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Performance assessment of deteriorated RC pier in marine environment

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ABSTRACT: The aim of the present work is to develop a smart procedure for the assessment of aged and deteriorated RC structures. The effects of aging, especially in marine environment, must be considered in assessing both the static and seismic performances. Corrosion of steel reinforcement induced by chloride attacks from sea water is one of the most evident cause of strength and ductility loss for RC structures over time. On the other hand, the increased concentration of carbon dioxide in modern environments, principally due to industrial pollution, is the main cause of concrete carbonation. The adopted procedure to assess structures in adverse environments is a multi-scale analysis of materials up to structural system. Non-destructive evaluations and destructive tests and structural identification, as well as all possible methods in controlling deterioration are needed to evaluate the actual damage state and to predict future service life.

1 INTRODUCTION

"Pontile Nord" (Fig. 1a) is a reinforced concrete pier that in the past served as working pier for the handling of cargos onto and off ships, especially for raw materials for the adjacent former steel industry, Italsider, in the area of Bagnoli, Naples (Italy). Today it has been transformed into a pleasure pier, a seaside promenade and it is one of the most beautiful touristic attractions of the city of Naples. "Pontile Nord" is about 896 m long and consists of four sections built in different periods (between 1936 and 1968) and according to different structural schemes. Each section is spaced by stiff caissons (Fig. 1b). Each section is made of a series of framed and braced structures (Fig. 1c) and has an horizontal bracing system, a truss structure, at 3.50 m and a rigid deck at 8.50 m on the sea level.

In particular the first section (Fig. 2a), built in 1936, is about 585 m long and is made of a narrow and a wider part. A portion of the narrow part is out of the water. The first section presents pier columns directly inserted in the seafloor and other columns fixed on a foundation system, made of piles. Those piles reach the sea level and come few meters outside seawater. The second section (Fig. 2b), built in 1958, about 100 m long, presents the external columns fixed on the foundation system and the internal pier columns directly inserted in the seafloor. The third section (Fig. 2c), built in 1962, about 100 m long, presents all the pier columns fixed on the foundation system. Finally, the fourth section (Fig. 2d), built in 1968, about 100 m long, presents all the pier columns directly inserted in the seafloor. The entire deck structure is: (i) for the first section, longitudinally restrained at one side by a caisson and free at the other side outside the water and (ii) for the second, third and fourth sections, longitudinally restrained at both sides by the caissons. In the transverse direction all the sections are simply supported

(a)

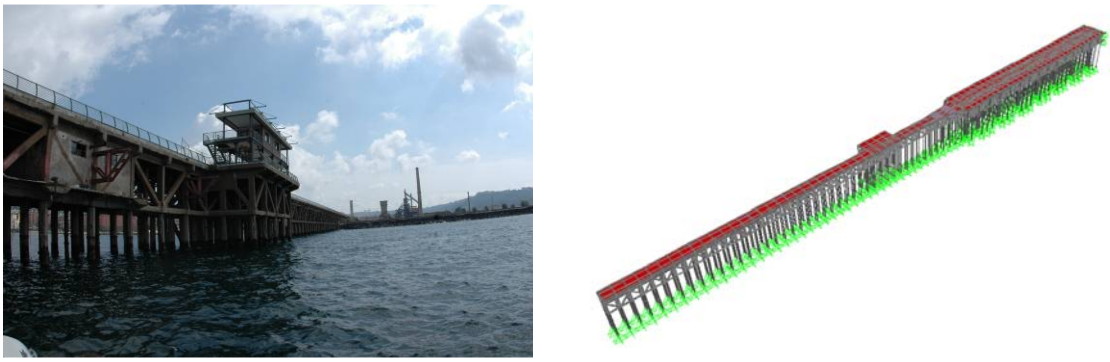
(b)

(c)

Figure 1. “Pontile Nord” RC pier: (a) global view; (b) caisson; (c) elements of the deteriorated deck structure.

