finished modeling the pier, the web application performs the last check verifying that all the needed parameters are present, and the values are valid. If the check fails, the interface shows the user the parameters with invalid values or the missing ones. Otherwise, if the check passes successfully, it is possible to start the analysis.
When the analysis starts, the developed web application converts the data into a OpenSeesPy model of the pier, according to the procedure defined in Sec. 3. Thus, it performs a step-by-step static nonlinear pushover analysis of the pier under constant

vertical load and increasing horizontal force applied at the top. The analysis is performed with a `DisplacementControl integrator` and the response of all fibers is constantly monitored to detect and record specific events occurring at various steps, such as first longitudinal steel yielding and failure or concrete cracking and crushing. The analysis ends either when crushing of concrete confined core occurs or failure of the steel bar at any of the pier cross-section or when pier horizontal bearing capacity drop exceeds the 15% of the peak strength.
Fig. 4 shows the web application interface at the end of the analysis. From this page, other than visualizing the output of the analysis, it is possible to download them. It is possible to download the pushover response curve of the pier in terms of horizontal base reaction vs top displacement (Fig. 5). This also shows the loading steps where specific events occurred during the analysis with the corresponding markers, e.g., steel yielding and failure or concrete cracking and crushing. A second diagram placed side by side with the pushover curve shows the positions, along the pier, where these events occurred.

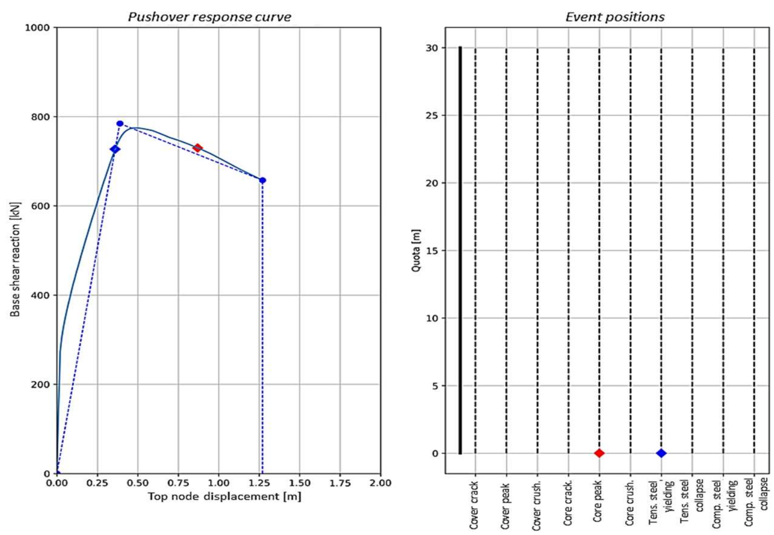


Fig. 5. Example of the generated pushover response curve with the indication of the relevant occurred events.

In addition, graphs reporting the bending curvature and moment distribution along the pier and their evolution during the analysis can be downloaded (Fig. 6).
All the data used to generate the graphs are stored in an Excel file, where many other numerical outputs of the analysis are included. This can be downloaded from the web interface together with the error log of OpeenSeesPy, if any, and the updated version of the input file containing the analysis parameters. This last file could be extremely useful if the user desires to save the data for further analysis or repeat the analysis with slight variations of the parameters. Of course, the generated file can be used as input into the “New analysis” page.

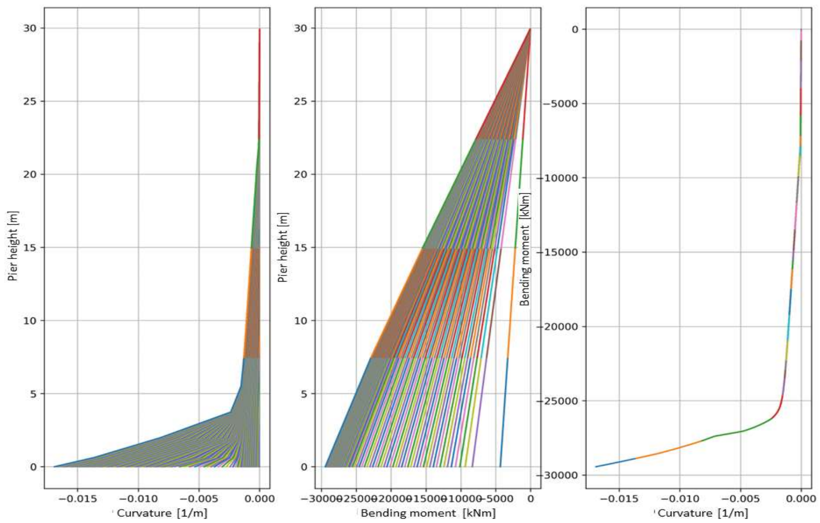


Fig. 6. Example of the generated bending curvature and moment diagrams.

5 Conclusions

This work presented a web application which allows the use of the multi-level numerical procedure proposed in [8]. This procedure leverages an OpenSeesPy fiber beam model to compute the pushover response curve of RC bridge piers subject to non-uniform deterioration phenomena.

The web application interfaces were developed with modern web frameworks (React, Boostrap) to guarantee the responsiveness of the interfaces such that they can be coherently visualized also on mobile devices. Instead, the backend uses the Flask framework for handling the web services and OpenSeesPy to implement the described procedures. The web application was designed to easily model real bridge piers with complex deterioration scenarios and improve the efficiency of professionals by re-using already defined elements and importing/exporting the parameter of the computations. The developed web interface can be easily used by professionals for the vulnerability assessment of existing bridges and viaducts that require the evaluation of the pier response under horizontal loads.

All relevant outputs of the analysis are available for the user in both graphical and Excel data format. Hence, easy integration of the results provided by the web interface in the user's technical documentation is possible.

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