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

Dimitrios S. Sophianopoulos[1a], Konstantinos S. Papachristou[2b], Theocharis Papatheocharis[3a], Panos Tsopelas[4a], Phillip Perdikaris[5a]

[a] Department of Civil Engineering, University of Thessaly, Volos, Greece

[b] WTM Engineers München GmbH, Munich, Germany

[1] Associate Professor, email: dimsof@civ.uth.gr

[2] Civil Engineer Ph.D., email: k.papachristou@wtm-m.de

[3] Civil Engineer, Ph.D. Candidate, email: th_papath@yahoo.gr

[4] Professor, email: tsopelas@civ.uth.gr

[5] Professor, email: filperd@civ.uth.gr

1. SUMMARY

The objectives of this study were to evaluate through theoretical and parametric analyses the effect and viability of using steel concentric X-braces in removing the seismic vulnerability of “pilotis” type reinforced concrete frames, mainly built before 1985, which make up a large part of the RC building stock in Greece. In doing so the study was divided in two parts: (1) a parametric study to establish the ranges of stiffness and strength the pilotis X-braces contribute to the overall frame response, and (2) an experimental investigation. The first part is presented in the present work, while the second part is presented in a companion paper. Software RUAUMOKO was used for the parametric study. Four types of frames were considered: bare frame, fully infilled frame, frame with pilotis, and braced frame (steel braces in the ground floor). Assuming that all upper floors have the same properties as the 1st one, and defining as $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ respectively the stiffness and strength ratios between the pilotis and the 1st floor, it was found that in order to remove the “pilotis vulnerability” the brace stiffness and strength should be calculated with $1.5<\boldsymbol{\beta}<2.5$ while $\boldsymbol{\alpha}\approx 1$.

2. INTRODUCTION

Reinforced Concrete (RC) structures represent the largest proportion of the built heritage in the Para-Mediterranean and Middle East countries. A large part of these structures however has been designed and constructed according to old Seismic Codes (and in some cases also for resisting gravity loads only). Hence they are highly vulnerable to seismic loading, since they do not satisfy ductility demands and shear capacity requirements, as dictated by modern Seismic Design Codes. This is the main reason that in recent years a growing interest in the establishment and development of innovative seismic protection systems (able to improve the behavior of such structures under strong ground motions) has been observed. For this purpose, the use of steel bracings in particular, has gained special attention among researchers in the field, starting from the early 80s. From the relevant publications one may quote the pioneer works by Jain [1], Jirsa and associates [2,3] and related research by the "Iranian school" [4,5]. From these experimental as well as analytical studies (and others not cited herein for brevity) it was concluded that: (a) in both analysis and experiments one must take cautiously into account the participation and the accurate modeling of masonry infills, as well as the realistic simulation of the inelastic behavior of RC and steel members, (b) the appropriate design of direct connections between braces and RC frame should carefully consider the level of interaction between frame and bracing system, while keeping eccentricities at the corner joints minimal, in order to avoid damage of the RC members at these locations, (c) among the three suggested types of connections between braces and RC frame, i.e. mechanical fasteners, mortar and special resins, the 1st solution is advantageous and, (d) X-braces, due to their ease in construction and fitting, their low cost and symmetrical behavior under cyclic loading, constitute an attractive solution as compared to other bracing configurations.

In view of the above, a research program was conducted by the authors [6]. Its aim was to study the viability of using regular steel concentric X-bracing elements as sacrificial strength and damping units, in order to enhance the seismic performance of RC frames with pilotis and masonry infilled upper floors designed and built before 1985. This work was divided in two parts: (1) a parametric study to establish the ranges of stiffness and strength that the "piloti" X-braces contribute to the overall frame response, and (2) experimental investigation of (i) a small-scale portal bare frame and its analytical prediction of response and (ii) a small-scale portal frame model fitted with X-braces. The modeling, the design philosophy, the procedures and the results of the former are the subject of the present work, while the latter will be described in a companion paper.

