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REINFORCED CONCRETE FRAMES STRENGTHENED BY TENSION-TIE ELEMENTS UNDER CYCLIC LOADING: EXPERIMENTAL INVESTIGATION

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Abstract. *The cyclic response of existing Reinforced Concrete (RC) frames upgraded using diagonal X-type steel elements as tension-ties is experimentally investigated. Test results of two single-story single-span RC frames subjected to cyclic imposed lateral deformations are presented. The dimensional and the reinforcement configurations of the examined frames are the same and represent typical RC frame structures that have been designed and constructed using old Code provisions without consideration of seismic design criteria. The columns of the tested frames have shear-critical character due to the inadequate amount of stirrups provided and their low height-to-depth ratio (short columns). The experimental program includes a bare frame and a strengthened one using a pair of two steel crossed tension-ties (X-type bracing). Emphasis is given to the unilateral behavior of the steel bracing elements that undertake only tension stresses. In a companion paper, the herein experimental results are simulated and used as a comparative basis for the calibration of a numerical approach concerning a typical example problem.*

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1 INTRODUCTION

Strengthening of seismically deficient Reinforced Concrete (RC) buildings is a current necessity in earthquake prone areas. It is known that the majority of the existing buildings in Greece were designed and built according to older Codes with inadequate seismic requirements regarding the provisions of modern Codes such as Eurocode 8. Many of these structures have insufficient transverse and longitudinal reinforcement, morphological problems such as soft story, short columns, lack of strong RC walls, weak column strong beam frames, etc., and low quality of building materials. Apparently, these RC buildings present weaknesses concerning their strength, ductility and stiffness in lateral seismic excitations. Thus, seismic upgrading in this type of structures is essential in order to avoid sudden total or local collapses, excessive damages or even loss of life from earthquakes [1-4].

Strengthening of existing RC buildings can be local and applied to specific RC members, or global in order to upgrade the structure as a whole. The response of beam-column connections in old RC frame structures is often characterized by the lack of ductility, sudden decrease of strength and low energy dissipation capacity due to the inadequate shear reinforcement provided. Examples of different local strengthening techniques have successfully been applied is typical cases of beam-column joints [5-9]. Further, global upgrading of RC structures can be achieved using various and well-known methods [10-13].

Concerning the strengthening of RC frames, tests of rehabilitated bare and infilled single-story single-bay RC frames using conventional retrofitting techniques under cyclic loading have been performed [14, 15]. Similar RC frames have also been strengthened in laboratory tests using an advanced steel bracing system that utilizes a small steel link element having an I-shaped cross-section connected to the RC frame through bracing elements [16]. The use of steel braces has proven to be an effective system in resisting lateral loads and became a popular method for the local or global strengthening of RC frames and structures. Several studies demonstrated that through the use of steel braces enhances the seismic performance of the strengthened frame improving strength, stiffness and energy dissipation capacity. A specific category in the brace strengthening technique of existing RC frames concerns the use of X-type cable elements [17-20].

In the present study, the efficiency of an easy-to-apply X-type bracing system that consists of two steel rods installed as tension-tie or cable elements, connected to the RC frame through steel brackets is experimentally investigated. Two RC frame specimens are tested under imposed lateral cyclic deformations, a bare frame and a strengthened one. The examined RC frames have dimensional and reinforcement configuration of typical earlier RC frame structures in Greece that have been designed and constructed using past Code provisions without proper seismic requirements. Such structures usually appear typical shear character problems due to the lack of adequate transverse reinforcement (stirrups) and the short shear length in the columns.

2 EXPERIMENTAL PROGRAM

2.1 Characteristics of the RC frame specimens

The experimental program consists of two single-story, one-bay and half-scale RC frame specimens subjected to lateral cyclic loading. The first RC frame is bare (Fig. 1) and the second has been strengthened using a X-type bracing system with diagonal tension-ties (Figs. 2 and 3). Both frames have the same dimensions and reinforcement configuration.

