Fuzzy based approach for the reliability assessment of reinforced concrete two-blade slender bridge piers using three-dimensional non-linear analysis.

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Abstract

A modern conceptual design of a bridge structure should be open to wider criteria, which assure that the structure is endowed with static, dynamic and ductile characteristics sufficient to tackle the seismic events. For the satisfaction of these requirements and for the exploration and the verification of innovative structural schemes, one must consider refined and subtle analysis formulations and tools. Such a kind of structural scheme is based on the two-blade slender bridge piers. These are elements subdivided into two parts with different geometric and mechanical properties. The first part has a box section, highly stiff; two flexible blades connected to the top compose the second part.

Due to the uncertainties involved in the problem, the geometrical and mechanical properties that define the structural problem cannot be considered as deterministic quantities. In this work such uncertainties are modeled by using a fuzzy criterion.

Keywords: Bridge Structure, Reinforced Concrete, Non-linear Analysis, Finite Element Method, Uncertainties, Fuzzy Logic.

1. The problem definition

In the conceptual design of bridges, in areas of moderate to high seismicity, the selection of ductile behavior is a general strategy inside the so-called Integral Bridge Design (Biondini [3]). Its implementation, either by providing the formation of a dependable plastic mechanism or by using base isolation and energy dissipating devices, must be decided.

The two-blade pier is a structural scheme that can furnish the right structural restoring (Figure 1). It has a double scope. First, there is the transmission of vertical loads to the foundation structures; second, there is the possibility to allow horizontal displacements (thermal effects, concrete shrinkage, etc.) without the use of cinematic mechanisms. The ratio between the low rigid box section and the high flexible two-blade section (parameter α) characterizes the structural behavior with respect to the horizontal loading system. If the rigid box section has a small height respect the total pier height, the behavior will have great ductility, but little strength. Instead, if the rigid box section is dominant, it increases the stiffness, with respect to the horizontal loads, but it decreases the ductility. The choice of the relative height of the rigid box section is of great importance because this has a great influence on the global structural behavior. A non-linear analysis is needed to show the global behavior of these structures. In this work a material non-linear analysis is developed. Shear behaviors and diffusion effects will also be considered, using a three-dimensional model. (Sgambi and Bontempi [7]).

In this work the maximum horizontal displacement and the maximum level of the horizontal load are investigate by a fuzzy approach. The pier analyzed (Figure 2) is *42.50 m* height and the vertical load is $V=30\ MN$ for each blade, the parameter α is 2/3. The mechanical characteristics are: $F_c = -31.5\ MPa$, $f_{sy} = 430\ MPa$, $E_s = 210\ GPa$, $\varepsilon_{su} = 1\%$.

Two fuzzy variable are assumed to have a triangular membership function: the Fc (cylindrical compression strength) with interval base equal to [0.7 – 1.3] and mean value 1, and the quantity of vertical reinforcement (ρ = area of steel bars / area of concrete section) with interval base equal to [0.5 – 1.5].

2. Non linear behavior

A three-dimensional generalization of membrane constitutive law (CFT, MCFT) has been implemented to study the material non-linear behavior (Vecchio [8]). The constitutive law is a rotating fissure and the non-objective mesh is also considered using a non-local damage regularization (Bontempi and Malerba [4]). The uniaxial law for the compression concrete is:

$$\sigma_d = \zeta \cdot f'_c \left[2\left(\frac{\varepsilon_d}{\zeta \cdot \varepsilon_0}\right) - \left(\frac{\varepsilon_d}{\zeta \cdot \varepsilon_0}\right)^2 \right] \text{ if } \left(\varepsilon_d \le \zeta \cdot \varepsilon_0\right) \tag{1}$$

$$\sigma_d = \zeta \cdot f'_c \left[1 - \left(\frac{\frac{\varepsilon_d}{\zeta \varepsilon_0} - 1}{\frac{2}{\zeta} - 1} \right)^2 \right] \text{ if } \left(\varepsilon_d > \zeta \cdot \varepsilon_0\right) \tag{2}$$