3. STEEL BRACE AND MASONRY INFILL WALL BEHAVIOR / MODELING

The outcome of the current parametric study depended on the accuracy and detail of the considered model for the structural members examined.

3.1. Steel brace behavior and modeling

The hysteretic cyclic behavior of a steel bracing member is quite complex. It involves phenomena such as buckling of the element, yielding of material at specific locations along the element, local buckling at the cross-section level, and post-buckling deterioration of compressive load capacity, due to Bauschinger effects and tangent modulus reduction. This complex behavior can be modeled by two classes of models, phenomenological models and physical theory models.

Physical theory models incorporate simplified theoretical formulations based on physical considerations, which allow the cyclic non-linear hysteretic behavior of a brace element to be computed. Unlike these, the input of physical theory models is based on material and geometric properties of a brace element/member. Among these, the one proposed by Remennikov and Walpole [7] is utilized in this study. This particular model is available in the RUAUMOKO software [8], which was chosen to aid the work in this study. A thorough parametric investigation at the component level (individual brace) of this model was conducted and the parameters controlling the behavior of a steel brace under cyclic loading were fully identified [6].

3.2. Modeling of Masonry Infill Walls

Masonry infills were modeled in RUAUMOKO with the spring type element combined with the masonry strut hysteretic rule [9]. The detailed input parameters and their values can be found in [6].

4. PARAMETRIC STUDY AND ITS PHILOSOPHY

A parametric study to evaluate the effect of relative stiffness and strength of the "piloti" to the upper floors has been undertaken. Establishing the variables/parameters of the study was challenging because:

(a) The considered structure should have been designed with the Hellenic seismic provisions in effect before 1985. The designs completed at that time only considered bare frames, while the presence of masonry infill walls at all levels was assumed beneficial, an extra bonus to safety. Another justification/explanation, which is commonly recalled, is that in spite of the infill wall high stiffness (and strength), their highly brittle behavior leads to failure rather quickly and therefore this does not contribute to stiffness and strength after the first "significant" cycle of loading.

(b) When the terms "retrofit" or "removing the piloti vulnerability" by providing braces (X-braces or diagonal braces) are used, someone can interpret it as: **(a)** the provided braces have such properties (stiffness and strength) as to bring the structural system (bare frame) up to the current (modern) codes, or **(b)** the provided properties at the "piloti" level are such that will eliminate the piloti's discontinuity in relation to the upper floors without retrofitting any other member of the structural frame to comply with the current seismic codes.

The interpretation (**b**), which the term "removing the piloti vulnerability" seems more representative, appears more attractive, because of the obvious lower cost compared to the full retrofit to bring the structure in compliance to the modern codes. This second interpretation was adopted in the present study.

Four types of frames were considered: a bare frame, a fully infilled frame, a frame with "piloti" and a braced frame (steel X-braces at the ground floor), as depicted in Fig.1. The parameters characterizing the floor properties of all the frames considered are described below:

K_{BF} : Stiffness of the upper floors of the bare frame
K_P : Stiffness of the ground floor of the bare frame and the piloti frame ($K_P = K_{BF}$)
K_{IN} : Stiffness of the masonry infills in a floor
K_X : Lateral stiffness of all the X-braces in the ground floor of a braced frame
V_{BF} : Strength of the upper floors of the bare frame
V_P : Strength of the ground floor of the bare frame and the piloti frame ($V_P = V_{BF}$)

V_{IN} : Strength of all masonry infills in a floor
V_X : Lateral stiffness of all the X-braces in the ground floor of a braced frame