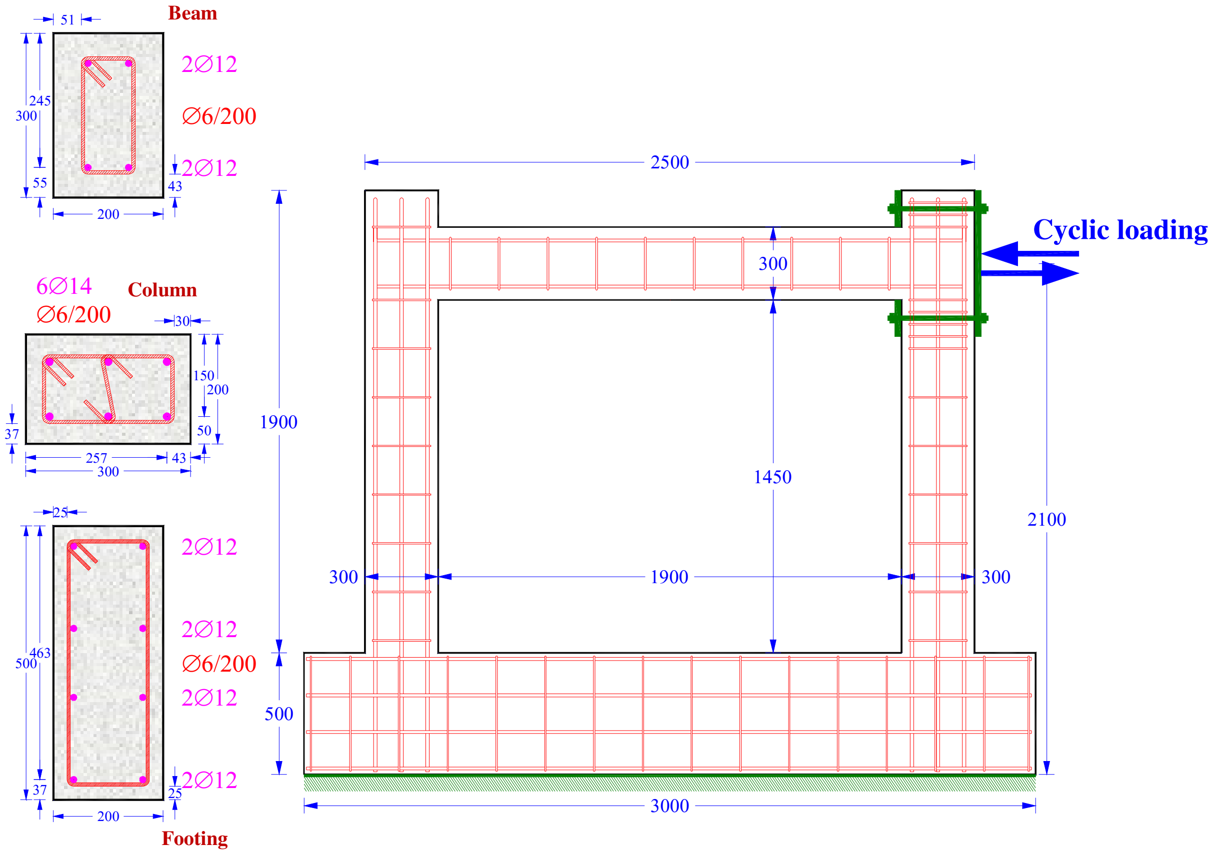

Fig.1. Dimensions and reinforcement configuration of the bare RC frame specimen

The cross-sectional dimensions of the beam and the columns of both RC frames are 200 x 300 mm. The longitudinal reinforcing bars of the beam and the columns have diameter ∅12 and ∅14 (deformed steel bars in mm), respectively. The transverse reinforcement of all structural members of the RC frames consists of mild steel closed stirrups of 6 mm diameter uniformly distributed throughout their length with 200mm spacing (∅6/200 mm). The dimensional and reinforcement configuration of the examined RC frames represents a typical RC frame of an old existing RC frame structure designed in accordance with past Code Standards in Greece.

It is noted that the shear ratio of the RC columns is low and equal to $\alpha_s = M_{Ed}/(V_{Ed}\,h) = L_s/h = 0.925/0.30 = 3.1$ (> 2.5). Also, the ratio of the column net height to the maximum sectional dimension is 1.45 / 0.30 = 4.8 (> 3). Therefore, the columns of the RC frames could be considered as shear-critical elements due to the inadequate stirrups provided [21- 23].

The first, bare RC frame is the reference specimen, whereas the second one has been strengthened using two rods of St46 structural steel with diameter of 16 mm that have placed diagonally inside the RC frame in X-type arrangement (steel X-bracing). These rods have been connected to the columns of the RC frame very close to the upper and lower joints of the frame using steel brackets. Each steel rod has been installed in order to operate only in tension as a cable element (see also Figs. 2 and 3).

