DVANAESTO MEĐUNARODNO NAUČNO – STRUČNO SAVETOVANJE
OCENA STANJA, ODRŽAVANJE I SANACIJA GRAĐEVINSKIH OBJEKATA

Originalni naučni rad

A. Liolios, B. Folic, K. Liolios, D. Partov

EFFECTS OF ENVIRONMENTALLY ALTERNATING AXIAL FORCES ON RECYCLING AND SEISMIC RESPONSES OF BRIDGE RC-BENTS STRENGTHENED BY TENSION-TIES

***Abstract**: Varying and alternating axial forces, compressive or tensional ones, can be appeared in Reinforced Concrete (RC) framed structures when they are subjected to seismic excitations. This especially holds for highway overcrossings under transverse horizontal or vertical seismic excitations, and especially for two-column framed-piers (bents) of RC bridges. The influence of such alternating axial forces on the behavior of RC shear-critical framed structures, ether bare or seismically strengthened by tension-tie elements, is investigated experimentally and computationally. For this purpose, a specimen of a two-columns one-story RC frame subjected to a recycling loading simulating seismic excitation is investigated. The relevant results show that the effects of alternating axial forces, and especially of tensional ones, can reduce the shear capacity of columns and be very important for the seismic behavior of RC framed structures and bridge-bents.*

***Key words**: Reinforced Concrete framed Structures, Bridges Bents, Alternating Axial Forces, Seismic Strengthening by Tension-Ties, Multiple Earthquakes Simulation*

EFEKTI ALTERNATIVNIH AKSIJALNIH SILA U ŽIVOTNOJ SREDINI NA RECIKLAŽU I SEIZMIČKE ODGOVARAJUĆE KRIVICE MOSTOVA POJAČANE ZATEZNIM VEZAMA

***Rezime:** Promenljive i naizmenične aksijalne sile, pritisne ili zatezne, mogu se pojaviti u armiranobetonskim (RC) okvirnim konstrukcijama kada su izložene seizmičkim pobudama. Ovo posebno važi za prelaze autoputa pod poprečnim horizontalnim ili vertikalnim seizmičkim pobudama, a posebno za dvostubne uokvirene stubove AB mostova. Eksperimentalno i računski je istražen uticaj ovakvih naizmeničnih aksijalnih sila na ponašanje ramovskih AB konstrukcija sa kritičnim smicanjem, osnovnih ili seizmički ojačanih zateznim elementima. U tu svrhu istražuje se uzorak dvostubnog jednospratnog AB okvira podvrgnutog cikličnom opterećenju koje simulira seizmičku pobudu. Rezultati pokazuju da efekti naizmeničnih aksijalnih sila, a posebno zateznih, mogu da smanje smičući kapacitet stubova i da budu veoma važni za seizmičko ponašanje AB konstrukcija i mostova.*

***Ključne reči**: armiranobetonske okvirne konstrukcije, savijanja mostova, naizmenične aksijalne sile, seizmičko ojačanje zateznim vezama, simulacija više zemljotresa*

1. INTRODUCTION

As well-known [1-5], the response of reinforced concrete (RC) framed structures can appear variations in axial forces due to alternating environmental actions. For example, in multi-floor RC buildings, the axial loads of the columns are continuously changing during a seismic excitation. These variations in axial force can influence strength, stiffness, bending and shear behaviour, and deformation capacity of RC columns.

Especially in low-rise RC buildings and bridge RC-bents, that do not have additional vertical loads, the above changing axial forces do not always remain as compressive ones during a seismic excitation. So, axial forces can be alternated from compressive to tensile ones, meaning that their sign switches from negative to positive ones. The same may hold for highway overcrossings under transverse horizontal seismic excitations, and especially for two-column framed-piers (two-column bents) of RC bridges, when the vertical earthquake component is important for near-field seismic excitations [6,7].

Generally, excessive tension or tensile strain of the column may lead to shear strength degradation, and therefore vertical excitation can be one of the causes of shear failure. Moreover, tension in the columns has the potential to degradate the shear capacity, which is mainly due to the degradation of the concrete contribution to this capacity.

The above shear capacity degradation and other degradation reasons (seismic, environmental, anti-seismic design according to old codes, etc.) can result to the necessity of seismic strengthening and rehabilitation of RC structures. As well-known, various traditional methods for such seismic strengthening are available [1,2]. Among them, steel bracing systems can be used, and especially buckling resistant braces (BRB), [8]. So, the above appearance of alternating axial forces may also be the case for RC frames seismically strengthened with tie-tension (cable) elements [9-11]. Particularly for these cable elements, which are tension-only elements [9-14], their unilateral behavior must be strictly taken into account. This leads to the problem formulation as an Inequality Problem of Structural Engineering, for which a numerical solution requires the use of optimization methods [15].

In the present study, the effects of alternating axial forces, compressive or tensile ones, on the recycling behavior of a typical bridge-bent is experimentally and computationally investigated. It concerns a single-span single-story shear-critical RC specimen-frame, seismically strengthened with two diagonal tie-tension steel rods (X-bracing). This specimen-frame has dimensions and reinforcement configurations that refer to older RC substandard structures, which have been constructed in Greece and in other seismically active regions without anti-seismic design provided by current Seismic Codes. So, this RC specimen-frame appears typical shear failure problems, such as insufficient concrete confinement and low shear ratio in the columns and beam. In both experimental and computational investigation, the frame response is examined first as bare, and then as strengthened by tension-ties. The frames do not have additional vertical loads, so the changing axial force does not always remain compressive, but changes sign. This concerns the cases where the vertical component is important in near-field seismic excitations or spatial variability of ground motion has to be taken into account.