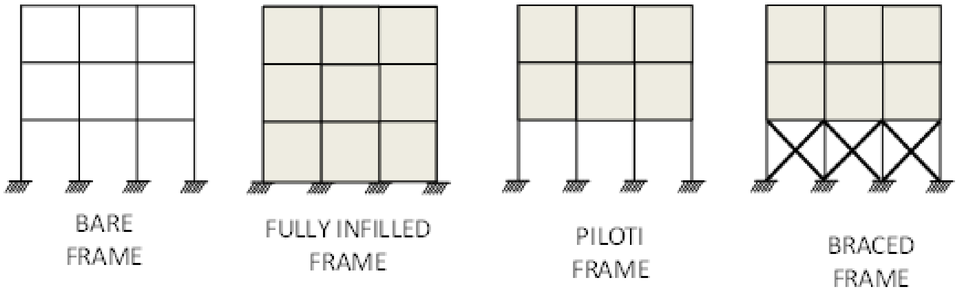

Fig. 1 The four types of frames considered

The above parameters, except K_X and Vx, were calibrated/evaluated from increasing amplitude cyclic loading analyses of models of the bare frame (K_{BF} and V_{BF}), the piloti frame (K_{IN}, V_{IN} and K_P, V_P) and the fully infilled frame (K_{IN} and V_{IN}). Since the objective of the study was to "remove the piloti vulnerability" by filling the openings in the ground floor, it was reasonable to treat the fully infilled frame as the benchmark/basis. Assuming that masonry infills were provided in the piloti, their lateral strength and stiffness can be hand calculated using the axial strength and stiffness of the diagonal struts, modeling the infills following the equations:

$$V_{INF} = \cos\theta \ (0.5 f_m) \sum_{i}^{nb} w_{si} \, t_i \ , \ K_{INF} = \cos^2\theta \ E_m \sum_{i}^{nb} w_{si} \, t_i \tag{1}$$

where, n_b is the number of bays in a floor, f_m is the masonry prism strength in MPa, E_m is the elastic modulus of masonry in MPa ($E_m \sim 500\ f_m$), w_{si} is the effective width of the corresponding strut model, θ its angle with the horizontal and t_i the thickness of the infill. The constant 0.5 is to account for the fact that masonry cracks and loses strength at very low deformations, and thus $0.5f_m$ is an estimate of the effective or dependable strength of the masonry in the lateral strength calculation of an infill.

Therefore, in the absence of infills in the ground floor the V_{IN} and K_{IN} will be the deficit in the lateral strength and stiffness of the piloti frame compared to the fully infilled frame. Defining the ratio between the strength of the pilotis and the 1st floor (and assuming that all the upper floors have the same properties to the 1st floor) as $\boldsymbol{\beta}$ and the corresponding ratio of stiffness as $\boldsymbol{\alpha}$ we can write:

$$\boldsymbol{\alpha} = \frac{\left(K_A + K_P\right)_{piloti}}{\left(K_{BF} + K_{INF}\right)_{1^{st}}} \ , \ \boldsymbol{\beta} = \frac{\left(V_A + V_P\right)_{piloti}}{\left(V_{BF} + V_{INF}\right)_{1^{st}}} \tag{2}$$

where K_A and V_A are the stiffness and strength deficit of the piloti frame as defined above. These values will be substituted by K_X and V_X in the case of the braced frame. Values of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ unity indicate uniform distribution of stiffness and strength between the ground floor and 1st floor. The lower bound of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are calculate from the equations (2) for K_A and V_A zero. The values of the other parameters involved in the above equations can be evaluated through numerical experiments (as was done in this study) or through hand calculations if these equations are utilized during the design process. Considering that K_A and V_A are to be evaluated after setting $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ we get:

$$K_A = \alpha\left(K_{BF} + K_{INF}\right)_{1^{st}} - \left(K_P\right)_{piloti} \ , \ V_A = \beta\left(V_{BF} + V_{INF}\right)_{1^{st}} - \left(V_P\right)_{piloti} \tag{3}$$

4.1. Description of RC frame structures utilized in the parametric study

The parametric analyses considered two typical 3-bay RC frames, a 3-story and a 5-story one, designed in accordance to the Hellenic Seismic Code in effect before 1985. The plan and details of their typical floor can be found in [6], while the parameters considered where 0.9, 1, 1.2, 1.5, 2, 3 for $\boldsymbol{\alpha}$ and 1, 1.2, 1.5, 2, 3 for $\boldsymbol{\beta}$. The stiffnesses and strengths were obtained from numerical analyses as mentioned previously.

