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Capacity design of a reinforced concrete bridge using the seismic Algerian code (RPOA-2008)

*R. LARBI [1)], M. NAILI[2)], A. KIBBOUA[2)] and A. BOURZAM [3)]

[1] *Laboratory of Public Works and Construction LARBI (LTPCL) Bouira, Algeria, rym_potter@yahoo.fr.*
[2] *National Earthquake Engineering Research Center (CGS), Algiers, Algeria.*
[3] *University of Sciences and Technology Houari Boumediene (LBE/USTHB), Algiers, Algeria.*

ABSTRACT

A new seismic design specification for bridges has been recently enforced in Algeria. Until 2010, most of the Algerian bridges were designed according to the seismic coefficient method which considers the seismic lateral force as a percentile of the whole structural weight.

In this paper, a typical RC bridge located in an area of moderate seismicity designed according to the old specifications is taken into account to check its safety with respect to the new specifications. The bridge is made of a voussoir deck supported by hollow piers restrained to the ground. A comparative study between an elastic approach where, the seismic force is evaluated from the elastic response spectrum of the Algerian building code RPA-1988, and a capacity calculation using RPOA-2008, where the seismic force is evaluated from the design spectrum is performed.

Reinforcements obtained by the capacity calculation approach were safer than the existing ones. The capacity curves of the piers were derived and compared to the seismic demand in terms of reduced force. The consistency criterion has been then checked through a set of numerical iterations. It is worth mentioning that the deduced reduction factor is very close to the unity. Thus, there was no specific motivation to conduct the capacity design approach which is longer and tedious. Elastic calculation is recommended for this kind of bridge.

1. INTRODUCTION

Algeria is a prone seismic region where several destructive earthquakes have occurred in the past. If the 1981 Algerian seismic design specification for buildings has been enforced immediately after the 1980 El Asman destructive earthquake, the

[1)] Magister, Civil engineer, LTPC LARBI
[2)] PhD, Senior Researcher, CGS
[2)] PhD, Senior Researcher, CGS
[3)] PhD, Associate Professor, LBE/USTHB

bridges and roadways structures were still designed according to the seismic coefficient method.

Hence, a new seismic design regulation for bridges was recently enacted in Algeria in 2011. Therefore, most of the existing bridges do not comply with the new requirement in terms of safety and seismic performance.

To prevent the collapse of those bridges in case of the occurrence of future earthquakes, the assessment of their seismic vulnerability constitutes a prerequisite for their continuous serviceability and safety.

2. CAPACITY APPROACH

The new seismic Algerian code for bridges (RPOA-2008) proposes two calculation methods; elastic and capacity approaches. The capacity approach concept has been recently adopted by Algerian engineers. This can be explained using the example of the link, first introduced by Paulay (Paulay 1995) as shown in Fig. 1 where the central link is ductile and all the other links are brittle.

For the elastic calculation, the design of links is done using Fy (the maximum force that can undergo brittle links), whereas, for a dimensioning by a capacity approach, the links are evaluated from Fu (ultimate force of the ductile link). Therefore, the ductile link will behaves like a fuse; and all the other links will never reach collapse.