2. THE EXPERIMENTAL INVESTIGATION IN BRIEF

The realized experimental investigation is extensively analyzed in the publications [12, 13]. The research concerns the shear-critical RC frame-specimen shown in Fig. 1., which has no additional vertical loads other than the dead weight. This frame-specimen was first tested without strengthening (bare test-specimen). Subsequently, the same frame was tested after being strengthened with two diagonally mounted (X-bracing system) steel tie-tension rods of diameter 16 mm in cross-section, as shown in details in Fig. 2. The displacement-controlled loading history applied to both frames consists of five different and continuously increasing charging steps at ± 1.0, ± 3.6, ± 12.0, ± 22.5 and ± 45.5 mm and two equal charging cycles at each step, (as is further shown in Fig. 8 (d)).

The mode of failure of the control specimen (bare frame) of Fig. 1 is shown in Fig. 3. This is a flexure-shear mode of failure, not symmetric and much more pronounced at the left column, and it has been occurred for the imposed displacement of + 44.5 mm. As concerns the strengthened frame of Fig. 2 subjected to the same imposed displacement history, the cracking pattern at the end of the test is presented in Figure 4. There it is shown that critical flexure-shear failure of the left column has been prevented. Finally, the Figure 5 shows the comparative experimental load-displacement diagram for the bare and the reinforced frame, where the abrupt load reductions (strength decay) are due to effects of alternating tensional axial forces.

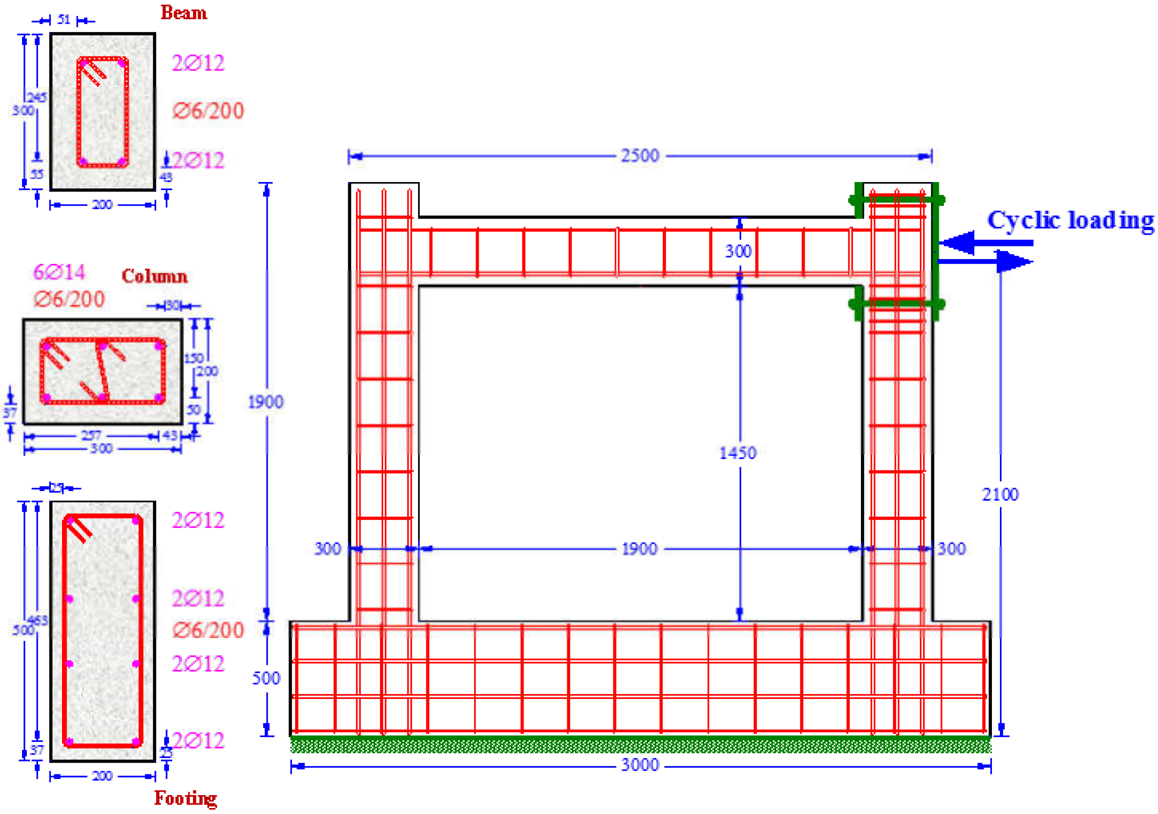


Fig. 1. Dimensions and reinforcement configurations of the bare test-specimen [12, 13].