where, the softened parameter $\zeta = \frac{1}{\sqrt{1 + 400 \cdot \varepsilon_{eq}}}$ is used to reproduce the compression strength if there is a transversal tensile strain. The equivalence strain is assumed as $\varepsilon_{eq} = \sqrt{\langle \varepsilon_1 \rangle^2 + \langle \varepsilon_2 \rangle^2 + \langle \varepsilon_3 \rangle^2}$ where $\langle \varepsilon_i \rangle$ is zero if the ε_i is of compression strain. The constitutive law for the tensile concrete is:

$$\sigma_r = E_c \cdot \varepsilon_r \quad \text{if } (\varepsilon_r \le \varepsilon_{cr}) \tag{3}$$

$$\sigma_r = f_{cr} \left(\frac{\varepsilon_{cr}}{\varepsilon_r} \right)^{0.4} \quad \text{if } (\varepsilon_r > \varepsilon_{cr}) \tag{4}$$

where $E_c = 9500 \cdot \sqrt[3]{f_c}$ is the initial elastic module, and the $f_{cr} = 0.25 \cdot \sqrt[3]{f_c^2}$ is the cracking tension.

The shear rigidity is assumed as:

$$G_{ij} = \frac{E_i \cdot E_j}{E_i + E_j} \tag{5}$$

The rigidity matrix $\underline{\underline{D}}$ is valued in the principal directions system for means of the uniaxial laws of equations (1-5). The rigidity matrix $\underline{\underline{D}}_{xyz}$ in the global reference system is:

$$\underline{\underline{D}}_{xyz} = \underline{\underline{T}}^T \cdot \underline{\underline{D}} \cdot \underline{\underline{T}} \tag{6}$$

where $\underline{\underline{T}}$ is a rotation matrix.

The reinforcement steel is assumed elastic perfectly plastic.

3. Results

At first, we have assumed as independent the uncertainties linked to the compression strength and the quantity of vertical reinforcement. To study this case, 18 simulations have been executed (9 for the uncertain variable): the variable parameters are summarized in the Table 1.

Using the results of the non-linear analysis and the membership functions of the input variables (Fc and ρ) it is possible to create the membership functions of the output variables (maximum horizontal displacement and maximum horizontal load). These curves represent the output fuzzy set. By the de-fuzzification process is possible to calculate a deterministic result for the value of the strength and the displacement. Several methods are present in the literature to de-fuzzificate a fuzzy set: here a Center of Gravity method is assumed.

$$x' = \frac{\int \mu(x) \cdot x \cdot dx}{\int \mu(x) \cdot dx} \tag{7}$$

For the Fc variable, the maximum strength and the maximum horizontal displacement result:

Maximum strength = 10.97 MN

Maximum displacement = 0.45 m

Instead, for the ρ variable, the maximum strength and the maximum horizontal displacement result:

Maximum strength = 11.00 MN

Maximum displacement = 0.44 m

A more accurate analysis can be executed if the variations of the parameter Fc and ρ are assumed correlated. In this case, one's need much more analysis because it is necessary to reproduce the surfaces of variation of the output variables (Figure 3 – a/b).

In the Figure 3 – c, are shown the two new fuzzy set, and the relative membership functions. Using these membership functions it is possible to create a membership surface (Figure 3 – d) that represents the uncertainties domain of the two output variables (the two membership functions shown in Figure 3 – d are the orthogonal projections on the planes μ – maximum force and μ – maximum displacement). By the de-fuzzification process (center of gravity of a three dimensional solid) the deterministic value of the horizontal strength and the horizontal displacement are:

Maximum strength	= 10.9 MN
Maximum displacement	= 0.40 m

4. Conclusions

A modern conceptual design of a bridge structure should be open to wider criteria which assure that the structure is endowed with static, dynamic and ductile characteristics sufficient to tackle the seismic events. It is worth noting that a correct conception of the structural morphology, besides the achievement of better guarantees with regard to the seismic behavior, may also lead to economic advantages either in the realization of the whole structural system, or in the adoption of seismic devices, with a consequent possible reduction of the management cost of the structure as well. In the context of a quality design, aimed to the achievement not only of strength requirements but also of the durability and the functionality of the structure, one can also consider the possibility to convoy the damage towards some regions of known location, possibly planning also the modalities of the restoration, in the project itself.