2 RESEARCH SIGNIFICANCE

The need to assess the safety of this touristic structure is mainly caused by the evident deterioration of the RC elements. Nowadays this structure seems to be evidently oversized because it was designed to carry the heavy trains loaded by raw materials to be moved to the steel industry from the ships. The original construction documents were stored by the owners of the structure, although many variations were performed during the construction. Before any structural analysis, it was fundamental to evaluate the mechanical properties of the aged materials, by means of a wide number of Non Destructive Tests (NDT) and Destructive Tests. A wide variability was expected because the construction time ranged between the ‘30s and the ‘60s of last century. The safety of the “Pontile Nord” was assessed by means of both static and seismic analyses as suggested by the Italian Design Code (NTC ’08). For each element type, it was evaluated a point cloud of the bending moment, axial and shear forces, for all the combinations of gravity and seismic loads. The un certainty on the effective reinforcement ratio led to evaluate both the cracking moment capacity and the flexural/axial capacity of the elements (for each cross section at Ultimate Limit State according to Italian Design Code - NTC ’08) for different reinforcement ratios. In this way it was possible to check if the concrete only (i.e. without any steel reinforcement) was able to carry the loads, or else what reinforcement ratio was needed to satisfy all the capacity checks. This procedure allowed evaluating if the designed steel reinforcement was able to guarantee safety or what level of steel bar degradation was feasible in terms of diameter loss, nowadays. Further details on the parameters adopted, assessment criteria, and main outcomes are reported briefly in the following sections.



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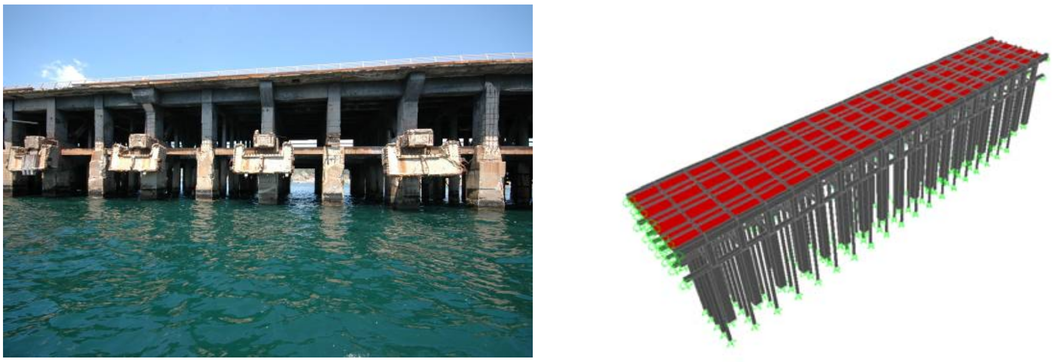

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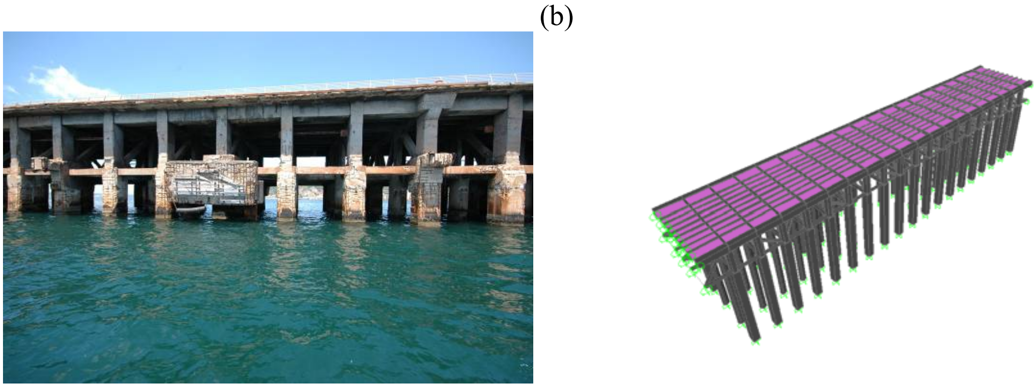