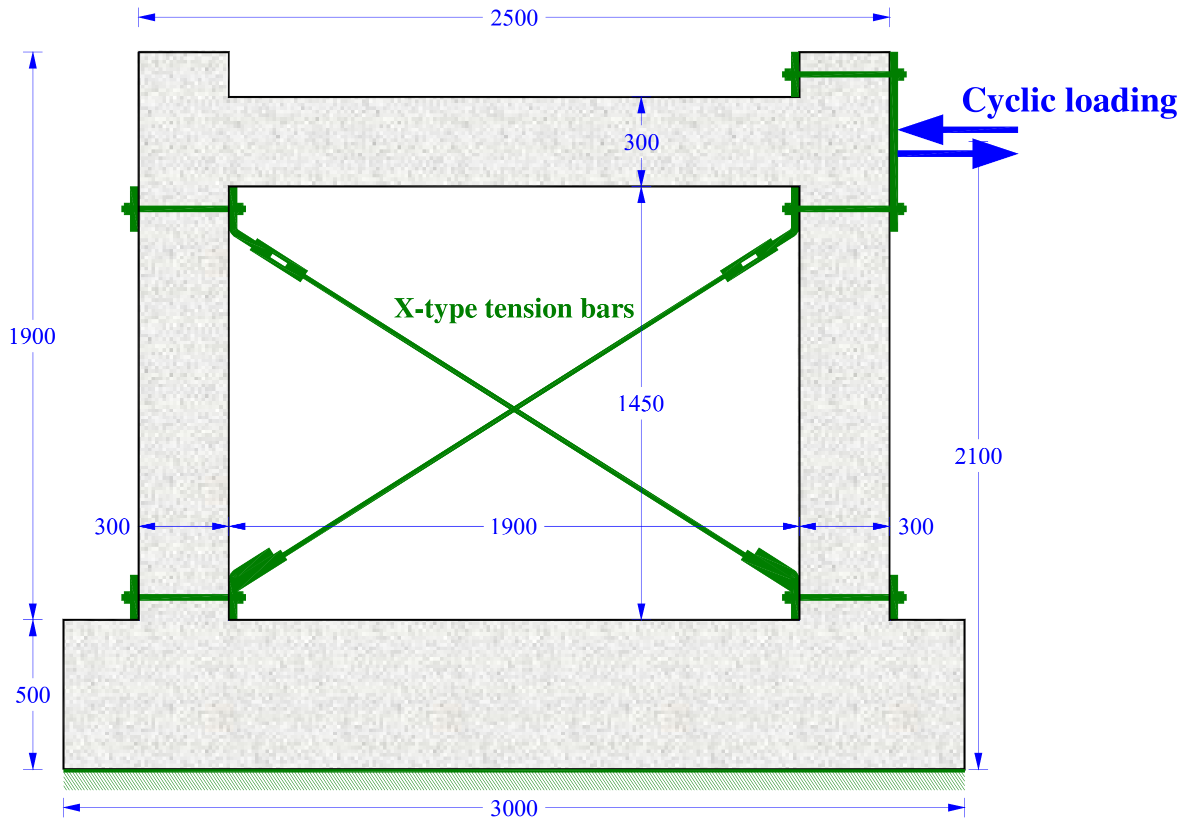

Fig.2. Dimensions and strengthening system of the steel X-braced RC frame specimen

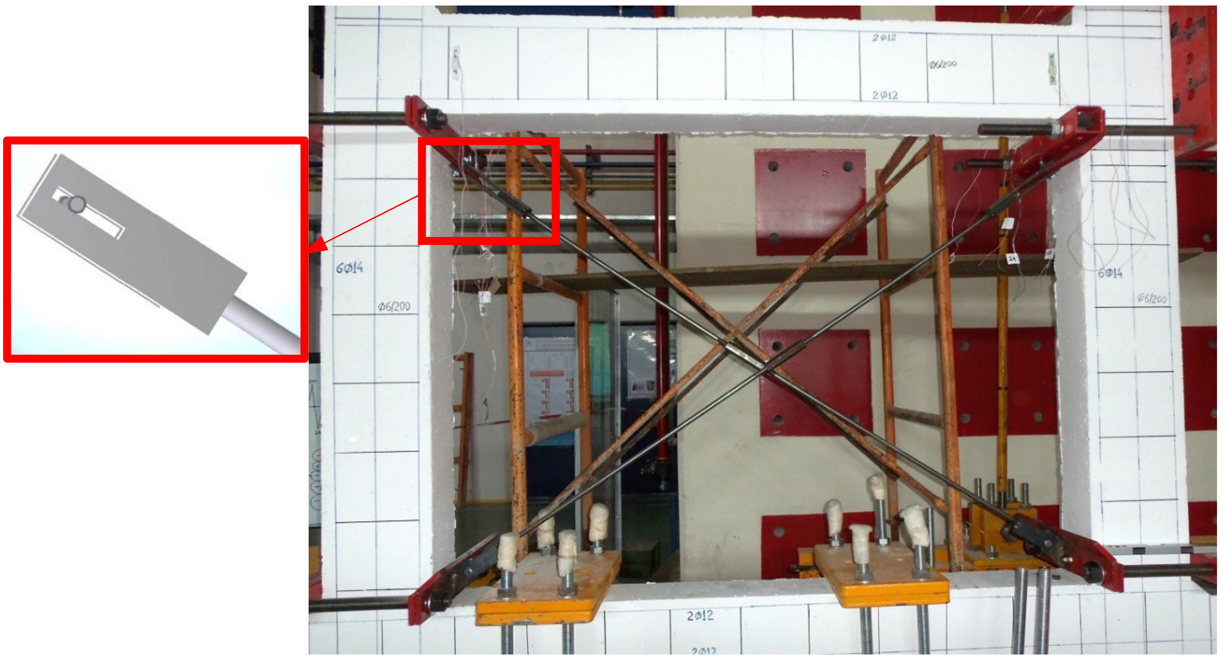

Fig.3. Details of the strengthened RC frame using X-type rods that operate only in tension as cable elements

2.2 Experimental setup

The examined RC frames have been tested under lateral cyclic in-plane displacement-control loading in the rigid RC floor - wall testing area of the Laboratory of Reinforced Concrete of Democritus University of Thrace (Fig. 4). The specimens were fixed to the rigid floor by bolts and nuts in order to prevent them from possible displacements. The load was imposed to the top corner of the RC frame using a double acting servo-hydraulic actuator fixed to the rigid wall of the laboratory with maximum capacity of 500 kN and 500 mm total stroke connected to an intermediate hydraulic control unit to ensure its smooth operation.

Displacements were measured via a number of digital strain gauges, positioned at different locations on the frame. Linear Variable Differential Transformers (LVDTs) and String Displacement Transducers (SDTs) were used (Figs. 4, 5 and 6). LVDTs were positioned on the top and bottom corners of the frame to measure the in-plane horizontal displacements of the frame and on the opposite faces to measure any possible twisting or out-of-plane deformation of the frame. SDTs were positioned on the internal diagonals of the frame to measure the diagonal displacements. SDTs were also diagonally positioned on the upper beam-column connection of the frame to measure the shear deformations of the joint area. All measuring devices were placed in appropriate locations and connected to data logger for digital recording.