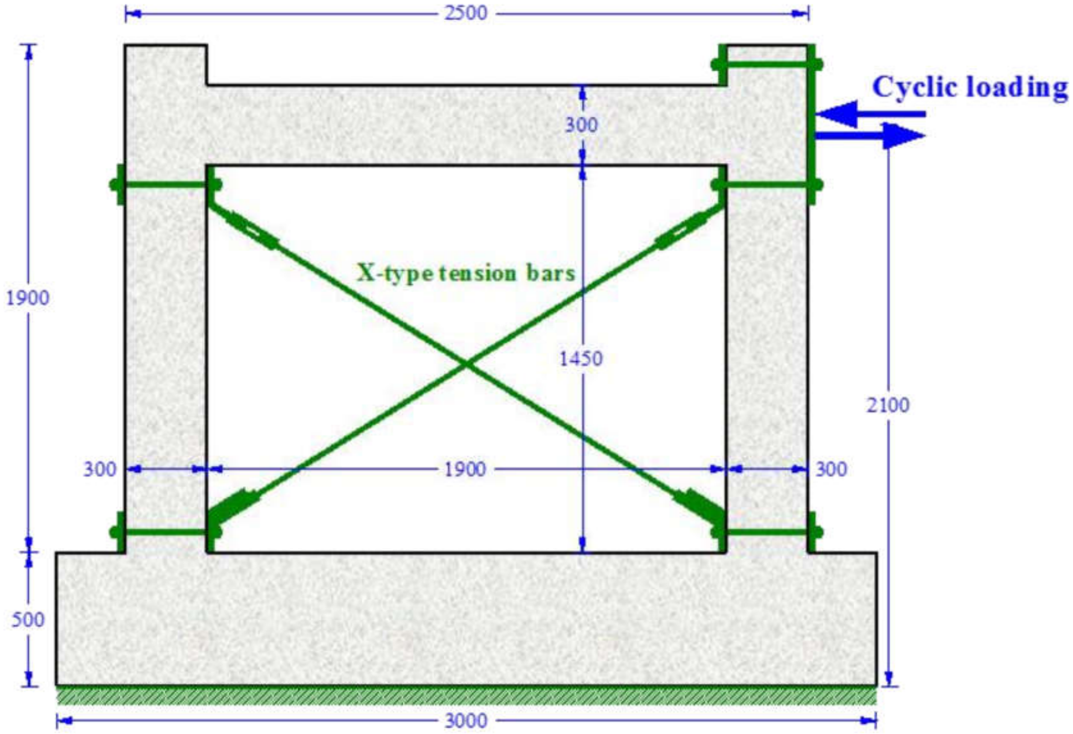


Fig. 2. Dimensions and X-bracing of the strengthened test-specimen [12, 13].

In general, the comparisons of the cyclic performance between the original bare and the X-bracing strengthened specimens indicate a significantly enhanced behavior: The load capacity in the bare frame is 120.82kN and in the strengthened frame is 178.18kN. So, an increase of 47.48% in the load capacity is recorded.

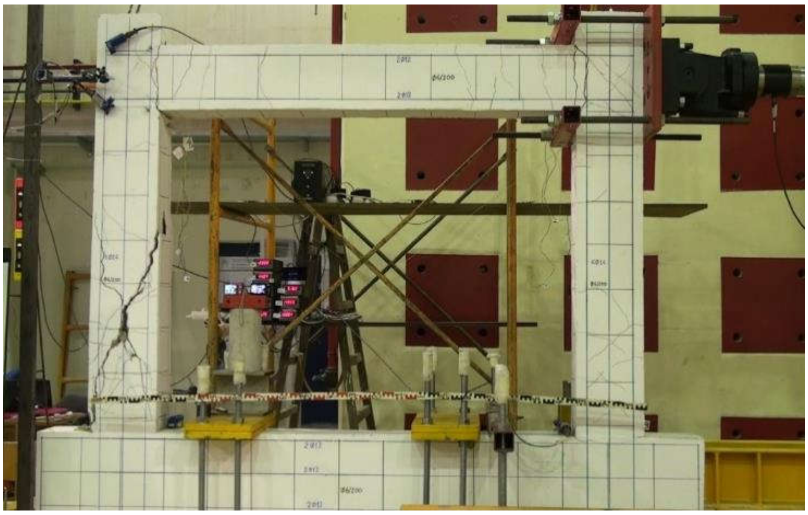


Fig. 3. Flexure-shear failure occurred at the left column of the bare test-frame [12,13].

Fig. 4. Cracking pattern of the steel X-braced RC frame at the end of the test [12,13].