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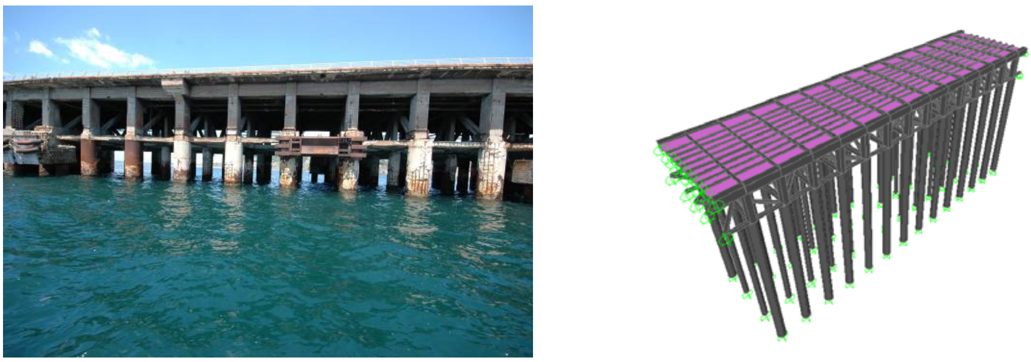


(d)

Figure 2. “Pontile Nord” RC pier: (a) first section; (b) second section; (c) third section; (d) forth section.

3 EVALUATION OF MATERIAL PROPERTIES

A huge variability in material properties was expected because of the construction period involving almost forty years. An extensive test activity was planned. For each section of the pier, many tests were conducted on steel and concrete materials from different structural elements (namely, piles, beams, columns, bracing elements). NDT tests mainly concerning acoustic emissions and rebound hammer were performed on badly deteriorated concrete. Their results were compared to destructive tests (Figure 3) on concrete samples got in the same locations where NDT tests were performed. The results of NDT were mainly jeopardized by crack damages, voids in the concrete due also to steel corrosion, surface degradation. Quite surprisingly, the concrete strength was almost similar for all the sections, despite the very different ages. Conversely, steel samples evidenced significant differences both in behavior as in the strength for each section and period. Corrosion was also a main issue because the environmental conditions was sea spray water and wet and dry conditions for the elements just above the sea level. However, below the sea level, the concrete and steel reinforcement of RC piles were perfectly undamaged, despite some plants and sea-weed. The design values have been obtained as ratios between tested average value and a confidence factor (1.20) as suggested by NTC ’08. The confidence with which the properties of the structure components are known, when calculating capacities is established from the knowledge obtained based on access to original construction documents (for geometrical dimensions of members and internal reinforcements, confirmed also by visual inspection), and from the assessment of mechanical properties (based on destructive and nondestructive testing of sampled specimens). The value 1.2 for the confidence factor has been established because of the sample size analyzed. In this evaluation also the reduced level of knowledge on the complex boundary conditions at the bottom of the structure above the foundation piles is considered.

(a) (b)

Figure 3. Destructive Material characterizations, failure of: (a) concrete specimens; (b) steel specimens

4 FEM LINEAR ANALYSIS

A complete three-dimensional FE model of the “Pontile Nord” structural complex has been built using commercial computer code SAP 2000. In particular the RC beams, columns and braces of the pier structures have been modeled by means of frame elements. Different kinds of external constraints have been applied according to different foundation systems of the pier columns. The 3D model consists of: (i) 1696 nodes and 2892 frames for the first section (Fig.2a); (ii) 472 nodes and 1002 frames for the second section (Fig.2b); (iii) 435 nodes and 875 frames for the third section (Fig.2c); (iv) 327 nodes and 648 frames for the fourth section (Fig.2d). Linear elastic behavior has been assumed, with Young modulus equal to 22 GPa and mass density equal to 25 kN/m^3. The gravitational loads have been applied given the mass density and as area loads on the shell elements of the bridge deck at 8.50 m over the sea level. In the case of columns built over the foundation system made of piles, two different analyses have been carried out considering a fixed restraint or a hinge restraint to account for the uncertainty on the restraint degree at that connection. A dynamic identification is planned to calibrate both the elastic modulus of concrete and the effective restraint degree.

4.1 The static and dynamic analysis

Linear static analyses have been performed considering a live load of 5 kN/m^2 over the deck. It is worth nothing that this live load is dramatically lower than the heavy loads on the deck in the past decades. Under gravity loads, the elements were primarily axially loaded and only the deck elements were loaded in flexure. The linear investigation was extended to a modal analysis in order to give an estimation of the dynamic response of the "Pontile Nord" pier. Figs. 4 to 7 show the results of the analyses in terms of deformed shapes, periods and participating mass ratios for the first two sections of the structure. For the first section, the first seven modes of vibrations are required to achieve the 85% of participating mass in the transverse direction. For the other sections, only first three modes are sufficient. The dynamic response of the last three sections is very similar. Hence, only the results for the second section are reported.