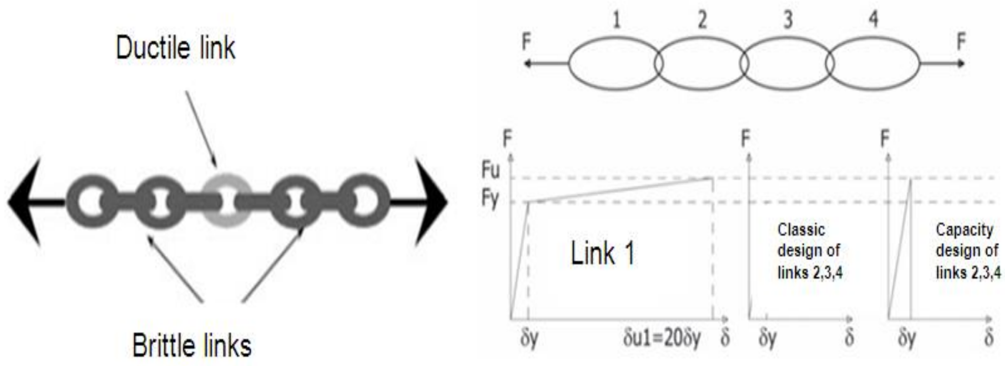


Fig. 1 Paulay’s definition of capacity design principal

3. STEPS TO FOLLOW FOR A CAPACITY DESIGN

The inelastic dimensioning using the seismic reduction factor q, is elaborated by considering the following steps (SETRA-SNCF 2000) :

- For ductile elements, start with an elastic calculation, considering design response spectra, and get elastic solicitations.
- Reduce obtained elastic solicitations by a seismic reduction factor q>1.
- Design the structure/elements for reduced solicitations.
- Check the coherence criteria by means of a group of iterations.
- Adopt the structural dispositions in terms of reinforcement positions, to insure that the plastic hinges will happened at the right place.

3.1 Overcapacity coefficient

In plastic hinges zones, the longitudinal reinforcement is calculated from reduced flexural moment Mrd and the most unfavorable normal force. Forces located out of plastic-hinge regions are amplified by an overcapacity coefficient $\gamma 0$ given in paragraph RPOA-2008

In the critic regions of plastic hinges, the longitudinal reinforcement is calculated from the reduced flexural moment M_{rd}.

3.2 Check of the coherence criterion

When the seismic reduction factor q is greater than one (q>1), it is considered that some sections are will behave in post elastic field. To be coherent with this hypothesis, it is necessary to verify that plastic hinges are located in the right place; and the coherence criterion by a group of iterations. Reduction of elastic forces starts with an initial value of q which will be increased until convergence (SETRA-SNCF 2000).

3.3 Plastic hinges

Reinforcement of plastic hinges concern a certain length defined in different ways according to experimental results. Plastic hinges have to be positioned at the top of piers, when fixed to ground at the bottom and articulated at the top (the top of the pier is considered articulated because of elastomeric bearings). Let's consider Priestley's formula given by Eq. (1) to calculate the length of plastic hinges (AZIO A.):

$$Lpl=ast.(0{,}08Lv+0{,}022fs.dbl)\ [mm] \tag{1}$$

Where:

ast : grade of steel coefficient.

$$\left\{ \begin{array}{l} ast=0{,}8 \text{ for steel rebars with } \frac{ft}{fs}<1{,}15 \\ ast=1 \text{ for steel rebars with } \frac{ft}{fs}\geq 1{,}15 \end{array} \right\}$$

Lv : shear length [mm].

fs : yielding point of longitudinal reinforcement.

ft : tension resistance of longitudinal reinforcement [MPa].

dbl : longitudinal reinforcement diameter [mm].

In literature, experimental resluts give an approximation of plastic hinges length; as the 1/10 of the total length of the considered ductile element.

4. DUCTILITY DEFINITIONS

4.1 Ductility of a section

The ductility of an RC section, is expressed by a curvature ductility. It is to define the capacity curve „flexure moment-curvature' using the fiber method. The ductility is defined by the Eq. (2)

$$\mu c = \frac{\varphi u}{\varphi y} \tag{2}$$

4.2 Ductility of a structure

The capacity in terms of ductility, of a RC element, is the ultimate capacity that structure can support without collapse, which is a fonction of the structure properties and the earthquake characteristics. We have to define the capacity curve „force-displacement' where:

F= external force applied at the top of the ductil element.
D= resulted displacement according to the applied force.

The capacity curve in F-D format, which traduces the whole structural ductility, can be determined using one of the following methods:

- Using a static non linear push over analysis.
- Using the flexure moment-cuvature' to establish the capacity curve in F-D format, considering a bilinear approximation and using the equations Eq. (3) to Eq. (8), define O, A and B shown in Fig. 2a (DAZIO A.)