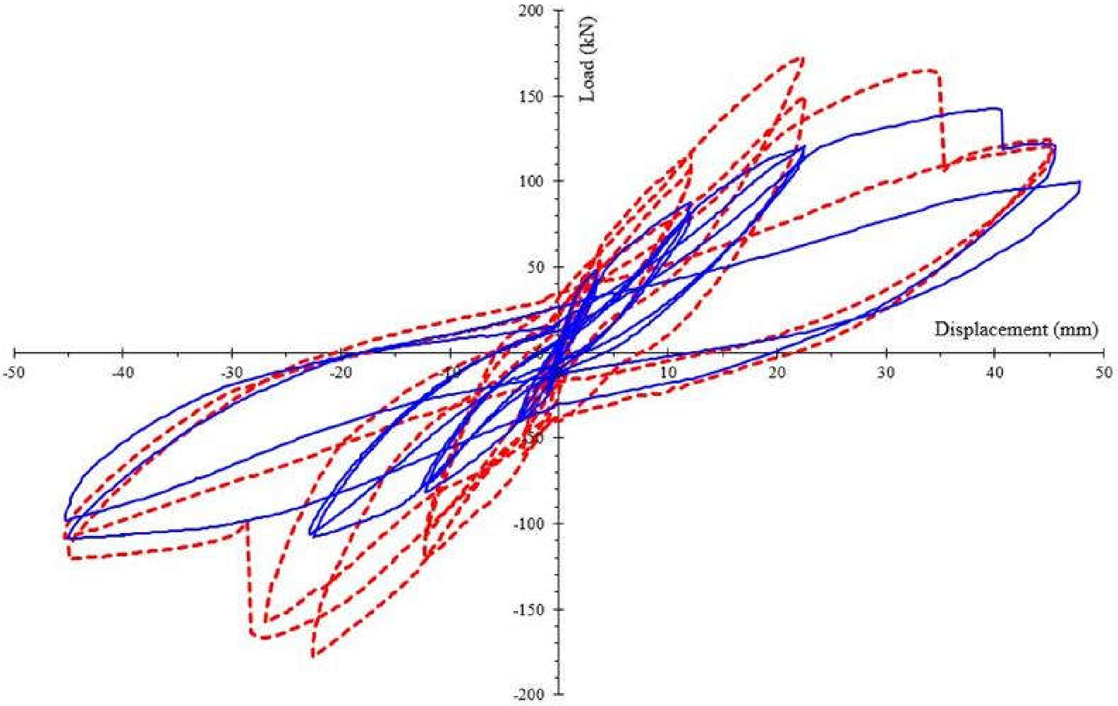


Fig. 5. Experimental hysteresis load-displacement diagramme of the ties-strengthened frame (dashed red lines) in comparison to the diagramme of the bare frame without ties (continuous blue lines).

3. THE COMPUTATIONAL SIMULATION OF THE EXPERIMENTS TAKING INTO ACCOUNT ALTERNATING AXIAL FORCES

The computational simulations of the above experiments concern in general the dymamic response of RC framed-structures strengthened by tension-tie elements. In references [11,12,14,16,17, 22] a developed methodology is presented in details, which concerns the dynamic analysis of RC structures strengthened by ties under multiple earthquakes. For this purpose, the Ruaumoko computational code [18] is used.

In order to simulate the imposed displacement-controlled loading, a pseudo - dynamic relaxation procedure [21] is applied simulating multiple earthquakes procedures [11, 12,16,17]. Thus, the imposed displacements are considered as pseudo-events of a seismic sequence. These are adjusted to have a time-duration much bigger than the fundamental eigen-period of the investigated frame. Special attention and treatment is given herewith to the effects of alternating axial force on the behavior of the shear critical structural elements, in particular with respect to the bending moment-curvature diagrams in sections, the active flexural stiffness and the cyclic shear strength, as discussed below.