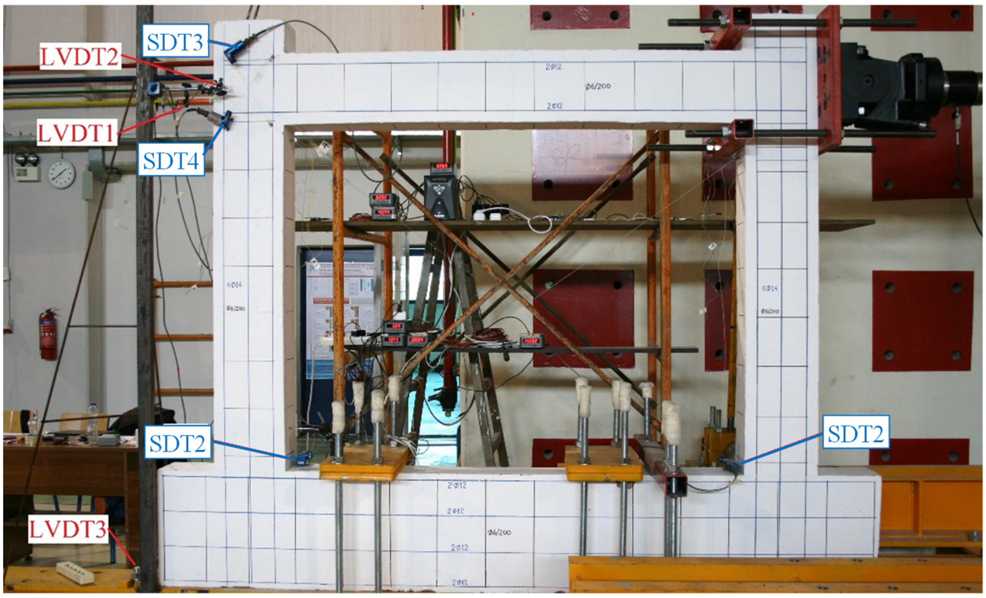

Fig.4. Test rig and instrumentation

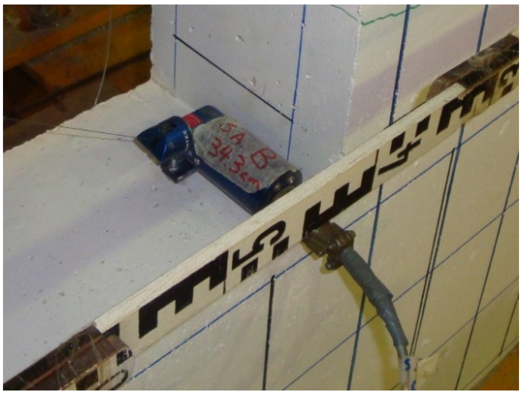

Fig. 5. SDT1

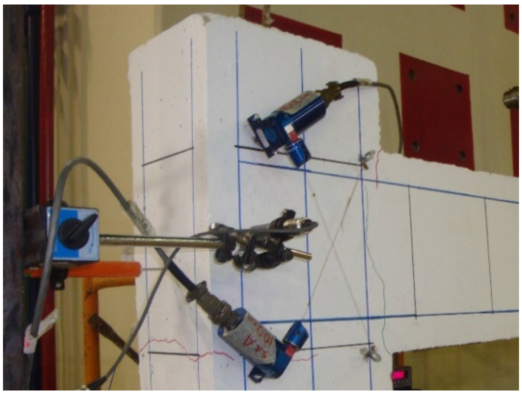

Fig.6. LVDT1, LVDT2, SDT3 and SDT4

2.3 Loading

The horizontal loading was imposed in a displacement control mode with a rate of 0.2 mm/sec. The displacement history applied to both RC frames includes five different increasing loading steps at ± 1.0, ± 3.5, ± 12.0, ± 22.5 and ± 45.5 mm with two equal imposed cycles at each step (Fig. 7).

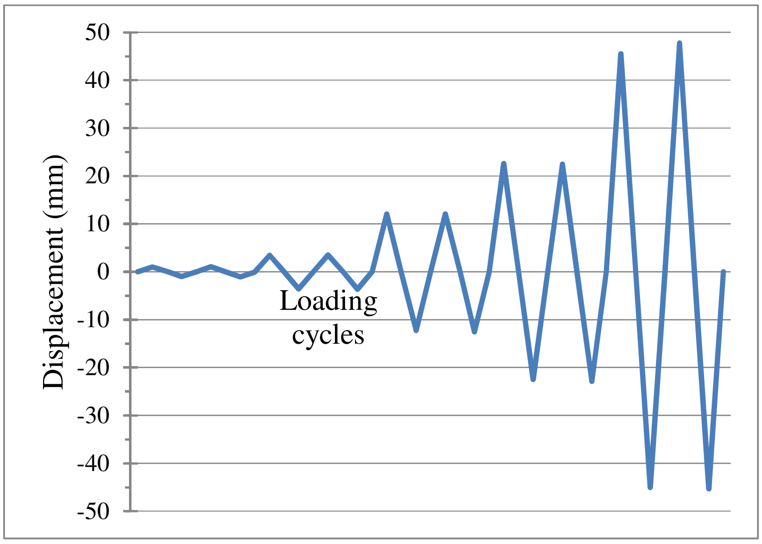

Fig.7. Imposed displacement history

3 TEST RESULTS

3.1 Bare RC frame (reference specimen)

The lateral hysteretic response of the bare RC frame specimen is presented in Figure 8 in terms of load versus horizontal displacement. The failure of the frame obtained at displacement equal to approximately 40 mm of the first positive cycle of the fifth loading step due to the sudden shear diagonal crack of the left column (Fig. 9). This failure caused a rapid and significant reduction of the load bearing capacity of the bare frame. It is obvious that this failure occurred due to the combination of the low length to depth ratio of the column that corresponds to a rather short element and the insufficient shear reinforcement, which results to low shear resistance, insufficient confinement and low ductility.