4.2. Seismic Excitations

The present study considered a number of seismic excitations, which were compatible to a specific target design spectrum; this was chosen compatible to the Hellenic Seismic Design Code for Soil Type B and Seismic Zone II. Using this spectrum artificially generated acceleration time histories were obtained using the software SIMQKE [10]. The spectrum is shown in Fig. 2a, while one of the time histories used in Fig. 2b.

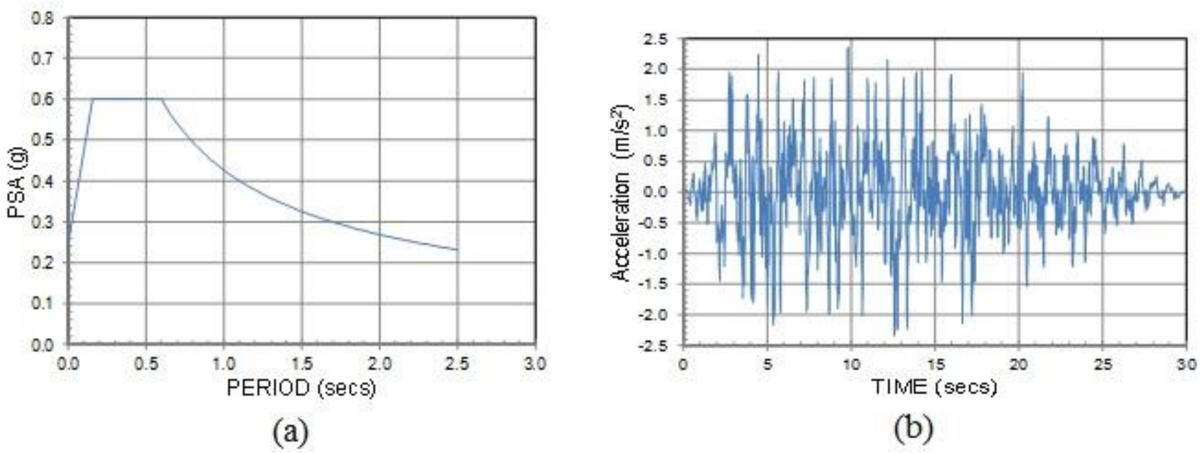

Fig. 2 Acceleration Spectrum (a) and compatible time history (b)

5. PARAMETRIC ANALYSES RESULTS AND MAIN CONCLUSION

Two parametric analyses sets were completed, one considering the investigation of the stiffness and the other the investigation of the strength of the X-braces in the “piloti”. For the values of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ in Tab. 1 the properties of the corresponding X-braces were calculated as well as the corresponding achieved values $\beta_{achieved}$ and $\alpha_{achieved}$ to ensure the values do not fall outside the bounds of those parameters, and the resulting X-braces are realizable. The values in Tab. 1 are those related to the analyses of the 3-story frame.

β	V_X (kN)	K_X (kN/m)	$\alpha_{achieved}$	N_y (kN)	α	K_X (kN/m)	V_X (kN)	$\beta_{achieved}$	N_y (kN)
1.0	30	3,714	0.73	12.7	0.9	19,700	159	1.54	67.6
1.2	78	9,657	0.80	33.1	1.0	29,300	236	1.86	100.5
1.5	150	18,572	0.89	63.7	1.2	48,500	391	2.51	166.3
2.0	270	33,430	1.04	114.7	1.5	77,300	624	3.48	265.1
3.0	510	63,146	1.35	216.6	2.0	125,300	1,011	5.09	429.7
-	-	-			3.0	221,300	1,787	8.32	759.0

Tab. 1: Results of parametric analyses of the 3-story frame

In Fig. 3a one can perceive in graphical form a summary of the state of the structural members (i.e. plastic hinge formation), except the infill masonry ones, in the X-braced frame for three values of **α**; the plastic hinge distribution of the frame for three values of **β** can be observed in Fig. 3b. In the same manner, graphical results for the 5-story frame are depicted in Fig. 4.

