THEORETICAL – EXPERIMENTAL INVESTIGATION AND OPTIMIZATION OF THE SEISMIC STRENGTHENING OF EXISTING RC BUILDINGS WITH PILOTIS VIA STEEL CONCENTRIC X-BRACES: II. EXPERIMENTS

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1. SUMMARY

The results of the experimental part of a study dealing with the use of concentric steel X-braces for the enhancement of the seismic performance of existing RC structures are presented. From the results of the tests and the intuitive configuration of the lower connections between diagonals and columns, a novel low-cost system is suggested, the application of which may be quite beneficial in reducing seismic vulnerability of old and new structures.

2. INTRODUCTION

Presented herein is the 2nd part of the project [1], and considered experiments on a i) small-scale portal frame model and its analytical prediction of response, and ii) small-scale portal frame model fitted with X-braces. The background material and the bibliography, that concerns the use of steel X-braces for the seismic rehabilitation of existing RC structures, can be found in the companion paper, which presents the analytical part of the whole study. After evaluating the baring capacity of the bare frame and calibrating it with its theoretically predicted value, three experiments were conducted with different X-brace configurations for the same RC frame. In all these, the lower column collars were not fixed to the base, but were allowed to freely slide upwards and/or rotate in the column. Hence (a) the potential damage would not propagate towards the upper floors, and (b) strains were kept low, avoiding low-cycle fatigue fracture of the braces accompanied by stable hysteretic loops. The overall behavior of all three designs appeared satisfactory, the strength as well as the ductility of the frame was improved and the inelastic response of the braces resulted in high ability to dissipate energy in a reliable manner. After complete failure of the braces, the strength of the system dropped to that of the damaged bare frame, and the failure mode of the X-braces came through weld fracture of one of the bottom collar edges. No cracking or fracture was observed on the braces or the gusset plates in spite of severe inelastic straining under large cyclic loading.

3. ANALYTICAL PREDICTION OF EXPERIMENTAL RESPONSE OF THE BF

The dimensions and properties of the bare frame (BF) are shown in Fig. 1. During the experiment, flexural failure of the columns was observed in the frame specimen as shown on Fig. 2a. The first cracks in the columns occurred at a lateral load of approximately 6 kN and the frame reached a maximum strength of 16 kN at a drift of 24 mm in the 1st cycle of loading.

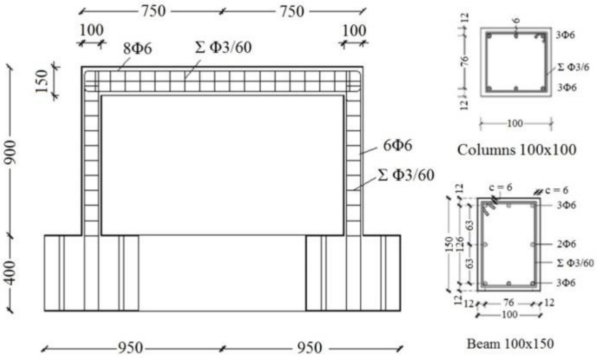
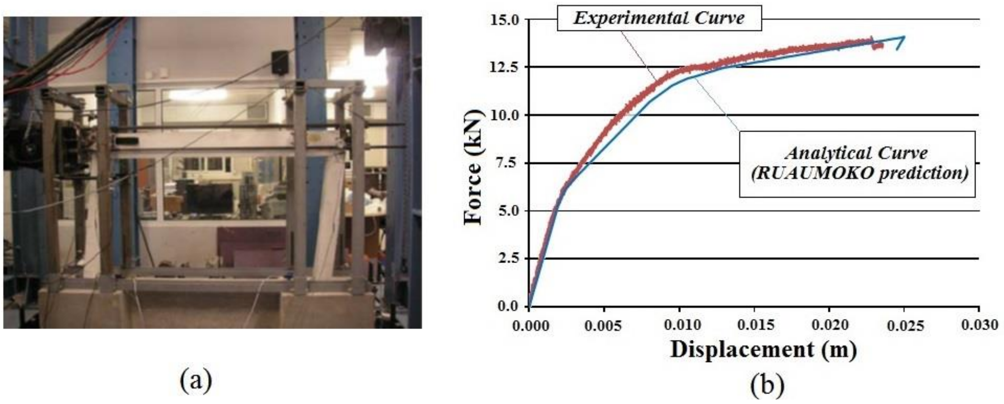