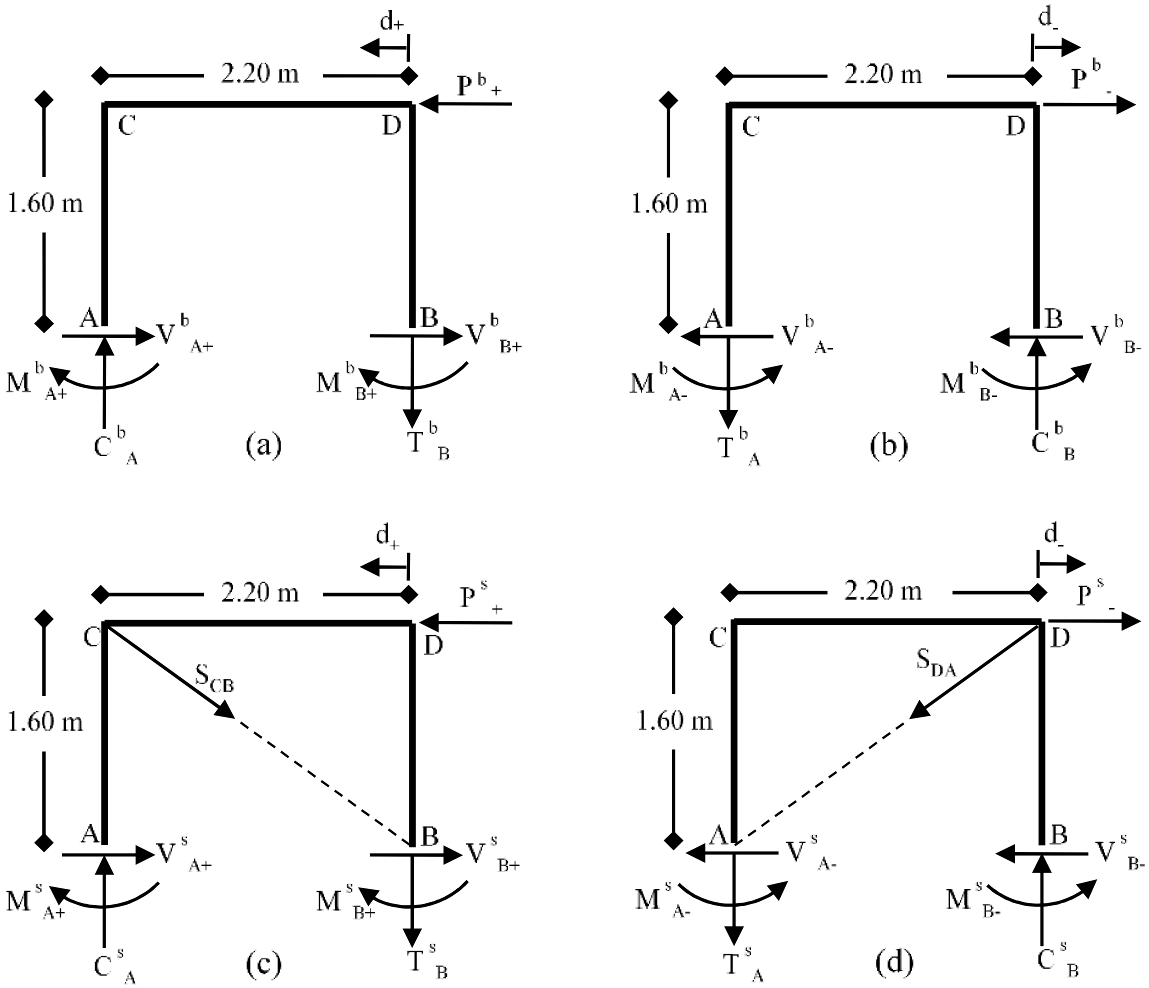


Fig. 6. The alternating behaviour of the specimen-frames for the cyclic imposed displacements: (a), (b) bare frame, (c), (d) strengthened frame.

In Figure 6 the alternating behaviour of the specimen-frames of Fig. 1 and Fig. 2 due to the cyclic imposed displacements is shown. As has been reported in sections 2, the load was imposed to the right top corner joint (see Fig. 1 and Fig. 2) denoted as node D in Fig. 6. Taking into account the real axial deformation of the beam CD, this loading on node D has as result a non-symmetric behavior. This means e.g. that the shear-reactions

V_A and V_B have no-equal value, but in any case, must satisfy the equilibrium condition $V_A + V_B = P$. So, equality for the shear-reactions V_A and V_B holds only under the theoretical linear-elastic assumption. Figure 6 shows the alternating frame behavior concerning the alternating axial forces, tensional or compressive ones, which are developed in the structural elements at each semi-cycle of imposed displacement, ($d_{+)}$ ή (d_-), for the bare and the strengthened frame. As concerns the strengthened frame, for positive imposed displacement d_+ only the descending tie CB is activated- see Fig. 6 (c). Similarly, for the reversal negative imposed displacement d_-, only the ascending tie AD is activated- see Fig. 6(d).

Obviously, for positive (from right to left) imposed displacement d_+ on node D - see Fig. 6, (a)-the right column BD is under tension axial load T_B, whereas the left column AC and the beam CD are under compression axial loads. On the contrary, for the reversal negative imposed displacement d_- on node D, the left column AC and the beam CD appear tension, whereas the right column BD appears compression - see Fig. 6. (b). Thus, in every semi-cycle of the imposed displacements, an appropriate adaptive estimate for the effective flexural stiffness EI_{eff} of the structural members has to be realized, taking into account whether they are in compressive or in tensional state. This is in agreement with the already mentioned-see also [3 - 7]- well-known fact, that variable axial force affects, due to by it induced cracking, on the one hand the effective flexural stiffness EI_{eff}. and on the other hand the available cyclic shear strength V_R.

Based on these alternating axial forces, the available cyclic shear strength V_R, according to Eurocode EC8 [19], is computed by the formula

$$V_{\mathrm{R}} = \frac{1}{\gamma_{\mathrm{el}}} \cdot \left[\frac{(h-x)\lambda_1}{2L_{\mathrm{s}}} + (1-0.05\lambda_2) \cdot \left[0.16\lambda_3 (1\text{-}0.16\lambda_4) A_{\mathrm{c}} \sqrt{f_{\mathrm{cm}}/\mathrm{CF}} + V_{\mathrm{w}} \right] \right] \tag{1}$$

For the meaning of the various symbols, see [19,20]. Especially for the parameter λ_1, it depends on the variable axial force $N(t)$, i.e. $\lambda_1 = \lambda_1(N)$, and must be emphasized that $N(t)$ is positive when it is compressive, but it is taken zero when $N(t)$ is tensional.

4. SOME REPRESENTATIVE COMPUTATIONAL RESULTS

Next, some representative results by applying the above numerical simulation for the experimental process are reported in Table 1 and in Figures 7 and 8.