Where :

- O: origine of graph.
- A: (Δy, Fy) first yield point.
- B: (Δu, Fu) collapse point.

$$\Delta y = \theta y . Lv \tag{3}$$

$$\theta y = \phi y . \frac{Lv}{3} \tag{4}$$

$$\Delta u = \theta u . Lv \tag{5}$$

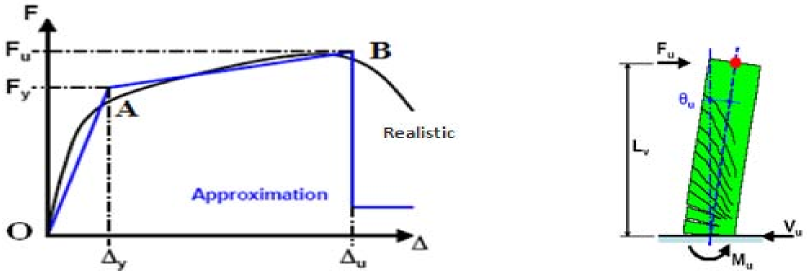
$$\theta u = \theta y + (\phi u - \phi y) . Lpl . \left(1 - \frac{0{,}5 . Lpl}{Lv}\right) \tag{6}$$

$$Fy = \frac{My}{Lv} \tag{7}$$

$$Fu = \frac{Mu}{Lv} \tag{8}$$

And :

θ : rope rotation as defined in Fig. 2b
θy : first yield rope rotation.
θu : ultimate rope rotation.
Lv : shear length which represents, for a RC element, the whole lenght of the considered element.
Lpl : Plastic hinge lenght.



a) b)

Fig. 2 a) Relation force-displacement non linear of a cantilever
b) Rope rotation definition

The structural ductility is defined by Eq. (9)

$$\mu\,\Delta = \frac{\Delta u}{\Delta y} \tag{9}$$

5. STUDY CASE

5.1 Introduction

The studied bridge is called OA203 and constructed in 2008. It is a part of the East-West highway, connecting El Adjiba to Bouira (Department of Bouira). The bridge was calculated in 2004 by an Italian firm. It has a straight layout with 5% of longitudinal gradient. The deck is realized in precast RC voussoirs, with variable inertia at the piers and constitutes a continuous beam in several spans (60 m + 4 x 100 m + 60 m) as shown in Fig. 3. The deck is connected to the piers by elastomeric bearings.

Seismic calculation of this bridge, consist to the evaluation of the seismic force from the response spectra proposed in the Algerian seismic code 1988 preserved to habitation buildings only, and curiously applied to this kind of structure. Let's note at that time, in Algeria there were no seismic specifications for bridges. Therefore, an elastic design was done for reinforcing the sections of piers.

The considered bridge contained five piers, with different heights. In this study, only three piers are focused:

- Rigid pier: the smallest one (pier N°01).
- Intermediate pier: the middle one (pier N°02).
- Ductile pier: the highest one (pier N°03).

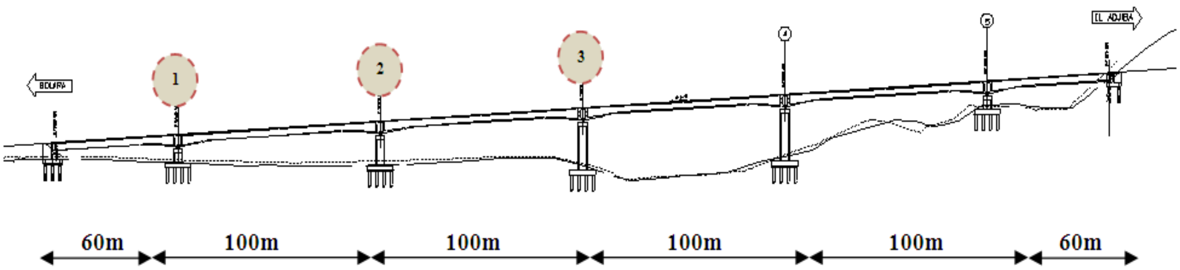


Fig. 3 Longitudinal section of the bridge (OA 203)

5.2 Materials

Materials used have the following mechanical properties:

<u>Deck</u> concrete of fc28= 35 MPa, Ec ≅ 36 000 MPa, Reinforcement : FeE400.

