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Influence of spatially heterogeneous deterioration patterns on strength and ductility of corroded reinforced concrete bridge piers

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Abstract

This work reports on some preliminary results obtained within the framework of a wide research project aimed to study the influence of the corrosion of in Reinforced Concrete (RC) piers on the overall seismic performances of bridges. In this context, after the statistical evaluation of a large database of real structures, a consistent set of bridges and piers has been selected as a sample representative of typical bridge profiles, pier heights and cross-sections as well as of material properties. In the first part of the project, pushover analyses of isolated piers with different corrosion patterns and intensity are carried out to evaluate the residual strength and ductility of corroded piers. In the second part, nonlinear static and dynamic seismic analyses of bridges with corroded piers are carried out to evaluate the influence of the deterioration on the overall seismic performance. Due to specific environmental conditions exposure or to water percolation from the superstructures, it is often the case that corrosion is non-uniformly distributed over piers producing non-homogeneous spatial deterioration patterns. The nonlinear modeling of this type of situations represents specific challenges related to the description of the deterioration patterns and the calibration of material properties. To this end, a multi-level modeling approach based on fiber-based finite elements has been developed and implemented in a specific OpenSeesPy software that allows users to accurately model RC piers subject to arbitrary corrosion patterns, up to their ultimate limit states. In this work, a specific case study of a typical RC rectangular hollow bridge extracted from the mentioned above database subject to different corrosion intensity and patterns is studied. In particular, the influence of the corrosion-induced deterioration on residual

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strength and ductility are studied. Results show that depending on the intensity and on the patterns significant variations of both strength and ductility can be observed with respect to the undamaged conditions.

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Keywords: Bridge piers, Reinforced concrete, Corrosion, Non-homogeneus Deterioration, Non-linear analysis.

1. Introduction

The evaluation of the influence of the corrosion-induced deterioration of Reinforced Concrete (RC) piers on the seismic performances of bridges located in earthquake-prone regions is an important topic for the assessment of the residual life of ageing structures.

A research project focused on the study of the impact of rebars corrosion on the seismic performances of bridges is currently ongoing and provides motivation for the present work. In this context, an important aspect is related to the fact that strength and ductility of RC bridge piers subject to horizontal actions can be significantly influenced by corrosion of reinforcement bars. To study this phenomenon non-linear numerical analyses of deteriorated RC structures can be carried out (Andisheh at al., 2016). Most of the available studies on corroded RC structures consider uniform distribution of corrosion on the element, or even on the entire structure (Li et al., 2018). However, in real bridge piers, due to water percolation from superstructures or specific exposures to atmospheric agents, strongly non-uniform corrosion patters are often observed. In the few studies available, the non-uniformity of corrosion is typically considered only in elevation, while no variation is considered within the section. The modeling of this type of situations is much more challenging than modeling the undamaged pier since constitutive laws and material properties become corrosion-dependent and need to be specified by proper constitutive laws over potentially complex geometries reflecting non-uniform corrosion patterns both in elevation and within cross-sections (Bernardini et al. 2022a).

2. Seismic performances of bridges with corroded RC piers

Seismic performances of bridges are essentially determined by the behaviour of the structural elements capable to transfer horizontal actions like piers, bearings and structural connections or restraints. Ageing structures are unavoidably subject to degradation of the performances of such elements and, therefore, the investigation of the possible consequences of structural deterioration on the seismic performances of existing bridges is a basic issue with significant scientific interest and technological impact (Gino et al. 2021, Castaldo et al. 2022).

A comprehensive study of this topic requires to progress in four main directions: a) development of nonlinear modelling and analysis tools for the capacity of deteriorated structural elements, b) extensive investigation of the correlation between deterioration of structural elements and seismic performances of bridges and piers, c) evaluation of the effectiveness of currently available intervention techniques, d) evaluation of the opportunity of defining a different value of the seismic action for the two main directions of the bridge, due to the orientation of the bridge relative to the soil (bridge located on the middle side of the hills, which is a typical layout of the Italian bridges).

The above mentioned aspects have been implemented as the main research lines of a, currently ongoing, project promoted by the Italian Ministry of Infrastructures and Sustainable Mobility with the participation of two universities (Rome La Sapienza and Basilicata) and then main concessionary company for the management of Italian highways (Autostrade per l'Italia). Within this framework, the preliminary step of the project consisted in the statistical evaluation of a large database of real structures including 5760 different RC piers. The analysis was aimed to define a consistent set of bridges and piers representative of typical bridge profiles, pier heights and cross-sections of Italian highways. After the definition of a sample of piers and bridges, real data about visual inspections have been reviewed and scrutinized in order to identify typical deterioration patterns and intensities in such a way to define a large set of deterioration scenarios deemed to be representative of the actal conservation state and its possible temporal evolution.