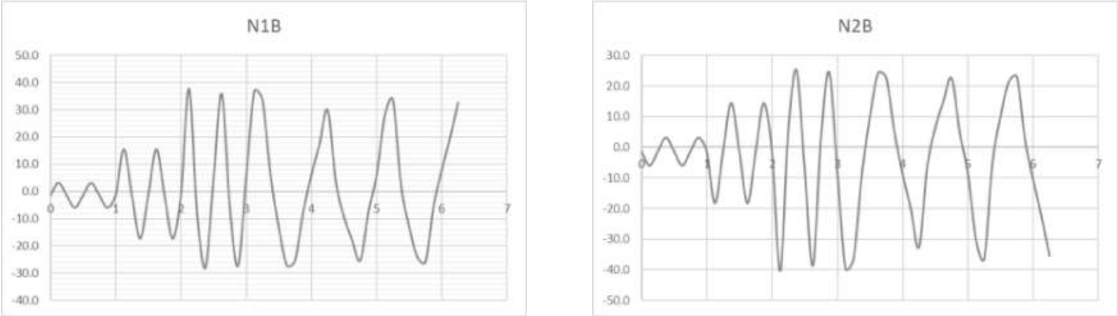
The range-values of the alternating axial forces for the bare frame, as well as for the strengthened frame, are shown in the Table 1. These axial forces are due to both loading: on the one hand due to dead weight loading and on the other hand due to imposed displacement loading. The first ones, i.e. the compressive (negative, -) axial forces due to static dead weight loading, are: -2.89 kN for the columns AC and BD, and -0.46 kN for the beam CD.

As the total values in Table 1 show, the tensional (positive, +) axial forces in the strengthened frame are slightly reduced in comparison to the corresponding values of the bare frame. On the contrary, the compressive (negative, -) axial forces in the strengthened frame are significantly increased in comparison to the corresponding values of the bare frame. So, the shear capacity for the members of the strengthened frame is increased.

The alternating axial forces developed in the columns AC and BD and in the beam CD of the bare frame are shown in Fig. 7(a), 7(b) and 7(c), respectively, in dependence of the imposed displacement history on node D shown in Fig. 7(d).

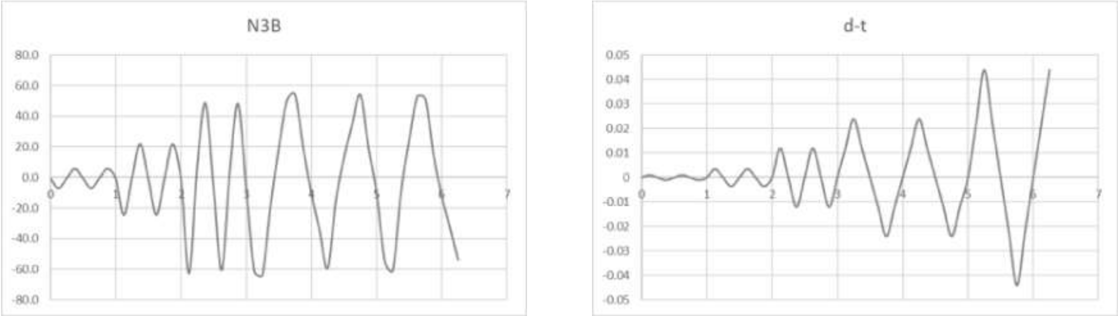
Structural Member	Bare Frame		Strengthened frame	
	max	min	max	min
Right column BD	+50.91	-35.97	+45.26	-91.17
Left column AC	+33.12	-48.11	+33.10	-109.08
Beam CD	+59.38	-68.47	+53.21	-147.48

Table 1: Extreme values [in kN] of the alternating axial forces in the structural members.



(a) Right column BD

(b) Left column AB



(c) Beam CD

(d) Displacement history on node D

Fig. 7. Alternating axial forces for the bare frame-specimen: (a) Right column, (b) Left column, (c) Beam, and (d): The history of the imposed displacement on node D.

Next, for the strengthened with ties frame-specimen it is shown in Figure 8 the computational hysteresis load-displacement diagramme (continuous blue lines) in comparison to the corresponding experimental diagramme (dashed red lines).

The comparative Figure 8 shows a good agreement between the computational results and the corresponding experimental ones. The load abrupt reductions (strength decay) due to alternating axial forces are covered (captured) very satisfactorily.