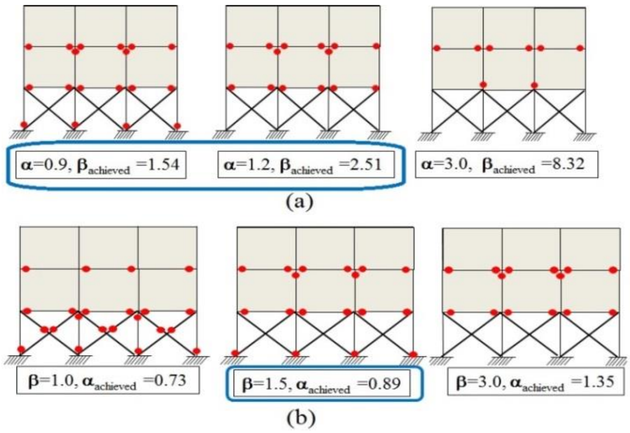

*Fig. 3 State of structural members of the 3-story frame at the end of the seismic excitation (a) for three values of **α** and (b) for three values of **β***

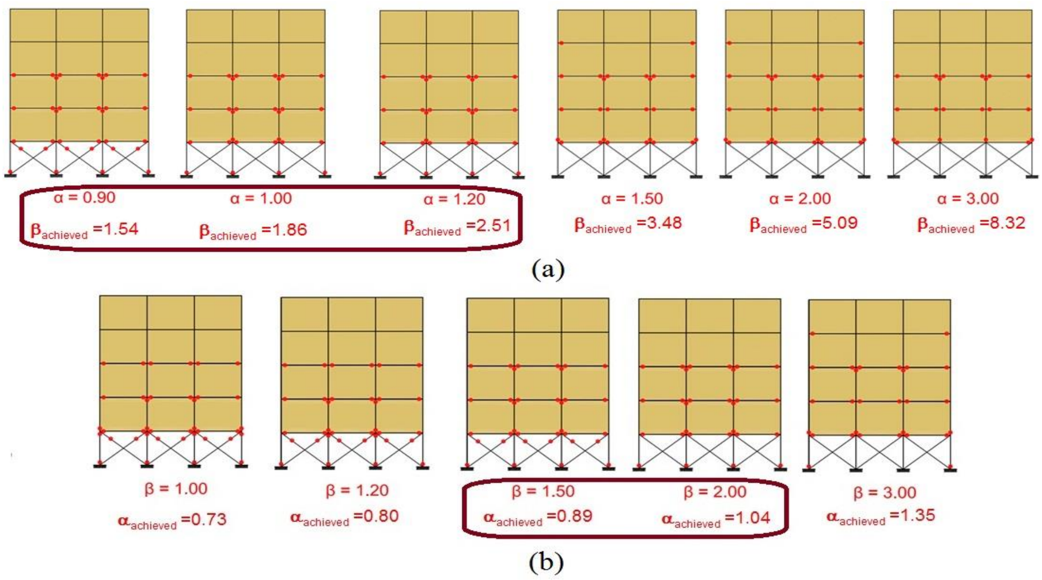

*Fig. 4 State of structural members of the 5-story frame at the end of the seismic excitation (a) for six values of **α** and (b) for five values of **β***

From the above results it is evident that as the stiffness of the "piloti" increase, the formation of plastic hinges is shifted towards the upper floors. For large values of the corresponding ratio **α,** the observed decrease of the number of plastic hinges is due to the increase of the achieved strength. Moreover, as the strength ratio **β** increases from 1 to 3, there is a clear shift of the plastic hinges from the ground floor to the upper floors, with a simultaneous increase of the total number of plastic hinges formed. It can also be seen that the increase of the achieved stiffness does not influence the results to a significant extent.