Research line a) of the project is focused on the development of suitable tools to model RC piers subject to non-uniform corrosion and the execution of pushover analyses of a large set of isolated piers with different corrosion patterns and intensity. Capacity curves, hence residual strength and ductility, of corroded piers under a variety of geometrical, mechanical features and corrosion scenarios are then computed. Research line b) then takes advantage of the information gathered from the analysis of deteriorated piers to carry out a large set of nonlinear static and dynamic seismic analyses of bridges with different configurations in terms of pier configuration and deterioration distribution. Such analyses will finally lead to the main goal of the project, namely the investigation of the relation between the various aspects of piers deterioration with the corresponding variations of the seismic performances of bridges.

3. Multi-level modeling approach for the modeling of non-uniform corrosion patterns

Within the above mentioned research line a), a specific modeling approach capable to predict the response of RC piers subject to arbitrary corrosion patterns by means of non-linear fiber-based beam-column elements has been proposed (Bernardini et al., 2022a, 2022c) and implemented within an OpenSeesPy framework (Bernardini et al., 2022b). As anticipated in the Introduction, corrosion-induced degradation is often strongly non-uniform. For example, often, two sides of the pier can be characterized by significantly different deterioration states so that, even in presence of constant geometry and reinforcement layout, material properties are different both at the cross-sectional level and in elevation. To model this type of situations, different material properties have to be defined according to the intensity of degradation for each fiber of each cross-section. The implementation of such a complex parameter management requires the development of specific modeling techniques.

The multi-level modeling approach to spatially non-uniform corrosion proposed in Bernardini et al. (2022a, 2022c) is based on the partitioning of structural elements into: *pieces, zones, regions* and *fibers*. From a detailed deterioration survey of the bridge pier (involving e.g. visual, photographic, GPR, laser scanner, material sampling or other techniques) it is possible to discretize the structure in pieces and zones (Figure 1). In this context, a *piece* of the structure is a volume with uniform properties, in terms of geometry, reinforcement layout and corrosion level, whereas a *zone* is a set of *region*s composed of several *fibers* of the same material (steel, confined or unconfined concrete) characterized by a uniform level of degradation for each one of the materials. On the basis of the available information, zones are then grouped into External, Superficial and Internal Zones (EZ, SZ, IZ) according to their position with respect to the propagation of corrosion attack and suitable rules are then defined to specify material properties for all fibers in the model.

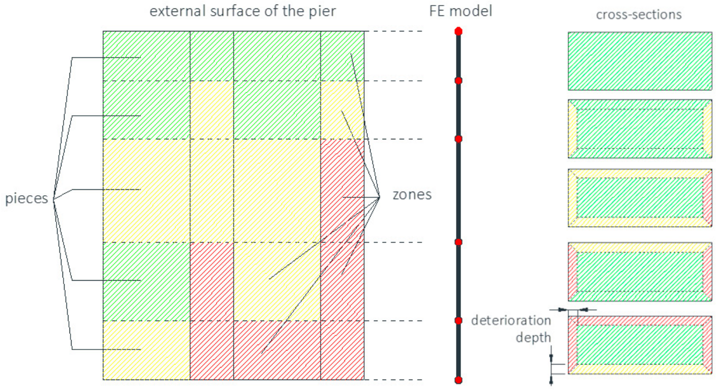

Fig. 1. Example of non-uniform corrosion modeling for a rectangular section of a pile (Bernardini et al. (2021)).

Deterioration intensity is then specified by assigning to each zone a Global Deterioration Index (GDI) defined as a set of material-specific Local Deterioration Indices (LDI) to be used to determine material properties of the fibers according to suitable degradation laws. In general, different GDI scales and different LDI can be used. In this work, a GDI scale based on 5 levels has been chosen to characterize possible deterioration intensities (Table 1). Each GDI is characterized by a specific value of 3 LDI: cracking width (w_{cr}) for unconfined concrete and steel mass loss for both longitudinal bars (ψ_L) and transverse reinforcement (ψ_T) (Table 1).

Table 1. Local Deterioration Index employed for each level of damage.