<u>Piers</u> concrete of fc28 = 27 MPa, Ec ≅ 33 000 MPa, Reinforcement :FeE400.

5.3 Piers description

<u>Dimensions</u> Piers are hollow but have a full concrete section at the top, to transfer gravity loads of the deck, correctly, to the rest of the element without crashing the hollow section. Details are shown in Fig. 4. Dimensions are indicated in Tab. 1.

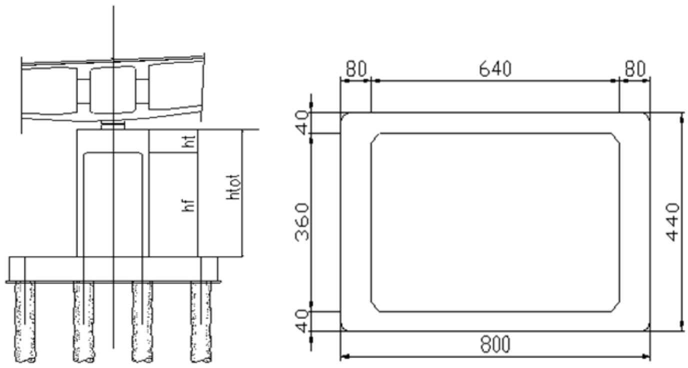


Fig. 4 High of piers and characteristics of geometry (cm)

	Chaussée droite		
N° pile	h_{tot}(m)	h_t(m)	h_f(m)
P1	5,0	2,00	3,00
P2	10,5	2,00	8,50
P3	18,5	2,00	16,50
P4	14,5	2,00	12,50
P5	3,5	3,50	0,00

Tab. 1 Geometrical characteristics of piers

<u>Reinforcement</u> Reinforcements are placed along the external and internal perimeter of hollow sections of piers in following percentages:

- Pier n°01 : (170+157) φ 25 , ρ=1,324%.
- Pier n°02 : (178+139) φ 25 , ρ=1,284%.
- Pier n°03 : (178+139+165) φ 25 , ρ=1,946%.

5.4 Design approach of the OA 203

Having the dimensions and the renforcements of the hollow section (section considered are section at the bottom of piers, where plastic hinges are supposed to appear), we can establish the capacity curves, in F-D format, and compare the capacity of sections in terms of resistance and ductility, with the seismic demand in term of force, evaluated from the response spectra of Algerian seimic code RPA-1988 for buildings, as used by the Italian firm.

Obtained curves are shown in Fig. 5 and Fig. 6 (LARBI R. 2012):