The critical aspects that give clarity and coherence to the whole structural design need sophisticated analysis formulation and tools. A non-linear analysis is needed to show the global behavior of these structures. Where the ductility and the horizontal strength are important, the uncertainty treatment is also necessary for a correct evaluation of the mechanical behavior.

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Figure and Tables

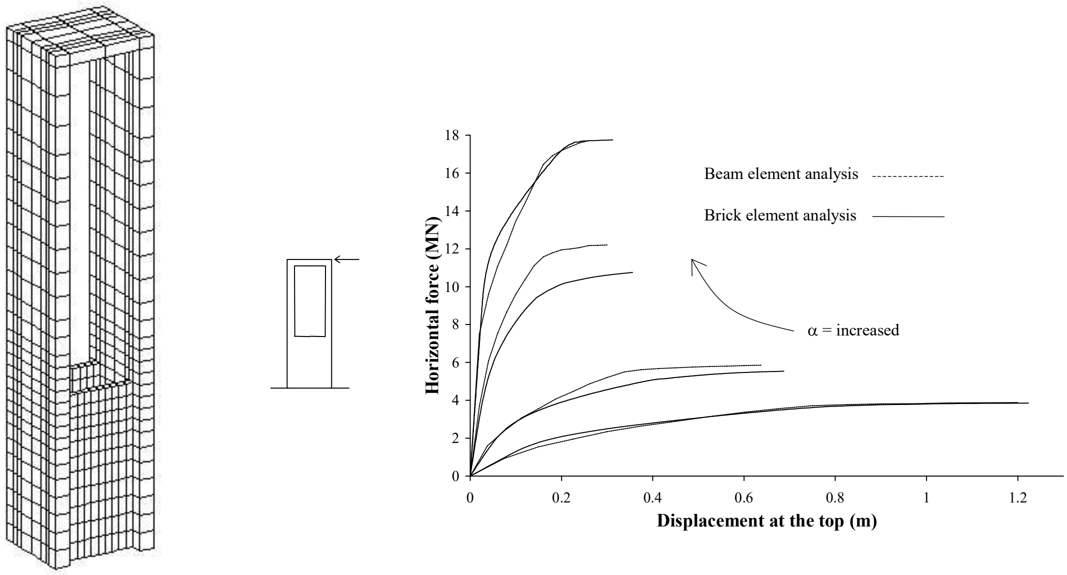

Figure 1

Horizontal load – displacement curves for α variable

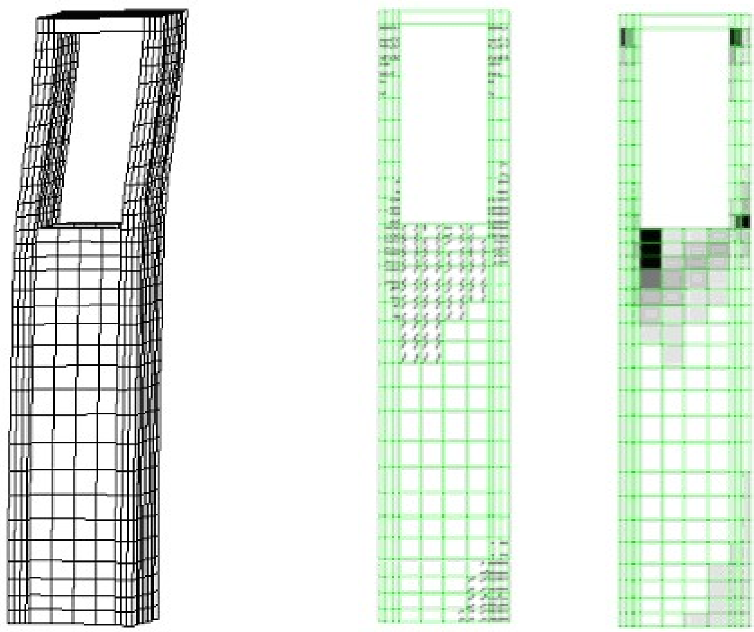

Figure 2

Deformation and damage for the pier analyzed (α = 2/3).