GDI	w_{cr} (mm)	ψ_L	ψ_T
I0	0	0.00	0.00
I1	1	0.05	0.05
I2	2	0.15	0.15
I3	3	0.20	0.20
I4	5	0.30	0.30

In the literature, several degradation laws are available for unconfined concrete, steel and confined concrete. In this work the relations proposed by Coronelli and Gambarova (2004) and by Vu et al. (2017) have been used, respectively, for unconfined and confined concrete. Concerning reinforcing steel, the degradation laws proposed by Imperatore et al. (2017) have been chosen to determine yield stress and ultimate stress and strain of deteriorated steel as a function of steel mass loss. Another important aspect of the modeling of non-uniform corrosion of RC bridge piers is related to the effects of corrosion on confined concrete. The latter is, inherently, a non-local phenomenon since the corrosion of a part of a stirrup influences the confinement of the whole concrete core. In the proposed multi-level modeling approach the confined concrete regions present in each cross-section are first grouped in a list Uniform Confinement Zones (UCZ) defined according to the transverse reinforcement layout and then material properties are assigned according to their position within the cross-section.

4. Evaluation of the influence of deterioration on a hollow rectangular pier

As discussed in Section 2, a set of bridges and piers representative of real structures in the italian highways has been defined on the basis of the statistical evaluation of a large database. In the following, first results about residual strength and ductility of a specific pier extracted from the large sample are presented.

Specifically, a cantilever bridge pier characterized by hollow rectangular cross-section and a total height of 15.0 m (Figure 2a) is considered with the aim to evaluate its strength and ductility degradation under different deterioration scenarios. Specifically, geometrical reinforcement ratio of the pier is equal to 1.0% whereas material properties of undamaged materials are assumed as follows: 43 MPa for unconfined concrete strength, 517.5 MPa and 621 MPa for yield and ultimate steel stresses. The effect of confinement is described according to Mander (1988). Nonlinear analyses are performed by means of the, specifically developed, OpenSeesPy-based web application described in Bernardini et al. (2022b) by using the “Concrete02” material model for unconfined concrete and “Reinforcing steel” for longitudinal bars.

5. Definition of deterioration scenarios

A deterioration *scenario* is defined by three aspects: the partition of the cross-sections into zones with different deterioration levels (*sectional deterioration pattern*), the assignment of a GDI to each deteriorated zone (*deterioration intensity*), the distribution of the various sectional patterns over the height (*elevation deterioration pattern*).

In the following, 5 Sectional Deterioration Patterns (SDP), differing for the sides where corrosion is assumed to occur, are considered. Specifically, the following configurations are defined: deterioration on a single shorter side (pattern A), on a single longer side (pattern B), on two shorter sides (pattern C), on two longer sides (pattern D) and, finally, on all sides (pattern E).

For each one of the above mentioned SDP, the 5 different deterioration intensities defined in Table 1 are considered and associated to a specific color, later used to represent the results (I0: green, I1: yellow, I2: light orange, I3: orange, I4: red). The GDI assigned to each deteriorated side according to the sectional pattern is applied for a deteriorated depth of 2 times the cover depth, whereas the remaining parts of the cross-section are considered undamaged.

A single Elevation Deterioration Pattern (EDP) characterized by the presence of a given SDP in the piece ranging from the base section to an elevation of 5% the pier height, corresponding to 0.75 m.Combining the above mentioned patterns and intensities, a total of 25 deterioration scenarios are obtained. For each scenario, pushover analyses of the isolated pier subject to an increasing top horizontal displacement taking into account geometric nonlinearity are performed for two different loading directions, corresponding to strong and weak structural loading directions, hereafter denoted SD and WD, respectively. Moreover, for the non-symmetric cases, i.e., scenario A for SD and scenario B for WD, both positive and negative loading directions (Figure 2a) are considered and denoted by acronyms: SD+, SD-, WD+, WD- .

6. Response of the undamaged pier

The aim of the present work is to evaluate the degradation on the structural behavior due to rebar corrosion. To this end, the response of the undamaged pier (I0) is computed first to set up the reference condition with respect to which the influence of corrosion is evaluated. The numerical model is the same used for the damaged pier and above described, with the only difference that no corrosion effects are considered ($w_{cr}, \psi_L, \psi_T = 0$).