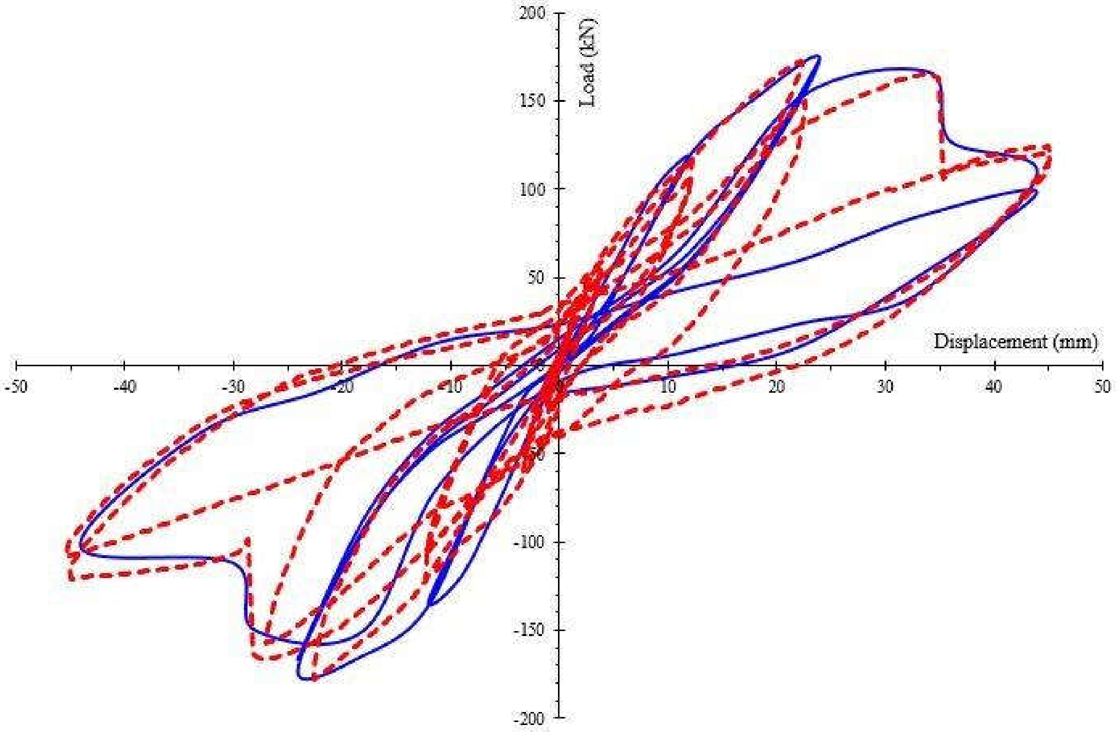


Fig. 8. Strengthened with ties frame: Comparison of the computational hysteresis load-displacement diagramme (continuous blue lines) with the corresponding experimental diagramme (dashed red lines).

4. A TYPICAL EXAMPLE CONCERVING THE APPLICABILITY OF THE PRESENTED INVESTIGATION

The results of the presented investigation can be taken into account for the practical cases of appearance of tensile axial column forces, in order to check their shear capacity. This holds especially when vertical seismic excitations are imposed to RC framed structures, see e.g. [6, 7]. Concerning a practical case reported in [7], Figures 9 and 10 show the case of a FHWA bridge with two framed- bent piers. Obviously, the above bents, i.e. two-column framed-piers, under transverse (to bridge axis) horizontal (along the bent) seismic excitations, may appear alternating axial forces on their columns.

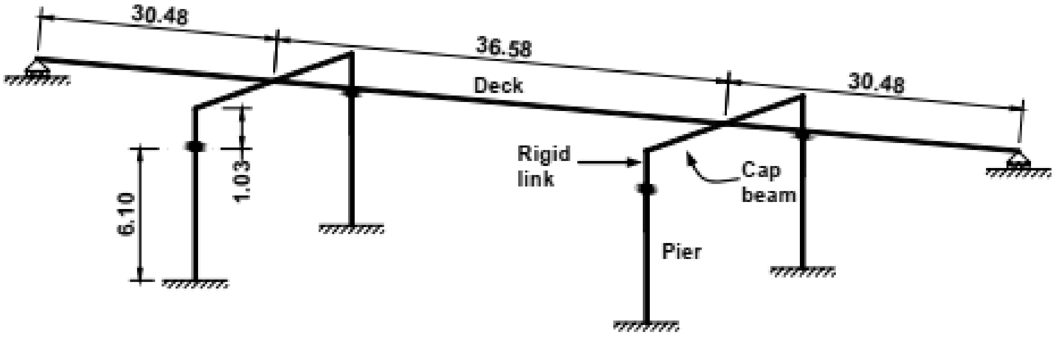


Fig. 9. The FHWA Bridge #4 considered in [7] with two-columns framed piers.

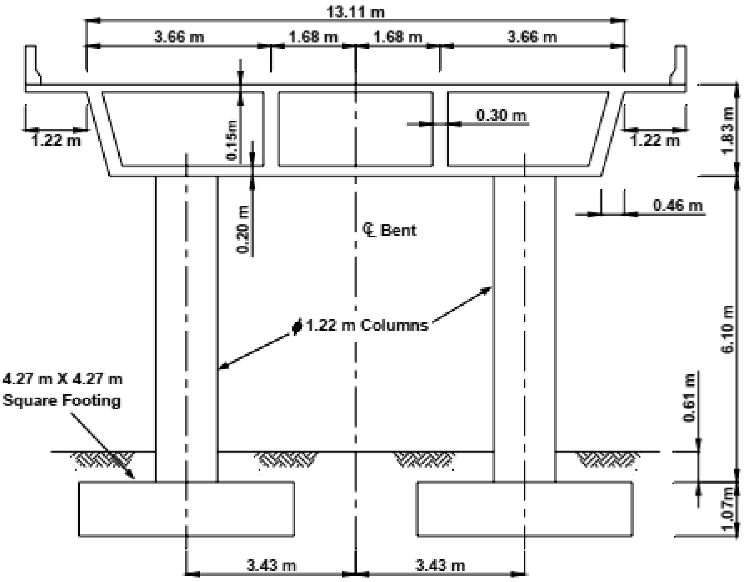


Fig. 10. The cross section of the two-columns framed piers in FHWA Bridge #4 of [7].

5. CONCLUDING REMARKS

As the experimental investigation has shown, the effects of alternating axial forces can be very important for the seismic behavior of RC framed structures and bridge-bents, either bare (as build) or strengthened by tension-ties. It has been shown that excessive tension or tensile strain of the columns may lead to a significant shear strength degradation. Therefore combined vertical and horizontal seismic excitations can be one of the causes of shear failure in columns. Moreover, tension in the columns has the potential to reduce their shear capacity, which is mainly due to the degradation of the concrete contribution to this capacity. These tensile effects can result in abrupt reductions (strength decay) for the shear resistance load capacity of columns and beams. As has been shown in the present study, the above behaviour can be controlled computationally by the herein presented numerical procedure, which provides results in a very good agreement with experimental ones.