The effect of restraint degree at the structure/foundation connection is clear for the first section, where the periods are much different for first modes, even if the participating mass was quite similar. For the other sections, this effect is evident only for the participating mass in the transversal direction, being the periods slightly closer to each other.

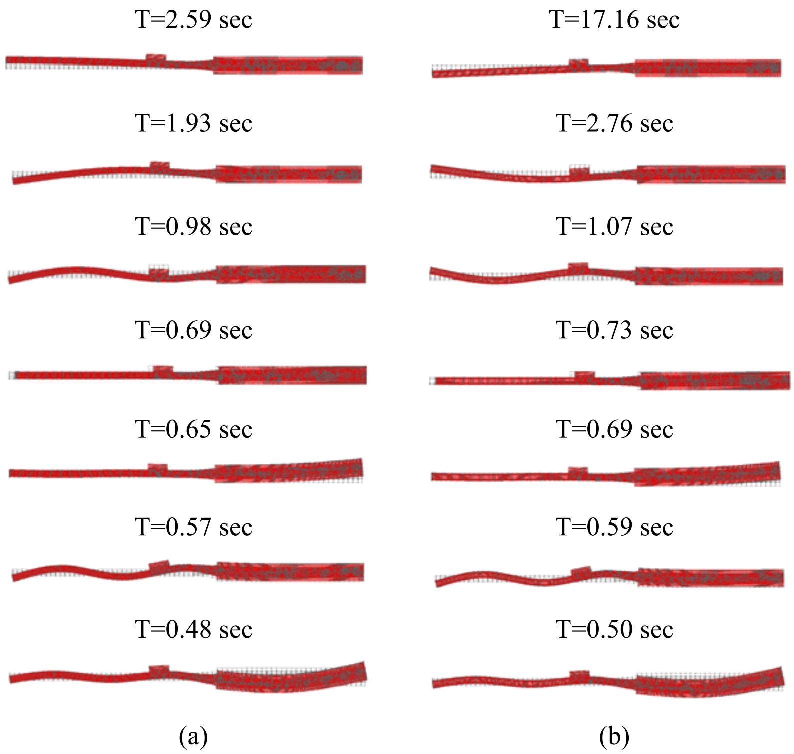
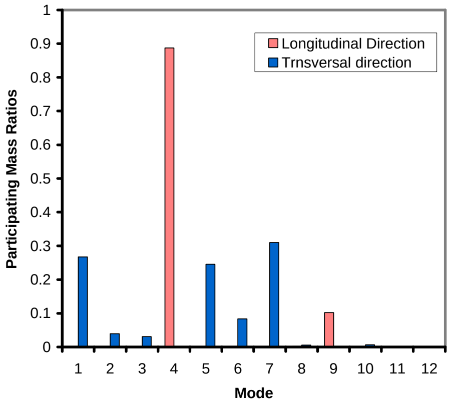


Figure 4. Modal deformed shapes and periods for first section: (a) fixed restraint; (b) hinge restraint.



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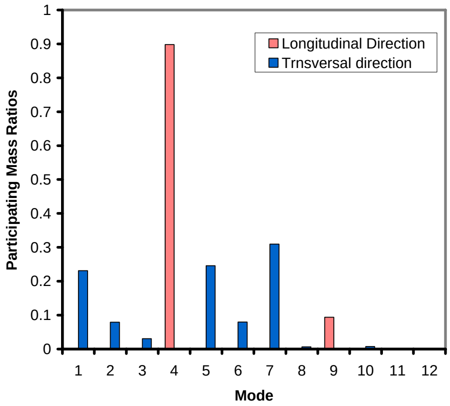
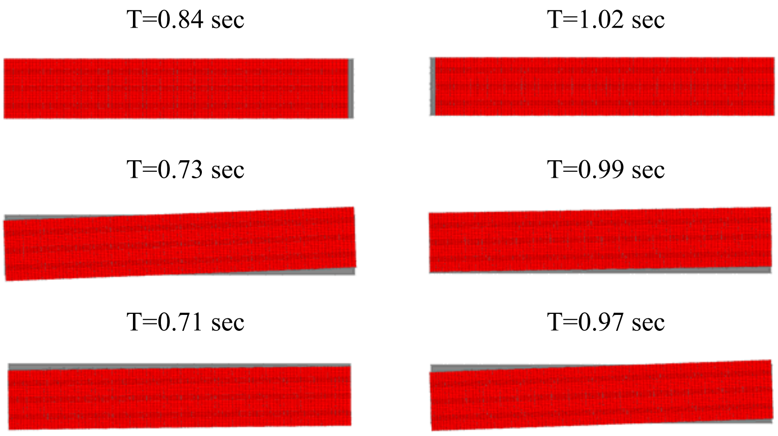