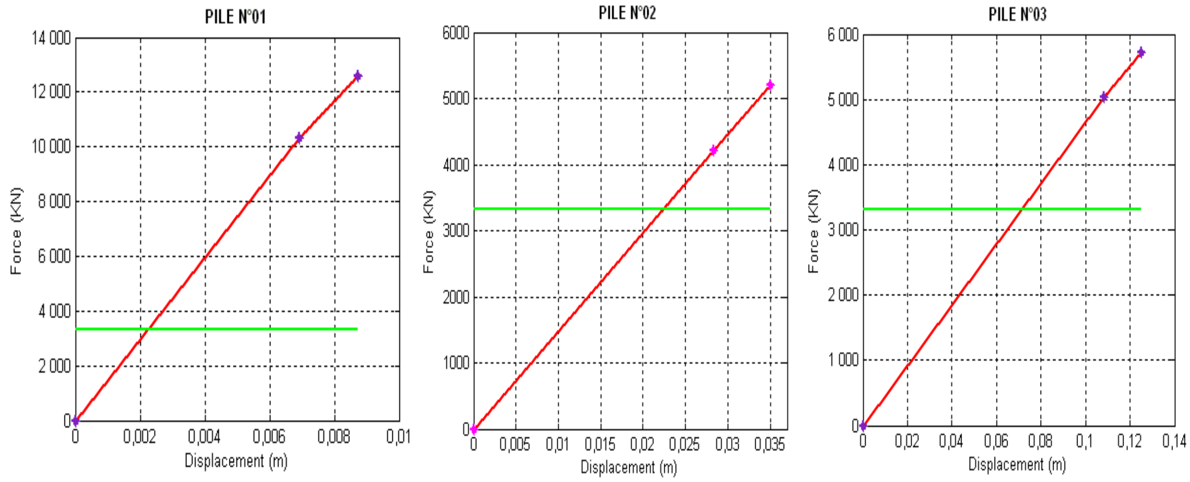


Fig. 5 Capacity-demand curves in longitudinal direction

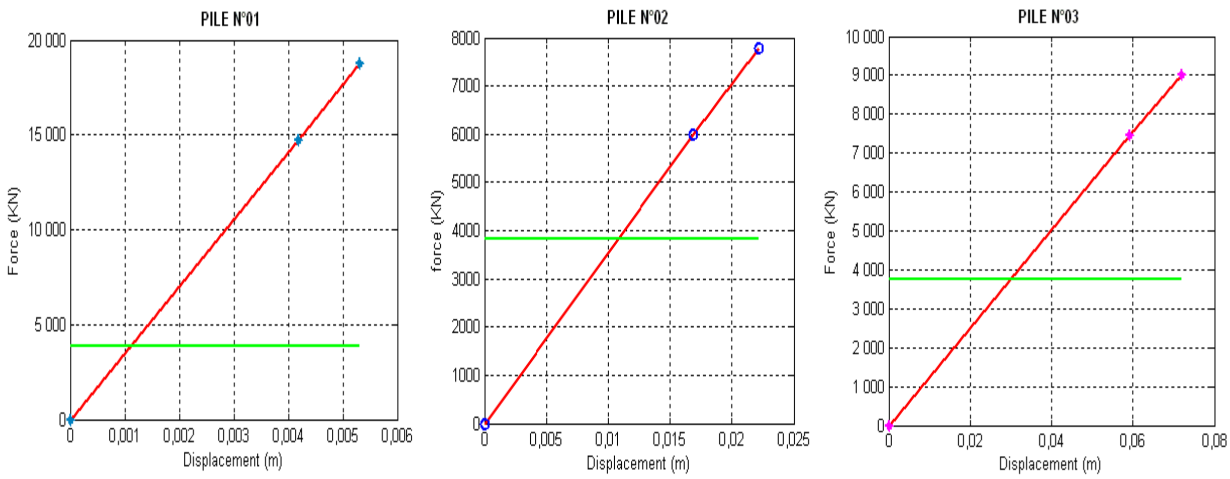


Fig. 6 Capacity-demand curves in transversal direction

Obtained results, by supperposing the curves, show clearly that **an elastic calculation have been done**, for all the piers; intersection of curves is in elastic part. It is generally the common approch for bridges with deck connected to piers by elastometric bearings.

For the three piers, and in both directions : longitudinal and transverse one, (Fu, Du) is more important than equivalent static force evaluated according to the RPA-1988.

5.4 Capacity design of the considered bridge

In the next part, we will follow the prescriptions of the new Algerian seismic specifications RPOA-2008 for a capacity design of the hollow RC sections (without changing geometric dimensions) to compare between the elastic calculation done and the capacity calculation when the new code is applied.

The whole structure is modeled with Sap Bridge (SAP 2000) to launch a modal analysis and determinate the fundamental period and all the proper modes. T=2,83 sec.

Seismic demand as prescript by RPOA 2008 Seismic force is evaluated from the design response spectra of the RPOA-2008 (indicated in paragraphe 3.2.2), taking into account the interaction of earthquake directions (30% rule) as a static equivalent force (Tab. 2) and distributed to piers according to their rigidity.

- The bridge is in zone IIa (intermediate seismicity) with an acceleration ground of A=0,25g.
- Coefficient η =1,848.
- Soil coefficient taken is S=1,1.
- Soil periods (T1=0,15s et T2=0,4s).
- Interaction between earthquake directions is taken into account (30% rule).