Fig. 1 Dimensions and reinforcement of the bare frame used in the experiment

For the analytical prediction of the experimental response the software RUAUMOKO [2] was utilized. A specialized concrete beam-column element, capable of accounting for nonlinear material behavior, was used for modeling of the frame members, while moment curvature and axial load-moment interaction diagrams were obtained with the software MyBiAxial [3]. The material properties obtained experimentally from concrete cylinder and steel bar specimens were also used. In Fig. 2b is presented the lateral strength of the frame vs the frame drift from the experiments and the predicted curve from the analysis with RUAUMOKO software. The computed force – displacement curve follows the experimental one in spite of some deviations within the cracking region.



(a) (b)

Fig. 2 Final state of the bare frame under static monotonic lateral loading (a), and comparison between experimental response of the portal frame and prediction for lateral monotonic loading (b)

4. EXPERIMENTAL PROGRAM

The following general design principles drove the design requirements of the X-braces:

(a) Strength of the X-Brace system not to exceed 5 times the strength (bending) of the reinforced concrete bare frame.

(b) Stiffness of the X-brace system should be of the order of the stiffness of an infill panel if the concrete frame had an infill brick panel.

(c) The gusset plate connections on the concrete frame have to be easily implemented in existing “piloti” frames.

One key aspect of the design was the connection of the four corner gusset plates on the concrete frame. Due to the difficulties of column-bottom gusset plates to be connected to the foundation (either on foundation beams or slabs) it was decided that these gusset plates will not be connected to the foundation in the horizontal direction. The connection to the column side of the corner was through a collar, e.g. through welded steel plates around the column. Again, the collar was not anchored on the column, it would rather be free to slide up the column (sliding down is prevented by the bottom plate the gusset plate is welded on and reacting against the ground).

The upper column and beam connection of the gusset plate was through a collar to the column (similar to the bottom connection the column collar is not bolted on the column) and through another collar to the beam. The collar to the beam, instead of bolts going through the beams width, was chosen for the experimental study only due to ease of implementation. In actual structures due to the floor slab beam collar cannot be implemented and bolts to secure the steel plates on the side of the beam have to be used. The column and beam collars were welded along the inner edge of the beam column corner thus the beam collar prevented the column collar from sliding down and the column collar prevented the beam collar from sliding sideways. A great advantage of these particular connections of the X-Brace to the concrete frame was that in real existing structures with pilotis the bottom and top column collars can be easily constructed since the columns at the piloti levels are free all around. This particular connectivity allows for limited rotation and/or upward motion of the bottom column collars only and only if the brace diagonals, connected to the collar, are in tension. In addition this limited flexibility provides the system with an additional apparent ductility.

Based on these general requirements, three X-Brace designs were considered. The first design called for single L20x3 brace members welded on the four gusset plates at the corners of the portal frame and on the gusset plate at the center of the portal. The welds were designed to have higher strength than the yield tension strength of the brace members. This design resulted to 2.6 times higher strength and to 3.6 times higher stiffness than the corresponding values of the bare frame as were measured from the experimental results. The second X-Brace design called for double L20x3 brace members. This design resulted in 5 times higher strength than the bare frame as was measured from the experimental results. In the first two designs the experimentally obtained strength values were relatively close to the values obtained in the preliminary design phase. The third design called for single L25X3 brace members and the resulted strength and stiffness obtained from the experiments were 1.9 and 3 times higher than the corresponding bare frame values respectively.