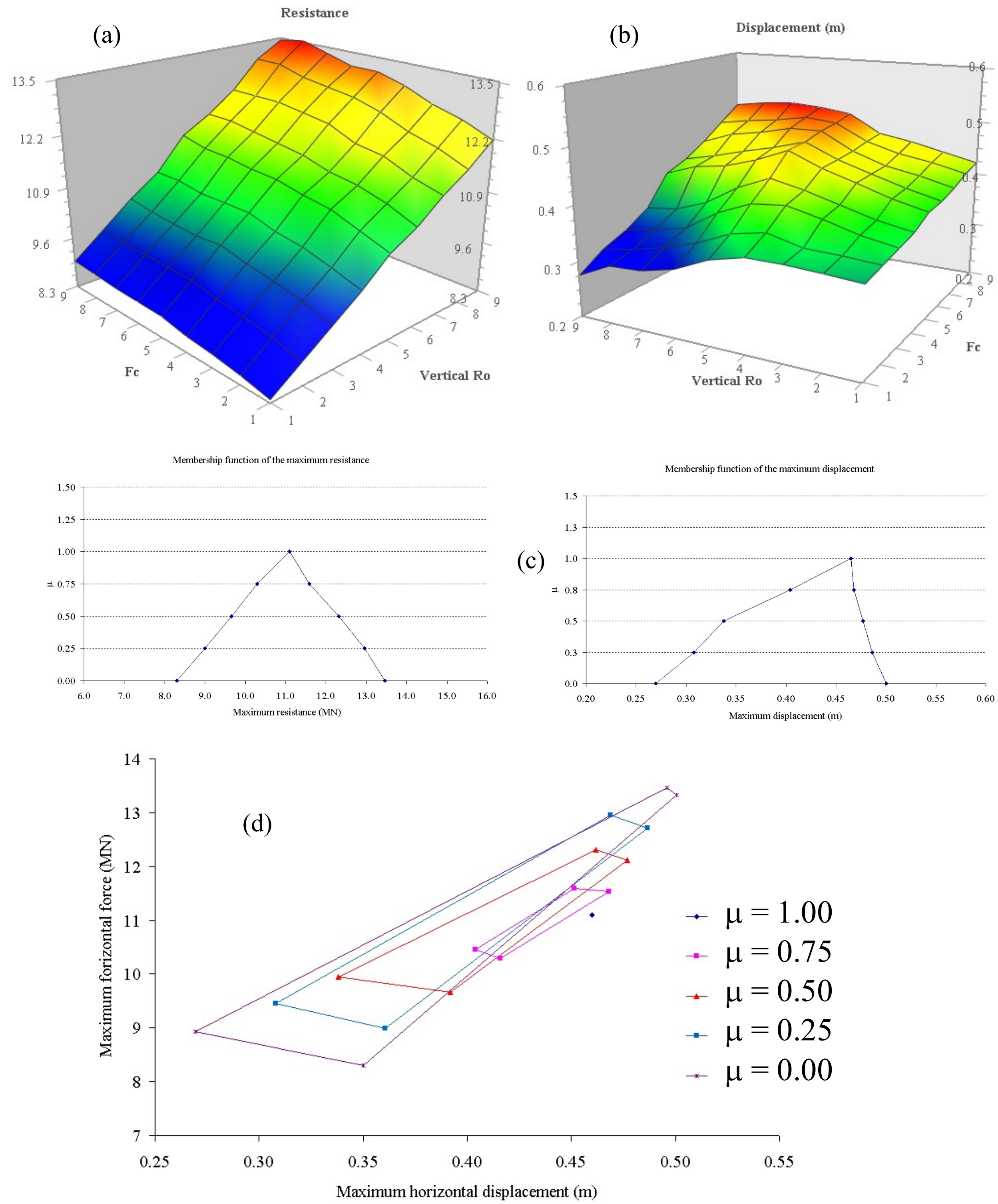

Figure 3

Variation of the horizontal strength (a), displacement (b), membership function of the output variable (c and d)

Variation of the compression strength Fc (Mpa)

22.50	24.50	26.80	29.20	31.50	33.85	36.20	38.50	40.80

Variation of the vertical ρ (%)

0.00550	0.00688	0.00825	0.00963	0.0110	0.0124	0.0138	0.0151	0.0165

Table 1

Variation of the compression strength Fc and vertical ρ.