Designation (KN)	*Longitudinal direction*	*Transversal direction*
F_{tot} (from design response spectra)	41 590,57	65 761,89

Tab. 2 *Seismic force according to RPOA-2008*

Order of size Obtained seismic force, as prescripd by the RPOA-2008 is very important ; it represents 21,99-34,77% of the total weight of the bridge.

Results Starting with a classic calculation, elastic obtained solicitations are first reduced by the seismic reduction factor, q_0 as defined in paragraph (RPOA 2008) because of the elastomeric bearings.

Reinforcement is calculated using BAEL code for RC elements (BAEL91 v.1999), using Robobat expert, bridge sections. Reversibility of earthquake directions is taking into account.

Sections are designed for elastic solicitations (corresponding to $q=q_0$) then seismic reduction factor q_1 is evaluated.

The elastic solicitations are once again reduced by the seismic reduction factor q_1. Sections are re-designed for these reduced solicitations (corresponding to $q=q_1$). Then seismic reduction factor q_1 is evaluated.

So, seismic reduction factor $q_{(i+1)}$ is evaluated from capacity curves of RC sections at iteration (i) and elastic solicitations are so reduced, until convergence for q_i.
Obtained results are mentioned in Tab. 3

	As reinforcement section (cm^2)			As final reinforcement section (cm^2)		
Iteration $q=q_0$	PILE N°1	PILE N°2	PILE N°3	PILE N°1	PILE N°2	PILE N°3
X direction	2X488,83	2X 594,58	2X 668,37	2 162,26	2 807,86	3 392,56
y direction	2X 592,3	2X 80,35	2X 1027,91	or 440φ25	or 572φ25	or 692φ25
				(ρ=1,778%)	(ρ=2,309%)	(ρ=2,790%)
Iteration $q=q_1$						
X direction	2X381, 03	2X 491,46	2X 569,25	1728,3	2364,2	2942,0
				or 352φ25	or 482φ25	or 600φ25
y direction	2X 483,12	2X 690,16	2X 901,75	(ρ=1,421%)	(ρ =1,942%)	(ρ =2,419%)
Iteration $q=q_2$						
X direction	2X382,43	2X 475,7	2X 553,01	1725,7	2291,94	2870.06
				or 352φ25	or 468φ25	or 586φ25
y direction	2X 480,42	2X 670,27	2X 882,02	(ρ=1,419%)	(ρ=1,885%)	(ρ=2,360%)
Iteration $q=q_3$						
X direction	2X382,43	2X 465,93	2X 551,05	1725,7	2007,1	2862,06
				or 352φ25	or 410φ25	or 584φ25
y direction	2X 480,4	2X 537,62	2X 879,98	(ρ=1,419%)	(ρ=1,650%)	(ρ=2,354%)

Tab. 3 Selection of reinforcements (iterations q_i)

Results All seismic reduction factors values are reported in Tab. 4
Obtained results show that $q_3 \approx q_4$. We can stop iterations at this level of precision.

	Pier n°01		Pier n°02		Pier n°03	
Designation	Longitudinal direction	Transversal direction	Longitudinal direction	Transversal direction	Longitudinal direction	Transversal direction
Iteration q_0	1,000	1,000	1,000	1,000	1,000	1,000
Iteration q_1	1,226	1,283	1,173	1,210	1,140	1,174
Iteration q_2	1,233	1,278	1,207	1,250	1,165	1,209
Iteration q_3	1,233	1,278	1,236	1,276	1,168	1,213
Iteration q_4	1,233	1,278	1,240	1,283	**1,171**	**1,216**

Tab. 4 Iterations (check of coherence criterion)

Remark Final seismic reduction factor is close to unity; therefore, there were no specific motivations to choose an elastic calculation. This approach is long and tedious, it is recommended, for this bridge, and for this kind of bridges, to choose an elastic calculation.