4.1 Material Testing

Flat rectangular material specimens from all the steel (S235 grade) X-Brace designs were cut and machined to the geometry according to E 8M-01 ASTM standard for uniaxial tension of metals. These tests were performed with a rate of 0.5 mm/min on an INSTRON electrohydraulic testing rig equipped with hydraulic grips. For the 1st and 3rd designs the steel had f_y = 325 MPa (38% higher than the nominal value used in preliminary design calculations), ε_y = 0.178% and f_u = 437 MPa. For the 2nd design the steel had f_y = 350 MPa (48% higher than the nominal), ε_y = 0.17% and f_u = 478 MPa.

4.2 Expected behavior of RC portal frame fitted with concentric steel X-braces

The expected behavior of the concrete frame with the X-braces, for all three designs under lateral deformations consists of the stages described below. When the loading is reversed, the same system goes through the same stages; however, the strength contributed by each component of the system at every stage will not be the same as in the 1st loading cycle, with the values attained expected lower.

(1) *Elastic behavior*: Both diagonals (tension and compression) are within the elastic range. The RC frame contributes strength to the system without having reaches is (bare frame) capacity.

(2) *1st Inelastic Buckling*: One of the diagonal elements under compression buckles after having reached its critical buckling load. The drop of the compressive load following buckling is being picked up by the concrete frame and by the diagonal in tension, which increases its load until it yields. The concrete frame still contributes strength to the system without having reached its capacity. The X-brace reaches its maximum capacity, by inelastic buckling of one of the diagonals and yielding of the other.

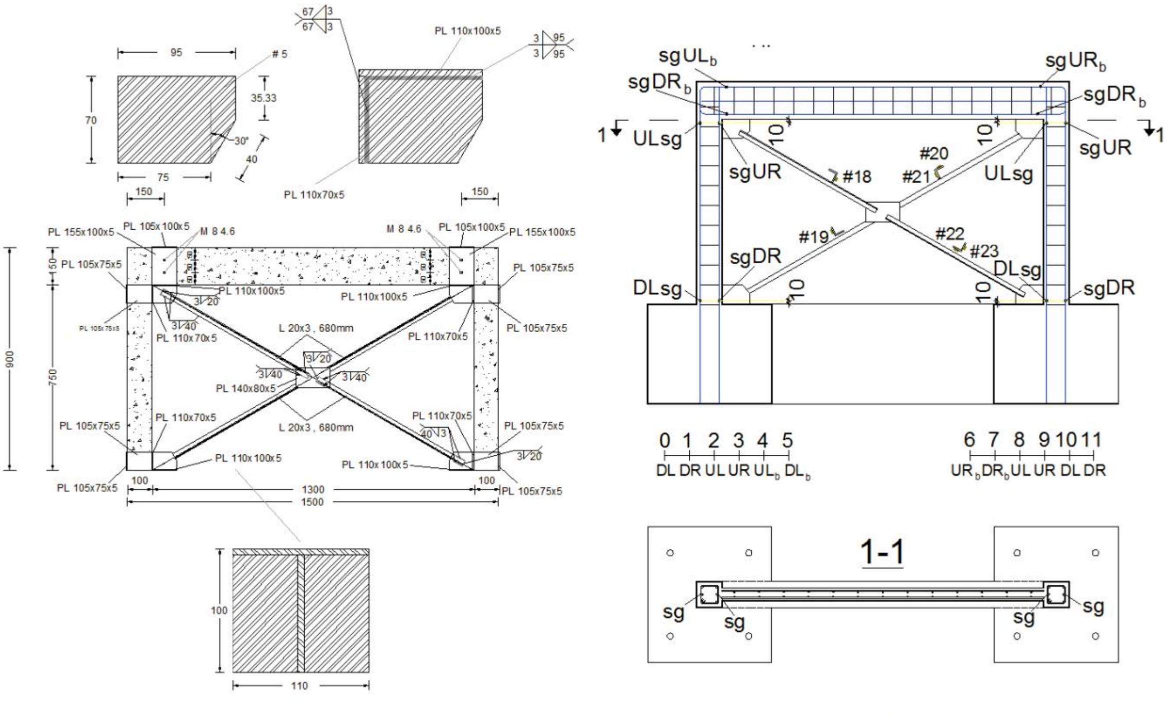
(3) *Plastic Hinging on Concrete Frame*: One of the diagonal elements has experienced buckling and the opposite tension diagonal has yielded, while the RC frame has reached its maximum capacity.