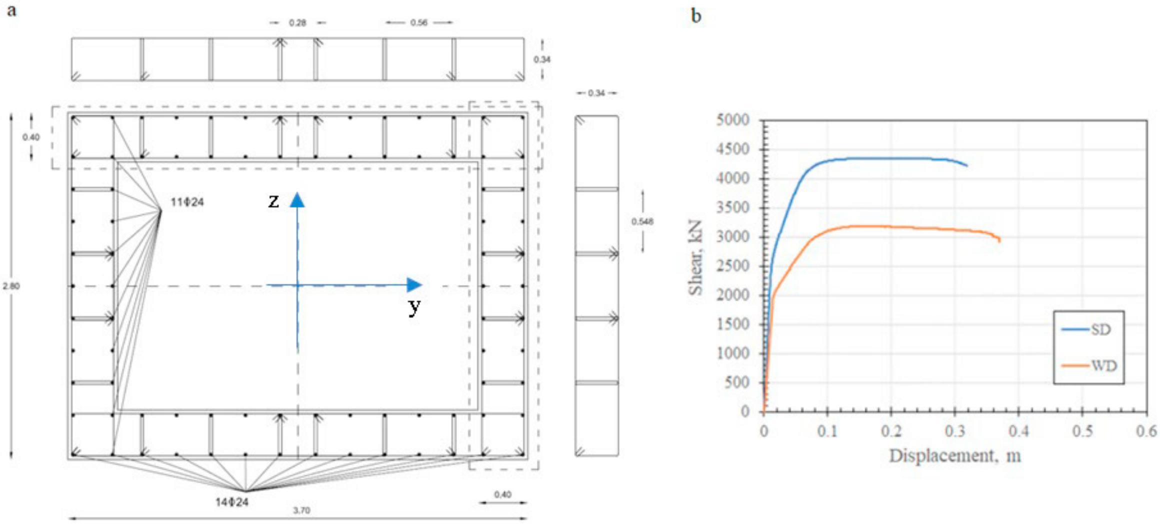

Fig. 2. (a) Cross-section of the studied pier. Transverse reinforcement bars have 10 mm diameter and 200 mm spacing, uniform over the height, clear concrete cover is 30 mm and (b) pushover profiles for the undamaged analyses, Strong and Weak loading directions.

Figure 2b then shows the obtained pushover curves of the undamaged pier expressed in terms of total base shear versus top displacement for loading displacement along positive Strong Direction (SD) and Weak Direction (WD).

7. Influence of deterioration intensity for the various sectional patterns

In this section the capacity curves computed for the different deterioration scenarios are presented by comparing the response obtained for each sectional pattern in presence of the various deterioration intensities, considering separately the two loading directions (Strong and Weak). In the legend and axes of most figures deterioration intensities are denoted by the same number preceded by the letter D instead of I. Namely, for example, intensities I1, I2,… defined in Table 1 are denoted D1, D2,… in the Figures.

7.1. Strong Direction

7.1.1. Patterns A+ and A-

Figure 3 shows pushover curves for each deterioration intensity (characterized by its own colour) together with the undamaged pier in green for the sectional pattern A where corrosion occurs on a single short side. Since pattern A is non-symmetric, analyses have been carried out for both positive and negative directions (A+, A-) (Figure 3 (a) and (b)).

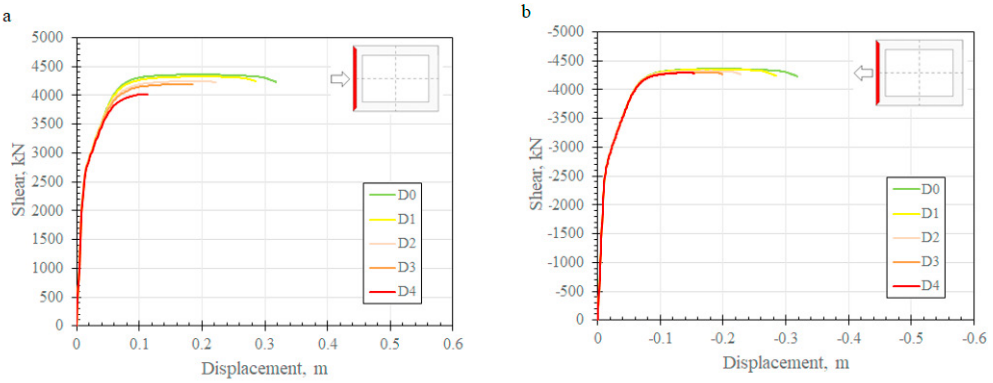

Fig. 3. Scenario A, comparison of the obtained results for all corrosion intensities: (a) Strong Direction positive (A+), (b) Strong Direction negative (A-).