Final seismic reduction factor We can define the global seismic reduction factor (for the whole structure) $q=q_4$. Global seismic reduction factor for the whole structure is taken as the smallest value of all the partial seismic reduction factor of the less ductile pier, (SETRA-SNCF 2000) in both directions: longitudinal and transverse one. Hence, the final values of seismic reduction factor coefficient are mentioned in Tab. 5

Designation	Longitudinal direction	Transversal direction
Iteration q_4	**1,171**	**1,216**

Tab. 5 Final seismic reduction factor

Reduced seismic force as prescript by RPOA 2008   Seismic force has to be reduced by the final seismic reduction factor, as prescript in RPOA-2008. (Tab. 6)

Order of size   Obtained reduced seismic force, as prescript by the RPOA-2008 is very important; it represent 18,78 - 28,59% of the total weight of the bridge.

Designation	Longitudinal direction	Transverse direction
F_{total} (design spectra)	41 590,57	65 761,89
F_{total} reduced	35 517,14	54 080,50

Tab. 6 Reduced seismic force

	Pier n°01	Pier n°02	Pier n°03		Pier n°01	Pier n°02	Pier n°03
Retained rebar	352	410	584	Retained ρ(%)	1,419	1,651	2,353
Existent rebar	328	318	482	Existent ρ (%)	1,324	1,284	1,946

Tab.7 Final reinforcement

Plastic hinges   Final reinforcement obtained (Tab. 7) has to be applied in all the plastic hinge length, at the bottom of piers which are all supposed to be ductile.
Plastic hinge lengths (Tab. 8) are calculated with Priestley formula given by Eq. (1)

	Longitudinal direction			transversal direction		
	Pier n°01	Pier n°02	Pier n°03	Pier n°01	Pier n°02	Pier n°03
Lv (m)	5	10,5	20,5	5	10,5	20,5
a st	1	1	1	1	1	1
fe (Mpa)	400	400	400	400	400	400
Longitudinal bars diameter (mm)	25	25	25	25	25	25
Lc x(mm) Priestley formula	620	1060	1860	620	1060	1860
Approximation Lc$\cong \frac{1}{10}$ Lv (mm)	500	1050	2050	500	1050	2050

Tab. 8 Plastic hinges length

5.5 Superposition capacity curves- seismic demand

Now, we can do a superposition of final capacity curves in F-D format, corresponding to the final obtained reinforcement, and the seismic demand in terms of reduced seismic force evaluated from the design response spectra of RPOA-2008. The global behavior of RC element (piers) is highlighted as shown in Fig. 7 and Fig. 8