3.2 Strengthened RC frame (X-braced specimen)

The lateral hysteretic response of the steel X-braced RC frame is presented in Figure 10 in terms of load versus horizontal displacement. The first failure of the specimen obtained at displacement equal to approximately 35 mm of the first positive cycle of the fifth loading step due to the sudden rupture of the first steel diagonal rod, Right afterwards, the second failure obtained at displacement equal to approximately 30 mm of the forthcoming first negative cycle of the fifth loading step due to the sudden rupture of the second steel diagonal rod. Nevertheless, the cracking pattern of the strengthened frame presented in Figure 11 indicates that critical shear failure of the column has been prevented, whereas two distinctive flexural plastic hinges have been formed in the beam extremities while both beam-column joints of the frame remained undamaged and practically elastic.

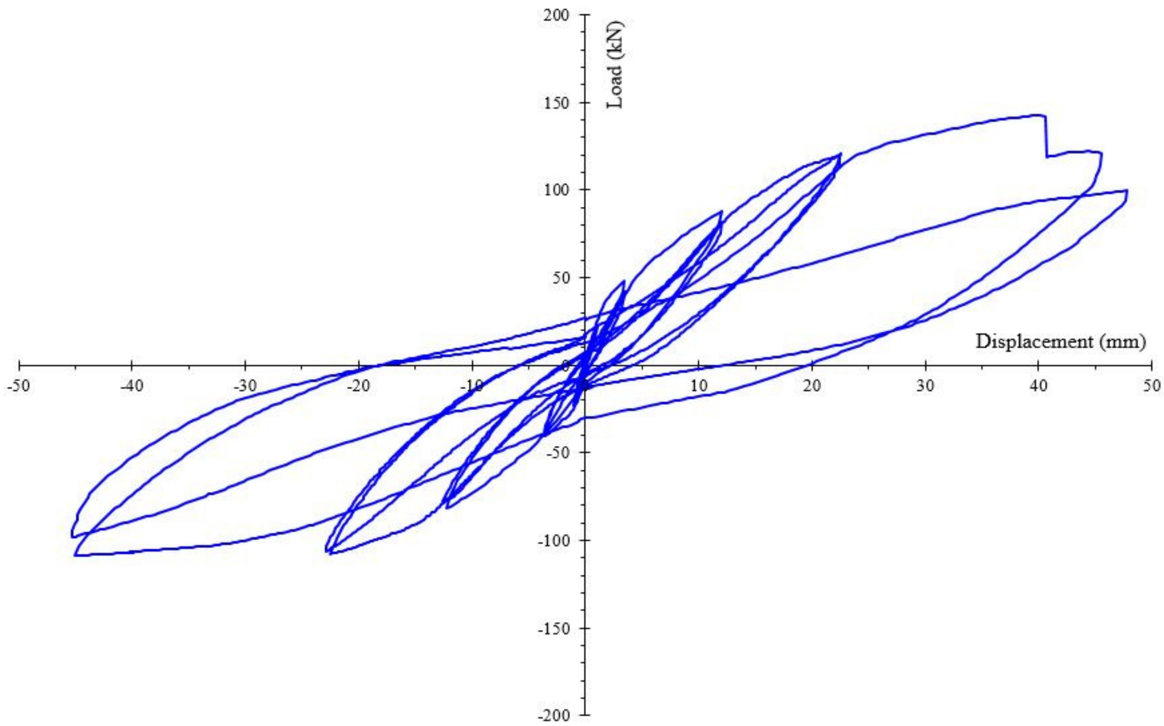

Fig.8. Load versus displacement hysteretic response for the bare RC frame specimen