5. EXPERIMENTAL RESULTS

Due to space limitations, only the description and the results of the 1st experiment will be presented in this section.

The 1st X-brace specimen design with details of implementation within the concrete portal frame is shown in Fig. 3a, while the corresponding instrumentation – strain gauge layout is depicted in Fig. 3b.

The cyclic loading protocol used in this test is presented in Fig. 4, in terms of lateral displacement imposed at the beam level by the actuator. The “Frame 1” LVDT was located at the middle of the beam (capacity ±22 mm) and its recordings were free of some limited slippage/gap, which occurred between the actuator’s head and the specimen. The recordings of this LVDT were used in the presentation of the experimental results except in the cases were displacements larger than 22 mm were utilized. A total of 32 cycles of loading were imposed on the concrete frame before the stop of the experiment due to severe damage of the concrete and the X-brace system.



(a) (b)

Fig. 3 View of the 1st X-brace specimen (a) and instrumentation of the experiment (b)

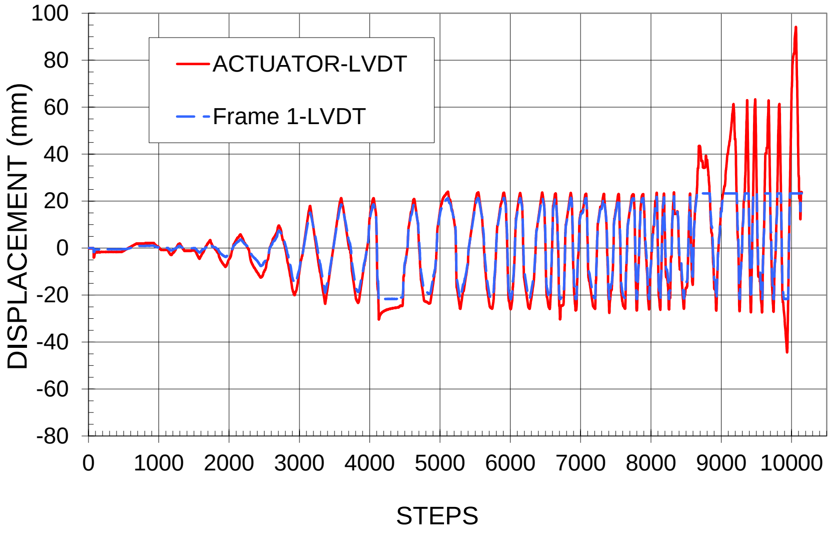


Fig. 4 Lateral displacement protocol imposed at the beam level

Figure 5 presents the force vs Frame 1 displacement for the initial 19 cycles of loading (blue line). The red line is the experimental response of the bare frames under half cycle of load (from a separate experiment with different specimen) while the green line represents the backbone curve of the concrete frame with the X-brace. The maximum strength contributed by the RC frame was 14 kN, while the one contributed by the X-brace was 36 kN. This value is close to the corresponding one from the preliminary design calculations (40kN).

During the first 3 cycles no deformation (in or out of plane) of the members in the brace was visible. In the 4th cycle (for a displacement of ±4mm) the UL brace experienced out of plane elastic buckling. During the 5th cycle this member experienced substantial inelastic buckling (at a load of-50 kN), with a plastic hinge forming in the middle of its span.