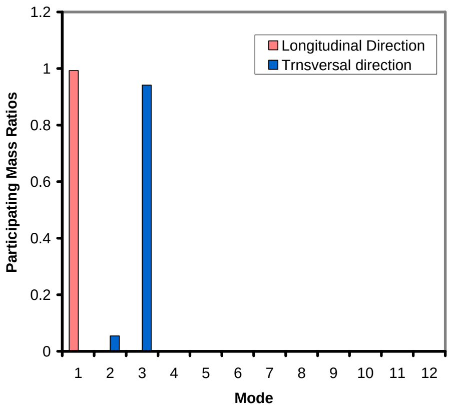
(b)

Figure 5. Participating mass ratios for first section: (a) fixed restraint; (b) hinge restraint.



(a) (b)

Figure 6. Modal deformed shapes and periods for second section: (a) fixed restraint; (b) hinge restraint.



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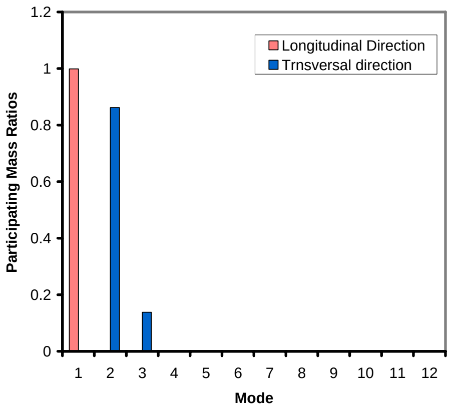

(b)

Figure 7. Participating mass ratios for second section: (a) fixed restraint; (b) hinge restraint.

4.2 The demand spectrum

In order to assess the effective seismic demand on "Pontile Nord" RC pier, the inelastic design spectrum provided by Italian Code (NTC '08) for the site of the pier was adopted, with a PGA equal to 0.167g. The inelastic spectrum is obtained from the elastic one through a q factor equal to 2, which accounts for the ductility and deformation capacity of this deteriorated RC structure. The response spectrum (Fig. 8) provided by the NTC'08 has been applied along the two main directions of the structure combined to the gravity loads in various analyses, as required by the Italian design code.

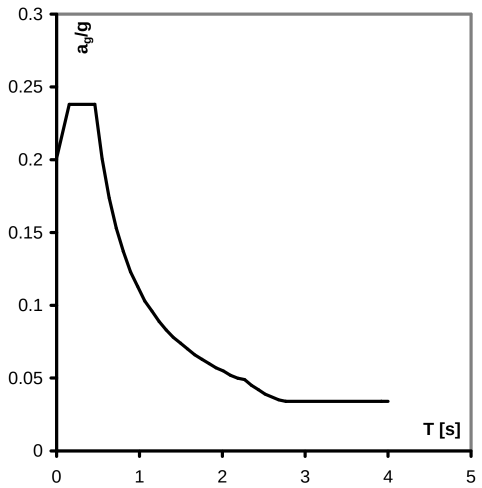

Figure 8. Response spectrum for seismic analyses.

5 STRUCTURAL SAFETY: EVALUATION CRITERIA

Structural safety for each RC element has been assessed both under static and seismic actions. In order to consider the deterioration of the RC elements due to marine environment, the structural capacity of the RC members has been derived considering the concrete core only (neglecting concrete covers). Two main assumptions were formulated in structural checks. To avoid considering badly deteriorated and corroded steel, a first check involved the cracking moment, M_{cr}, of the concrete cross section (i.e. neglecting internal steel reinforcement). A second series of checks involved a parametric analysis of PM capacity domains at Ultimate Limit State, built considering different internal steel reinforcement ratios ρ. Although the steel reinforcement's distributions are known, it is very difficult to reliably evaluate the steel corrosion (due to the adverse marine environment) and the effective contribution of residual steel to the strength of structural RC members. In fact, the corrosion of steel reinforcement induced by chloride attack from sea water is one of the most evident cause of strength and ductility loss for RC structures over time.