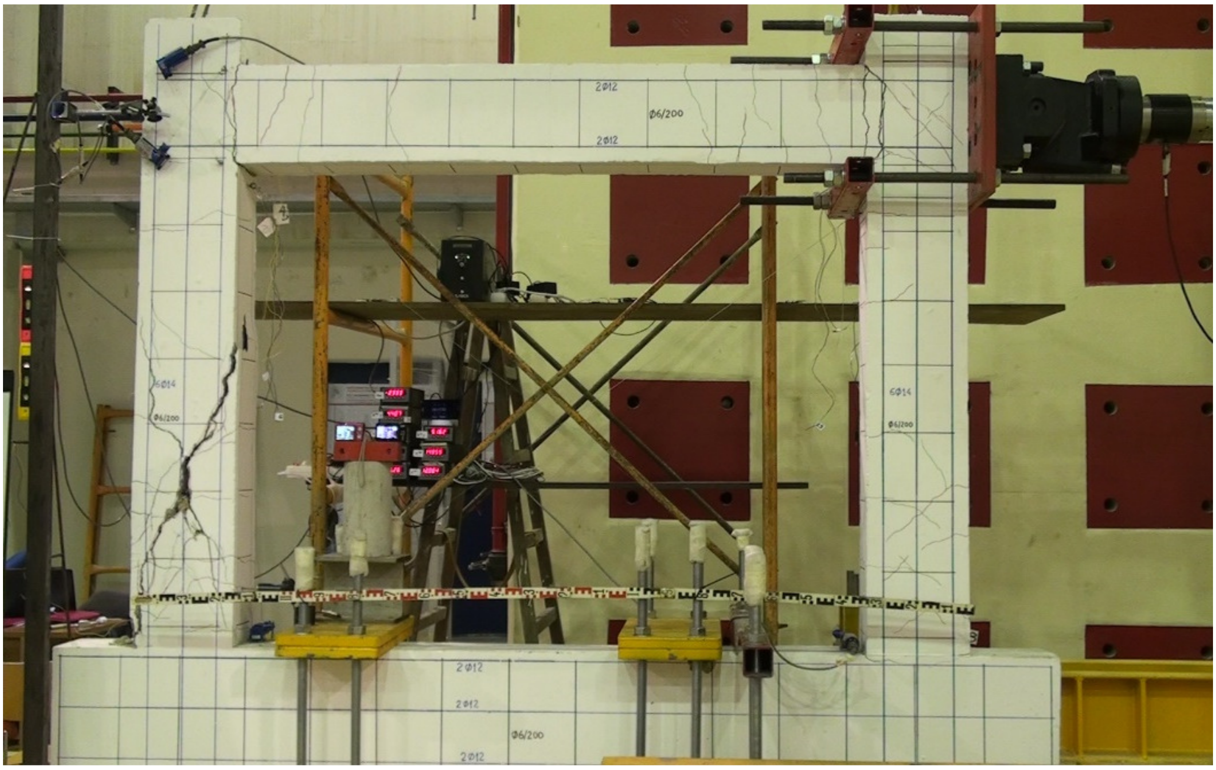

Fig.9. Shear failure occurred at the column of the bare RC frame

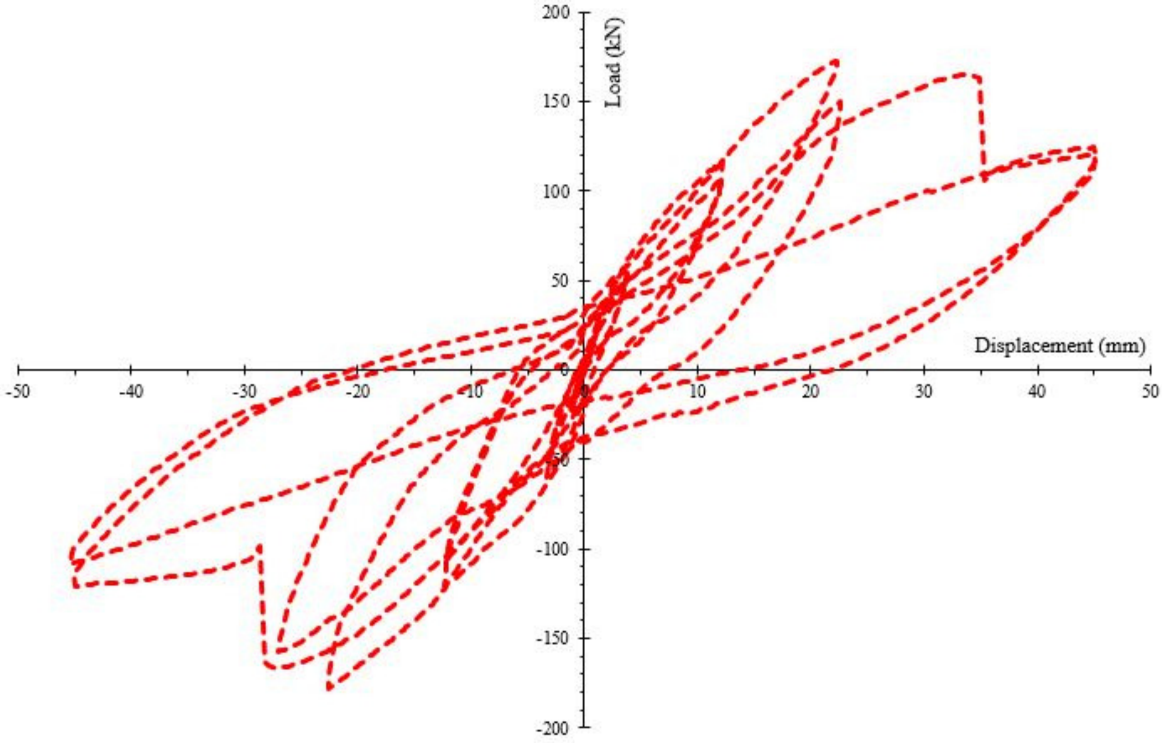

Fig.10. Load versus displacement hysteretic response for the X-braced RC frame specimen