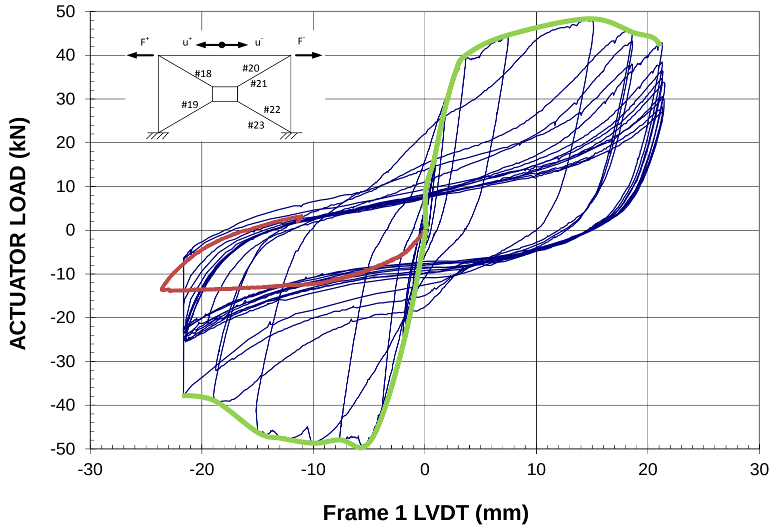
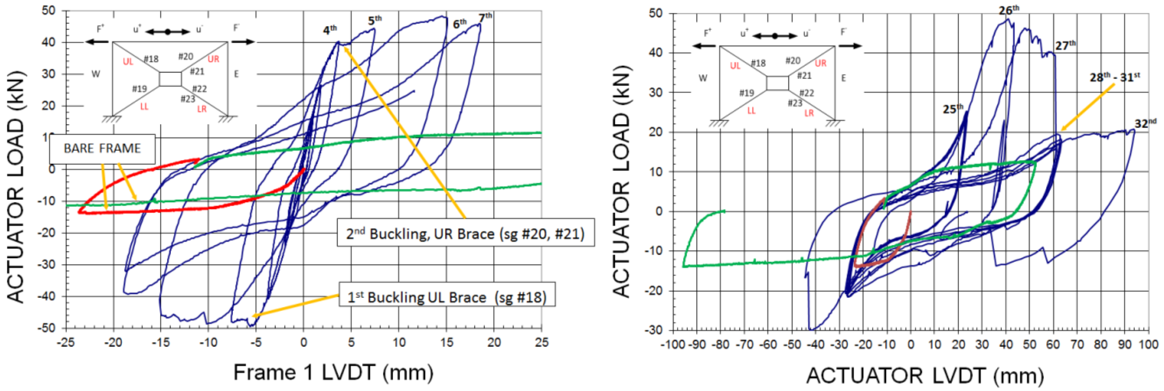


Fig. 5 Experimental lateral force vs horizontal displacement for the initial 19 cycles of loading

With the reversal of loading the opposite diagonal was in compression and before the completion of the 5th cycle (+4 mm, +40 kN) the UR member experienced inelastic buckling earlier than the previous cycle, accompanied with severely pronounced pinching behavior. This was not only due to inelastic buckling and the accumulation of residual displacements upon subsequent compression cycles, but also because when diagonals are in tension the lower collars tend to rotate. In the 6th cycle, the UL brace buckled once more with reduced stiffness (-50 kN), while at approximately -11 mm there were horizontal cracks observed at both the upper side of both columns at the interface with the beam. At the end of this cycle a small vertical crack on the welding of the lower collar at the left column was observed, which weakened the tension stiffness of the diagonal (LL to UR corners) resulting in strength drop at the next two cycles. From that moment on and up to the 24th cycle damage accumulated in the two collars at the bases of the columns (crack on welds), but the braces still contributed some strength for displacements higher than 15 mm. After the 25th cycle and in spite of severe damage of the whole system, it appeared to have reserved strength. This behavior was because the tension diagonal could still carry load because the LR column collar had not failed (through weld rupture) yet and the system strength came from yielding in tension of one diagonal and the remaining strength of the bare frame which had developed plastic hinges due to bending at the top and bottom of the two columns. All the above phenomena and the evolution of the system's behavior can be seen in Fig. 6.