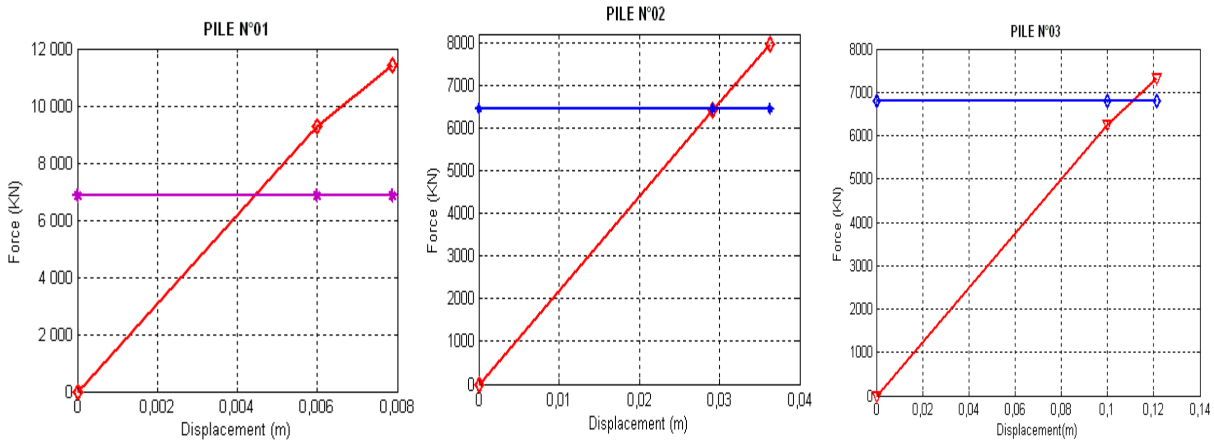


Fig .7 Capacity curves of piers in longitudinal direction

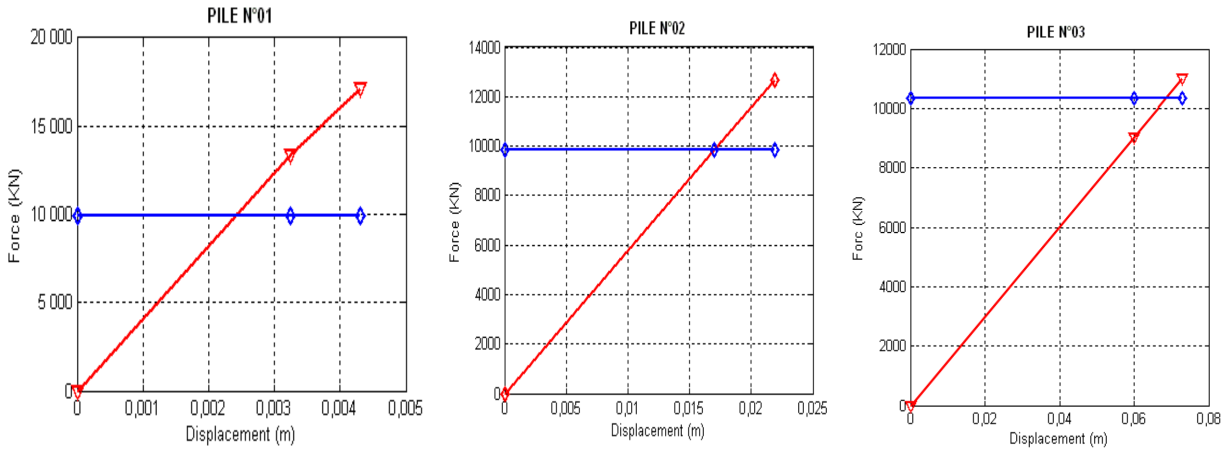


Fig .8 Capacity curves of piers in transversal direction

Discussion

- For pier N°01, this level of the earthquake intensity does not take into account the capacity of the pier in terms of ductility, but only the capacity of the considered pier in terms of resistance which is not reached yet.
- For piers N°02 and N°03, this level of the earthquake intensity considers the capacity of the pier in terms of resitance and ductility, it is just the right definition for the capacity design.
- Obtained results by supperposing curves show that intersection is situated in the post yield field, hence, piers can be called “perfoment”. In addition, the concept of ductility is clearly shown.
- Reinforcement obtained by the capacity design approach is safer than the existing one obtained using the elastic calculation. The final deduced seismic reduction factor is close to unity. There was no specific motivation to adopt the capacity design which is loguer and tedious.
- Elastic calculation is recommended for this kind of bridge when the final seismic reduction factor is close to unity.

REFERENCES

BAEL 91 version 1999, Fascicule 62, titre 1er CCTG- section 1 : Reinforcing concrete.

CAPRA Alain -VINCI main projets. « Plastic hinges theory – application to bridges».

Dazio Alessandro. « Bearing capacity of concrete structure », institut für Baustatik und Konstruktion, ETH Zürich.

LARBI R., « Contribution à l’évaluation de la vulnérabilité sismique des piles de pont en béton armé », Magister memory, (ENSTP) Kouba, Algiers, Algeria, 2012.

Paulay, T., "The Philosophy and Application of Capacity Design", Scientia Iranica, Vol.2, No.2, Summer 1995, pp. 117-143.

RPOA-2008 : Algerian seismic specifications for bridges, technical document of Ministary of Public Works, Algiers, Algeria, 2008.

SAP 2000 (2007). « Introduction to SAP2000/Bridge”, Version 14. Computers & Structures, Inc., Berkeley, California.

SETRA-SNCF (janvier 2000). « Ponts courants en zone sismique ».