Figure 9 synthetically shows an example of the two structural checks. The PM capacity domain was drawn to evaluate the safety for both gravity and seismic loads. The two plots provide a clear view of the residual reinforcement ratios needed to guarantee safety (compared to original reinforcement ratios provided at construction stage). For instance the static analysis (gravitational loads) led to a point cloud representing, in Figure 9, the columns, mainly axially loaded. Even without steel reinforcement (i.e. M_{cr}) the safety of the columns is guaranteed (stress points are inside the cracking moment domain). Conversely, under seismic load combinations, the columns, axially loaded under gravity loads, are now almost loaded in flexure. In this case the reinforcement ratio of 1% (design value according to original construction documents) guarantees a wide safety margin. A high corrosion level can be in this case acceptable because the minimum required reinforcement ratio is slightly lower than 0.5% to satisfy structural checks at Ultimate Limit State. It is worth noting that under seismic actions, the concrete core only is not able to guarantee the safety of the structure. The same procedure was repeated for all the other structural elements.

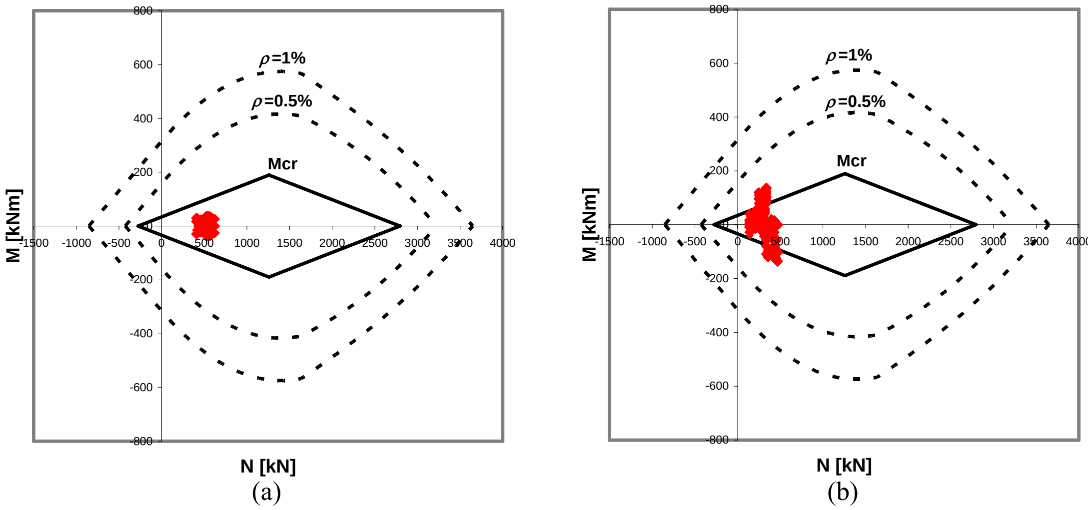

Figure 9. Structural evaluation: (a) static analyses; (b) seismic analyses

6 CONCLUSIONS

In this paper the "Pontile Nord" RC pier in Naples has been analyzed as a case of study to present a procedure for assessing structural behavior and seismic vulnerability of an aged and very deteriorated structure in marine environment. For this purpose, 3D linear analyses of the structural complex have been run through FE in the static and dynamic ranges. A comprehensive evaluation of basic mechanical properties of deteriorated materials was performed.

The effect of structural details and uncertainties on restraint degree in such complex structures was analyzed. The effects of aging, especially in marine environment, needs to be considered; in fact the corrosion of steel reinforcement induced by chloride attacks is one of the most evident cause of strength loss. A quick procedure to evaluate an acceptable level of corrosion (i.e. steel reinforcement ratio lost) for RC structures is proposed, accounting for both gravitational and seismic loads. According to the FE model, vertical elements (pier columns and columns of the deck structure) are the most vulnerable to seismic actions.

REFERENCES

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