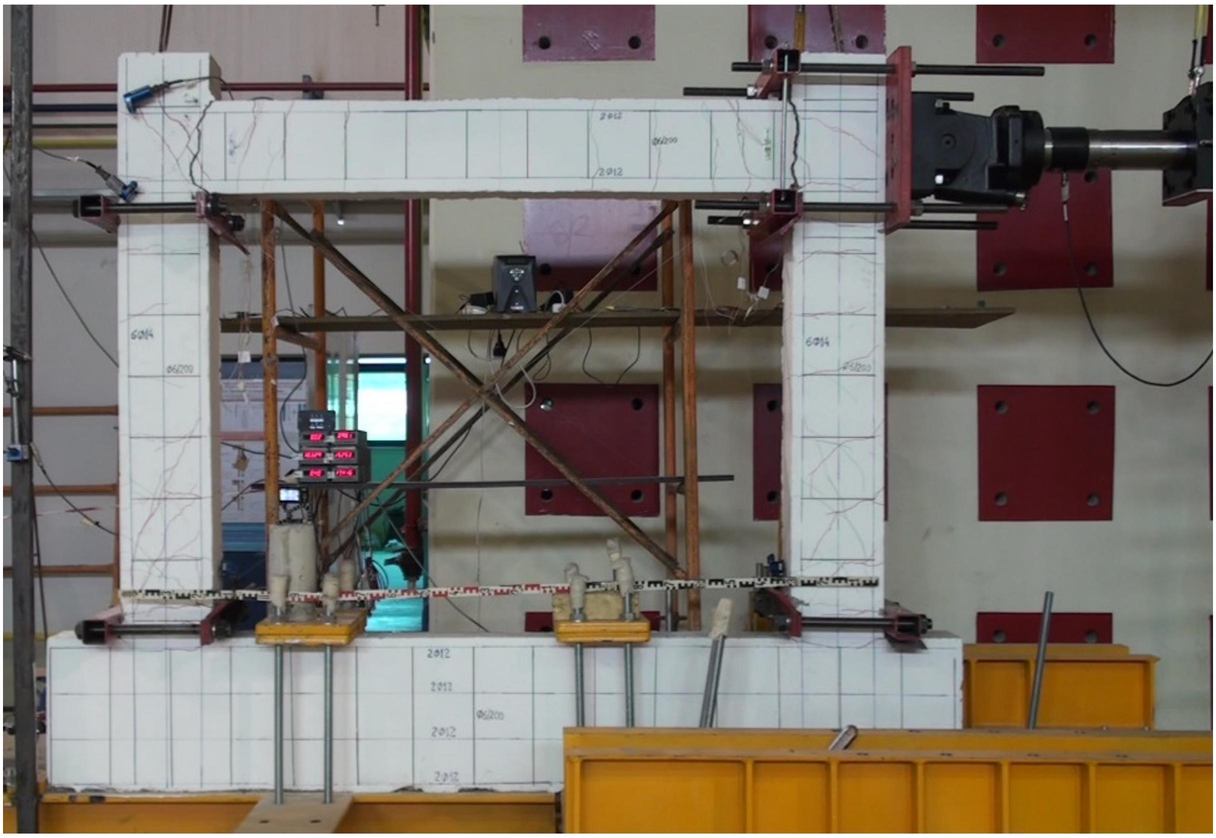

Fig.11. Cracking pattern of the steel X-braced RC frame at the end of the test (after the removal of the ruptured rods)

3.3 Increase of the frame load capacity due to steel X-bracing

Figure 12 shows the comparison of the hysteretic responses of the examined RC frames. Comparing the maximum values of load capacities it is concluded that the load capacity of the RC frame has been increased from 141 kN to 178 kN due to the application of the steel X-bracing. Thus, an increase for load capacity of about 26% has been obtained due to the applied strengthening.

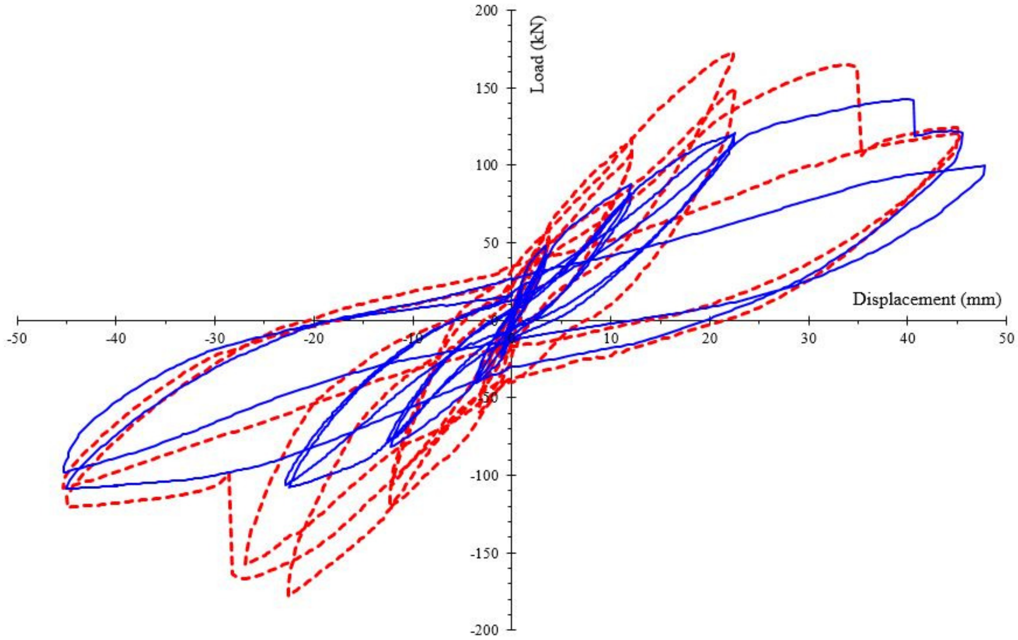

Fig.12. Comparative load versus displacement hysteretic diagram of the X-braced frame (red dashed line) and the bare one (blue continuous line)

4 CONCLUDING REMARKS

An experimental investigation concerning the lateral response of two single-story single-span RC frames under cyclic loading has been presented. Dimensions and reinforcement of the frame specimens are the same and represent typical old RC frame structures with insufficient shear reinforcement and short columns. The X-bracing system includes two steel rods placed diagonally inside the RC frame. These rods have been connected to the columns of the RC frame very close to the upper and lower joints of the frame using steel brackets. Each steel rod has been installed in order to operate only in tension as a cable element.