Finally, from all parametric analyses performed, it is clear that to achieve the goal of removing the seismic vulnerability of the "piloti" the X-braces should have a strength within the range of 1.5 < **β** < 2.5, with the corresponding stiffness kept close to the value of **α** = 1. This is the main conclusion of the parametric study reported herein.

It should be noted that the above results were obtained using 2-D analyses and assuming a regular plan of the simulated RC structure. Equally importantly, it should be taken into account that, using RUAUMOKO, when infill panels fail, the corresponding elements are removed from the subsequent steps. Since the masonry infills are not vertical load carrying elements, their state (failed, yielded, intact) at the end of the analysis is not depicted in Figs. 3 and 4.

6. ACKNOWLEDGMENTS

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Δημήτριος Σ. Σοφιανόπουλος[1a], **Κωνσταντίνος Σ. Παπαχρήστου**[2b],
Θεοχάρης Παπαθεοχάρης[3a], **Πάνος Τσόπελας**[4a], **Φίλιππος Περδικάρης**[5a]

[a] Τμήμα Πολιτικών Μηχανικών, Πανεπιστήμιο Θεσσαλίας, Βόλος, Ελλάς

[b] WTM Engineers München GmbH, Μόναχο, Γερμανία

[1] Αναπληρωτής Καθηγητής, email: dimsof@civ.uth.gr

[2] Δρ. Πολιτικός Μηχανικός, email: k.papachristou@wtm-m.de

[3] Πολιτικός Μηχανικός, Υποψήφιος Διδάκτωρ, email: th_papath@yahoo.gr

[4] Καθηγητής, email: tsopelas@civ.uth.gr

[5] Καθηγητής, email: filperd@civ.uth.gr

ΠΕΡΙΛΗΨΗ

Σκοπός του ερευνητικού προγράμματος ήταν να αξιολογήσει την επιρροή και αποτελεσματικότητα της χρήσης μη έκκεντρων χαλύβδινων Χ-συνδέσμων στην αφαίρεση της σεισμικής τρωτότητας πλαισίων από ΟΣ με πυλωτή, με σχεδιασμό σύμφωνα με αντισεισμικούς κώδικες πριν το 1985. Το εγχείρημα διαιρέθηκε σε δύο μέρη: (Ι) την παραμετρική μελέτη προσδιορισμού του ποσοστού επιρροής, σε όρους δυσκαμψίας και αντοχής, της παρουσίας Χ-συνδέσμων στην καθολική απόκριση των πλαισίων και (ΙΙ) σε πειράματα. Το Μέρος Ι περιγράφεται στην παρούσα εργασία ενώ το Μέρος ΙΙ σε σχετική συνοδευτική. Για την παραμετρική μελέτη, μέσω του λογισμικού RUAUMOKO, αναλύθηκαν τέσσερα είδη πλαισίων: γυμνό, πλήρως τοιχοπληρωμένο, με πυλωτή και με Χ-συνδέσμους στο ισόγειο. Θεωρώντας ότι όλοι οι όροφοι πέραν του 1^{ου} έχουν τις ίδιες ιδιότητες με αυτόν, και ορίζοντας ως **α** και **β** τους λόγους μεταξύ της δυσκαμψίας και της αντοχής αντίστοιχα της πυλωτής (με τους Χ-συνδέσμους) και του υπερκείμενου ορόφου, βρέθηκε ότι για να επιτευχθεί ο ως άνω τεθείς στόχος θα πρέπει να ισχύει ότι $1.5<\boldsymbol{\beta}<2.5$ ενώ $\boldsymbol{\alpha}\approx 1$. Τα αποτελέσματα βασίστηκαν σε δυσδιάστατες αναλύσεις, κανονικότητα κάτοψης ορόφων και χωρίς να ληφθούν υπόψη ποσοτικά βλάβες τοιχοπληρώσεων.