(a)

(b)

Fig. 6 Hysteretic experimental curves for the initial 7 cycles (a) and for the 25th to the last (32nd) cycle of loading (b), where the evolution of the system's overall performance is depicted

The main observation of this experiment (similar behavior was also observed in the other two experiments) was the large number of cycles sustained by the bracing system at large displacement amplitudes with minor strength reduction (see Fig. 6, first 27 cycles), in spite the extensive plastic deformations of the braces. This response is rather unusual for braces anchored at their edges. In this study the two lower column collars, where the diagonals were connected, were left free to slide vertically along the length of the columns when in tension, a configuration which helped maintain low levels of strain in the diagonals and resulted in extending their low-cycle fatigue life. Such a beneficial effect is sought after in seismic rehabilitation applications, where high ductility is desired.

6. CONCLUSIONS

The most important conclusions drawn from this experimental work are the following:

(a) Steel concentric X-braces constitute a quite effective, low-cost and easy to construct system for the seismic rehabilitation of RC frames.

(b) The inelastic response of the braces resulted in high ability to dissipate energy in a reliable manner. The failure mode of the bracing system came through weld fracture of one of the bottom column collars (connections with the X-braces), while no cracking or fracture was observed on the brace members or on the gusset plates, in spite of the strong inelastic straining experienced under large ductility cyclic loading.

(c) The brace anchoring system adopted (freely sliding along the length of the columns and able also to rotate) appeared to have perform adequately in all cases engaging the tension and compression diagonals of the brace and provide the frame with the observed increased strength and ductility (energy dissipation) capacities.

7. ACKNOWLEDGEMENTS

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ΠΕΡΙΛΗΨΗ

Το μέρος του προγράμματος που παρουσιάζεται εδώ, αφορά πειράματα που πραγματοποιήθηκαν 1) σε μοντέλο απλού (γυμνού) πλαισίου μικρής κλίμακας και στην αναλυτική πρόβλεψη της απόκρισης του, και 2) σε μοντέλο πλαισίου μικρής κλίμακας με Χ-συνδέσμους. Μετά τον υπολογισμό της φέρουσας ικανότητας του απλού πλαισίου και την βαθμονόμηση της σύμφωνα με τη θεωρητικά υπολογισθείσα τιμή της, πραγματοποιήθηκαν τρία πειράματα με διαφορετικές διατάξεις Χ-συνδέσμων στο ίδιο πλαίσιο από ΟΣ. Σε όλα, τα κολάρα περί την βάση των στύλων δεν κατασκευάστηκαν πακτωμένα, αλλά ελεύθερα να ολισθαίνουν καθ’ ύψος και να στραφούν, με αποτέλεσμα (α) αποφυγή διάδοσης της βλάβης σε υπερκείμενους ορόφους και (β) χαμηλές τιμές ανηγμένων παραμορφώσεων αποφεύγοντας έτσι κόπωση χαμηλών κύκλων και επιτυγχάνοντας σταθερούς υστερητικούς βρόγχους. Η συνολική απόκριση και των τριών διατάξεων ήταν ικανοποιητική, βελτιώθηκε η αντοχή και η ολκιμότητα του πλαισίου και η ανελαστική απόκριση των Χ-συνδέσμων οδήγησε σε μεγάλη δυνατότητα απορρόφησης ενέργειας. Δεν παρατηρήθηκαν ρηγματώσεις στις συνδέσεις και τα κομβοελάσματα, παρόλες τις ισχυρές ανελαστικές παραμορφώσεις υπό μεγάλες ανακυκλιζόμενες φορτίσεις.