REFERENCES

[1] Fardis, M.N. *Seismic design, assessment and retrofitting of concrete buildings: based on EN-Eurocode 8*. Springer, Berlin, 2009.

[2] Penelis, G., Penelis, Gr. *Concrete Buildings in Seismic Regions*. CRC Press, Taylor and Francis Group Ltd, London, 2nd edition, 2018.

[3] Abrams, D.P. *Influence of axial force variations on flexural behavior of reinforced concrete columns,* ACI Struct. J., 84(3), 246-254, 1987.

[4] Paulay, T. Priestley, M.J.N. *Seismic design of reinforced concrete and masonry buildings.* Wiley, New York, 1992.

[5] Priestley, M.J.N., Seible, F.C., Calvi, G.M. *Seismic Design and Retrofit of Bridges*. Wiley, 1996.

[6] Saadeghvaziri, M.A., Foutch, D.A. *Dynamic behaviour of R/C highway bridges under the combined effect of vertical and horizontal earthquake motions*. Earthquake Engineering and Structural Dynamics, Vol. 20(6), pp. 535-549, 1991

[7] Kim, S. J., Holub, C. J., & Elnashai, A. S. *Experimental investigation of the behavior of RC bridge piers subjected to horizontal and vertical earthquake motion*. Engineering Structures, 33(7), 2221-2235, 2011.

[8] Wei, X., & Bruneau, M. *Case study on applications of structural fuses in bridge bents.* Journal of Bridge Engineering, 21(7), 2016.

[9] Filiatrault A, Tremblay R. *Design of tension-only concentrically braced steel frames for seismic induced impact loading*. Eng Struct; 20(12):1087–96, 1998.

[10] Papagiannopoulos GA. *On the seismic behaviour of tension-only concentrically braced steel structures.* Soil Dyn Earthq Eng; 115: 27–35, 2018.

[11] Liolios, A.A. *A computational investigation for the seismic response of RC structures strengthened by cable elements*. In: Papadrakakis M. et al (eds), Proceedings of COMPDYN 2015, pp. 3997-4010, 2015.

[12] Liolios, A.A. *A study on the strengthening of reinforced concrete structures with emphasis on the use of tension-ties: Computational and experimental investigation*. PhD Dissertation Thesis, (in Greek), Democritus University of Thrace, Dept. of Civil Engineering, Xanthi, Greece, 2019.

[13] Liolios, A.A., Efthymiopoulos, P., Mergoupis, T., Rizavas, V. and Chalioris, C. *Reinforced concrete frames strengthened by tension-tie elements under cyclic loading: Experimental investigation*, In: Papadrakakis, M. et al.(eds.), Proceedings of COMPDYN 2017: Computational Methods in Structural Dynamics and Earthquake Engineering, paper C18197, 2017.

[14] Liolios, A.A., Chalioris, C. *Reinforced concrete frames strengthened by tention-tie elements under cyclic loading: A computational approach*. In: Papadrakakis, M., et al. (eds.) Proceedings of COMPDYN 2017: Computational Methods in Structural Dynamics and Earthquake Engineering, paper C18195, 2017.

[15] Panagiotopoulos, P. *Hemivariational Inequalities. Applications in Mechanics and Engineering*, Springer Verlag, Berlin, 1993.

[16] Hatzigeorgiou, G. & Liolios, A. *Nonlinear behaviour of RC frames under repeated strong ground motions*. Soil Dynamics and Earthquake Engineering, 30(10), 1010-1025, 2010.

[17] Liolios, A., Liolios, A.A., and Hatzigeorgiou, G. *A Numerical Approach for Estimating the Effects of Multiple Earthquakes to Seismic Response of Structures Strengthened by Cable-Elements*. Journal of Theoretical and Applied Mechanics, Vol.43, No. 3, pp. 21-32, 2013.

[18] Carr, A.J. *RUAUMOKO - Inelastic Dynamic Analysis Program*. Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, 2008.

[19] EC8, Eurocode 8 (CEN 2004). *Design of Structures for Earthquake Resistance, Part 3: Assessment and Retrofitting of Buildings*, (EC8-part3), EN 1998-3, Brussels.

[20] Makarios, T. *Modelling of characteristics of inelastic member of reinforced concrete structures in seismic nonlinear analysis*. Ch. 1, pp. 1-41, In: G. Padovani and M. Occhino (Editors): *Focus on Nonlinear Analysis Research*, Nova Publishers, New York, 2013.

[21] Papadrakakis, M. *A method for the automatic evaluation of the dynamic relaxation parameters.* Computer Methods in Applied Mechanics and Engineering, Vol. 25(1), pp. 35-48, 1981.

[22] Liolios A., Moropoulou A., Liolios K. and B. Folic. *A stochastic approach for old RC structures strengthened by ties to prevent progressive collapse under seismic sequences*. In: Radonjanin V., Vukobratovic V. and Lukic I. (Eds.), Proceedings of the 15th International Scientific Conference iNDiS 2021, (pp. 119-126), Novi Sad, Serbia, 24-26 November 2021.