As it can be seen, even if the sectional pattern is the same, significant differences between the two directions are observed. This is due to the fact that analyses A+ and A- (Figure 3a and 3b) are characterized by the presence of deterioration in the zone subject to tensile and compressive stresses, respectively.

When corrosion occurs in the compression zone a degradation of the ultimate displacement with essentially constant strength is observed. On the contrary, when deterioration occurs in the tension zone degradation of both strength and ductility is observed with more pronounced influence for more severe deterioration intensities.

7.1.2. Patterns C and E

The same comparison above described for the A+ and A- sectional patterns are here now presented for the patterns C and E which involve corrosion on both shorter sides and corrosion over the whole pier. Differently from the A scenario, these are symmetric scenarios, i.e., the pushover profiles for each corrosion intensity are plotted only for the SD+ (Figure 4 (a, b)).

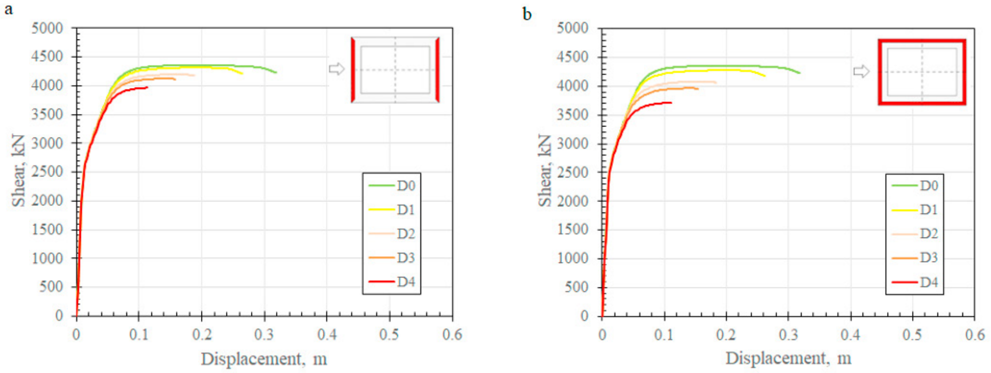

Fig 4. Patterns C (a) and E (b): comparison of the obtained results for all corrosion intensities in terms of pushover profiles.

As it can be seen, patterns C and E exhibit trends similar to those observed for pattern A+ with a combined degradation of both strength and ultimate displacement, increasing with corrosion intensity. Clearly, pattern E is characterized by a larger extension of the deteriorated zone hence the degradation entity is systematically more pronounced with respect to pattern C.

7.1.3. Patterns B and D

For the sake of completeness, Figure 5 (a) and (b) show the capacity curves of the pier obtained for sectional deterioration patterns B and D characterized by corrosion occurring, with different intensities, along one or both longer sides.

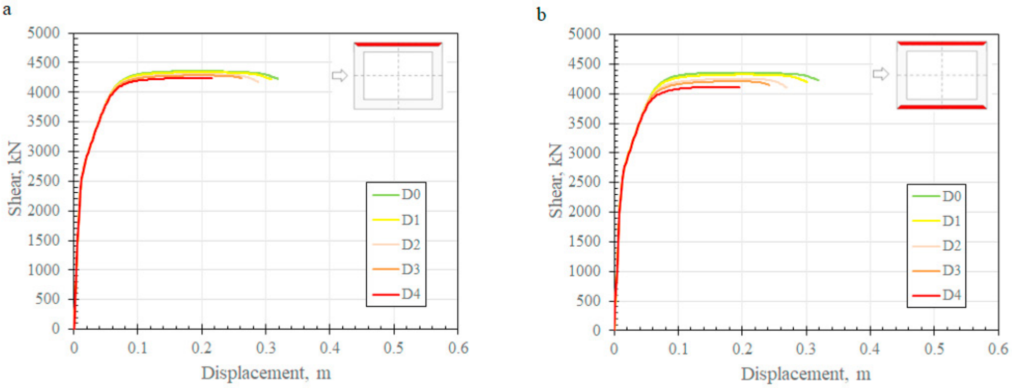

Fig 5. Scenario B (a) and D (b), SD+, comparison of the obtained results for all corrosion intensities in terms of pushover profiles.