Results of the tests reported indicate the effectiveness of the applied internal steel X-bracing as a shear resisting system and a strengthening method against lateral loading. The strengthened frame demonstrated increased load capacity and enhanced hysteretic performance. The bare RC frame failed due to the sudden shear diagonal cracking of the column, whereas in the X-braced one the shear failure has been prevented and two distinctive flexural plastic hinges have been formed in the beam.

The herein obtained experimental results are used in a companion paper [24] for the calibration of a numerical approach concerning the hysteretic response of RC frame structures strengthened by tension-tie elements.

REFERENCES

[1] Karayannis, C.G. (2014), *Seismic design of reinforced concrete structures*. Sofia Publ., Thessaloniki (in Greek).

[2] Karabinis, A.I. and Baltzopoulou, A.D. (2006). *Correlation of damage factor and repair cost in structures damaged after the 7th-9-1999 Athens earthquake*. In: Proceedings of 15th Greek Concrete Conference, Vol B3, 294-304 (in Greek).

[3] Kappos, A.J., Lekidis, V., Panagopoulos, G., Sous, I., Theodulidis, N., Karakostas, Ch., Anastasiadis, T., Salonikios, T. and Margaris, B. (2007). *Analytical estimation of economic loss for buildings in the area struck by the 1999 Athens earthquake and comparison with statistical repair costs*. Earthquake Spectra, 23(2), 333-355.

[4] EC8, Eurocode 8 (CEN 2004). *Design of structures for earthquake resistance, Part 3: Assessment and retrofitting of buildings*, (EC8-part3), EN 1998-3, Brussels.

[5] Karayannis, C.G., Chalioris, C.E. and Sideris, K.K. (1998). *Effectiveness of RC beam-column connection repairing using epoxy resin injections*. Journal of Earthquake Engineering, 2(2), 217-240.

[6] Karayannis, C.G., Chalioris, C.E. and Sirkelis, G.M. (2008). *Local retrofit of exterior RC beam–column joints using thin RC jackets - An experimental study*. Earthquake Engineering & Structural Dynamics, 37(5), 727-746.

[7] Karayannis, C.G. and Sirkelis, G.M. (2008). *Strengthening and rehabilitation of RC beam–column joints using carbon-FRP jacketing and epoxy resin injection*. Earthquake Engineering & Structural Dynamics, 37(5), 769-790.

[8] Tsonos, A.-D.G. (2008). *Effectiveness of CFRP-jackets and RC-jackets in post-earthquake and pre-earthquake retrofitting of beam-column subassemblages*. Engineering Structures, 30(3), 777-793.

[9] Tsonos, A.-D.G. (2014). *A new method for earthquake strengthening of old R/C structures without the use of conventional reinforcement*. Structural Engineering and Mechanics, 52(2), 391-403.

[10] Penelis, G.G. and Kappos, A.J. (1997), *Earthquake-resistant concrete structures*, E&FN Spon (Chapman & Hall), London.

[11] Penelis, G. and Penelis, Greg. (2014), "*Concrete buildings in seismic regions*", CRC Press, Taylor & Francis Ltd.

[12] Dritsos, S.E., (2001). *Repair and strengthening of reinforced concrete structures* (in greek). University of Patras, Greece.

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

[14] Kakaletsis, D.J. David, K.N. and Karayannis, C.G., (2011). *Effectiveness of some conventional seismic retrofitting techniques for bare and infilled R/C frames.* Structural Engineering and Mechanics, 39 (4), 499-520.

[15] Kakaletsis, D.J. and Karayannis, C.G., (2009). *Experimental investigation of infilled reinforced concrete frames with openings.* ACI Structural Journal, 106(2), 132-141.

[16] Karalis, A. A., Georgiadi-Stefanidi, K. A., Salonikios, T. N., Stylianidis, K. C., & Mistakidis, E. S. (2011). *Experimental and numerical study of the behaviour of high dissipation metallic devices for the strengthening of existing structures*. In: M. Papadrakakis et al, (eds.), Proceedings of COMPDYN 2011, ECCOMAS: Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Corfu, Greece, 26-28 May 2011.

[17] Markogiannaki, O. and Tegos, I., (2011). *Strengthening of a multistory R/C building under lateral loading by utilizing ties.* Applied Mechanics and Materials, 82, 559-564.

[18] Massumi, A. and Absalan, M. (2013). *"Interaction between bracing system and moment resisting frame in braced RC frames".* Archives of Civil and Mechanical Engineering, 13(2), 260-268.

[19] Lee, K. S. (2015). *An experimental study on non-compression X-bracing systems using carbon fiber composite cable for seismic strengthening of RC buildings.* Polymers, 7(9), 1716-1731.

[20] Liolios, A., & Chalioris, C. (2015). *Reinforced concrete frames strengthened by cable elements under multiple earthquakes: A computational approach simulating experimental results*. In: Proceedings of 8th GRACM International Congress on Computational Mechanics, pp. 12-15, Volos, Greece.

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

[22] Salonikios, T.N., Kappos, A.J., Tegos, I.A. and Penelis, G.G. (2000), "*Cyclic load behavior of low-slenderness reinforced concrete walls: Failure modes, strength and deformation analysis, and design implications*", ACI Structural Journal, Vol. 97, No. 1, pp. 132-142.

[23] Fardis, M. N., Carvalho, E. C., Fajfar, P., and Pecker, A. (2015). *Seismic design of concrete buildings to Eurocode 8.* CRC Press, Taylor and Francis Group, New York.

[24] Liolios A. and Chalioris C. E. (2017). *Reinforced concrete frames strengthened by tension-ties 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.