The results clearly show that, as expected, corrosion distributed along the sides parallel to the loading direction has less influence with respect to the one produced by deterioration with the same intensity but occurring along sides parallel to the neutral axis of bending.

7.2. Summary of the results for the Strong Direction and results for the Weak Direction

In Figure 6 all the results obtained by pushing the pier along the SD are summarized and compared through plots of strength and ultimate displacement normalized with respect to the corresponding values of the undamaged pier, versus the deterioration intensity. The comparison shows that the various deterioration patterns and intensities produce significantly different influences on the pier capacity, leading to strength reductions up to 15% and ultimate displacement reduction up to 65% with respect to the undamaged pier for the case of pattern E (corrosion on the four sides) and the higher intensity I4.

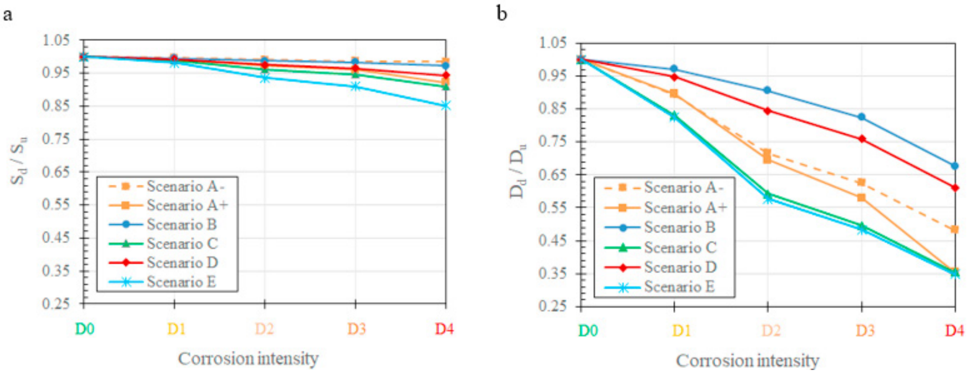

Fig 6. Comparison of the obtained results for all corrosion intensities: (a) degradation of pier resistance (Shear) and (b) ductility (Displacement) with respect to the undamaged case (Su, Du), Strong Direction.

Figure 7 finally shows the analogous comparison for the analyses carried out by pushing along the WD which shows similar trends to those observed for SD, with patterns B and E playing the same role as patterns A, C.

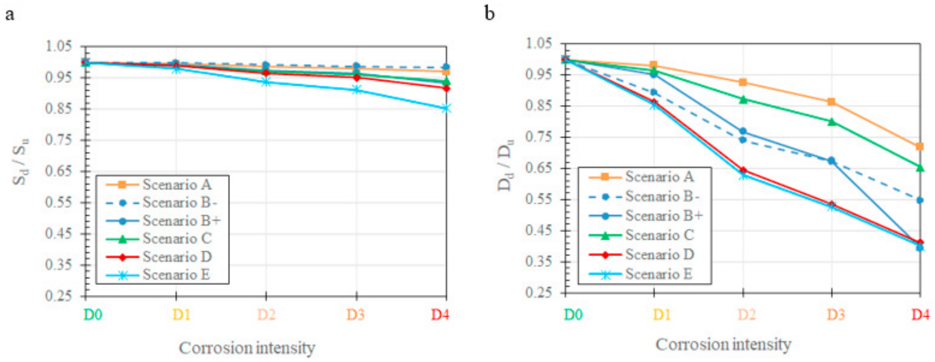

Fig 7. Comparison of the obtained results for all corrosion intensities: (a) degradation of pier resistance (Shear) and (b) ductility (Displacement) with respect to the undamaged case (Su, Du), Weak Direction.

8. Conclusions

In this work, a few preliminary results obtained within the framework of a research project aimed to investigate the correlation between corrosion-induced deterioration of RC piers on the seismic performances of bridges have been presented. Specifically, capacity curves under horizontal actions of a rectangular hollow pier have been computed under different deterioration scenarios. Nonlinear analyses have been carried out by an OpenSeesPy-based web-application implementing a multi-level deterioration modeling approach using fiber beam-column finite elements.

Results show that non-uniform corrosion can produce significant strength and ultimate displacement reductions with respect to the capacity of the undamaged piers with different influence for corrosion taking place in compression or tension zones. Several developments are currently ongoing with the aim to take into account further phenomena such as shear capacity, bar-slip, rebar buckling and to study different piers and different materials

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