STEEL FRAMES WITH REINFORCED CONCRETE INFILL WALLS. FINITE ELEMENT ANALYSIS USING A COMPUTATIONAL MODEL AND COMPARATIVE STUDY WITH EXPERIMENTAL RESULTS

Tzanetis Voghiatzis
PhD Candidate
Aristotle University of Thessaloniki
Thessaloniki, Greece
E-mail: tzanetisvoghiatzis@civil.auth.gr

Aris Avdelas
Professor
Aristotle University of Thessaloniki
Thessaloniki, Greece
E-mail: avdelas@civil.auth.gr

Themistoklis Tsalkatidis
Lecturer
Democritus University of Thrace
Xanthi, Greece
E-mail: ttsalkat@arch.duth.gr

1. ABSTRACT

Composite wall systems when properly designed have shear strength and stiffness comparable to those of pure reinforced concrete shear wall systems. This paper reports on the behaviour of a composite structural system, which is formed by a partially-restrained steel frame with a reinforced concrete infill wall attached compositely to the steel frame around the perimeter of each wall panel (PRSRCW). This composite structural system combines advantages of both steel frames and reinforced concrete infill walls and thus receives increasing recognition in seismic areas. The composite interaction between steel frame and infill walls is achieved by the use of shear connectors. In order to investigate the main characters such as general behaviour, local response and force distribution of the composite structural system a three-dimensional finite element model is developed. The numerical results of the computational model are evaluated, after being compared to experimental ones, from the international literature.

2. INTRODUCTION

Structures are designed to resist not only vertical loads, such as self-weight, but also horizontal ones, such as earthquake forces. In particular, in Greece earthquake loads are significant and can cause huge damage to structures. Therefore, civil engineers must implement mechanisms within the structures that are able to resist horizontal forces and to dissipate energy. For steel buildings, especially multi-story ones, composite steel-reinforced concrete wall systems are considered a new solution when designing under earthquake loads. Partially restrained steel frames with reinforced concrete infill walls (PRSRCWs) - Type 1 composite walls according to Eurocode 8 [1], are a good alternative because of their low construction cost and their repairability possibilities, while their response when subjected to cyclic loading is ductile [2]. The PRSRCW system is not treated in a separate chapter in Eurocode 8 [1]. The design for the frame steel profiles should be according to Eurocode 3 [3], complemented by references in Eurocode 8 [1]. The design of the concrete infill wall is according to Eurocode 2 [4]. The design of the composite connection at the interface of steel and concrete is according to Eurocode 4 [5]. PRSRCWs only provide stiffness in the plane of the wall, so it is necessary to have those lateral resistance elements placed in, at least, two orthogonal directions.

In recent years, using ANSYS finite element software, many research works have been successfully performed in order to simulate the seismic behaviour of reinforced concrete elements (beams, walls, columns, etc.). These studies show that ANSYS can precisely simulate concrete, and results show a very good accuracy, being close to the experimental ones [6].

3. DESIGN OF THE MODEL

The PRSRCW considered for this research is the experimental specimen designed and tested [7] as an idealized representation (one-third scale) of the bottom two stories of a prototype six-story building (after[8]). *Fig. 1* shows the building plan and the elevation view of the considered infilled frame W1. The building was assumed to be in seismic area 7 [9]. The design lateral force acting on infill wall W1 was determined according to the Equivalent Lateral Force Procedure of National Earthquake Hazard Reduction Program of U.S.A. (NEHRP) [9], including an acceleration coefficient A_α of 0.4 , a velocity coefficient A_u of 0.4, and a response modification factor R of 5.5. The results were further verified by using the 1997 NEHRP seismic guidelines [10, 11].

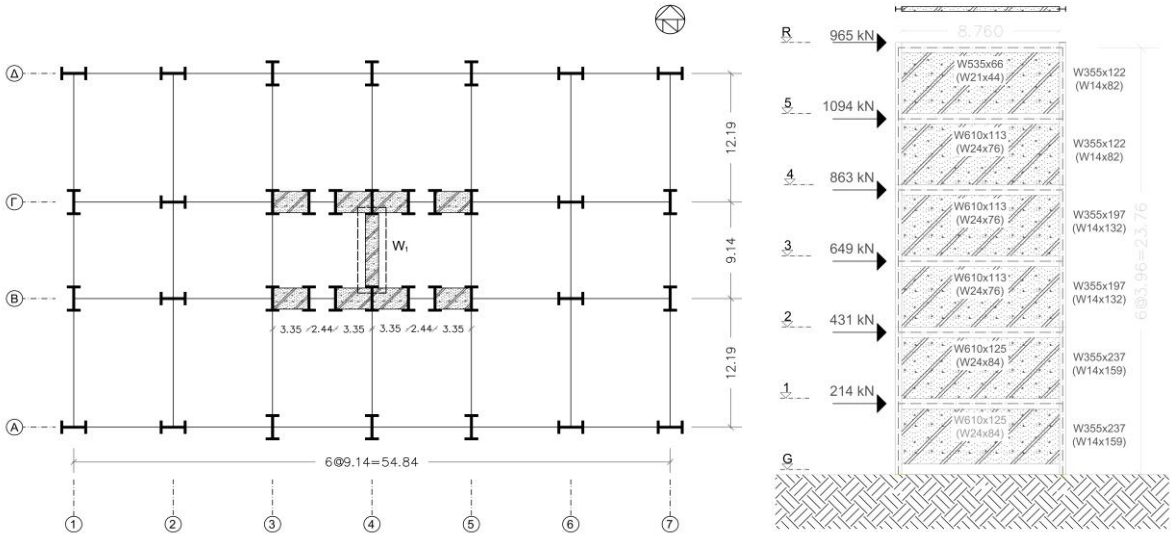

Fig 1: Building plan and considered infilled frame W1 (units: kN and m)

The PRSRCW specimen is a two-story, one-bay structure with a Partially Restrained (PR) steel frame as the boundary element and a RC shear wall embedded inside the frame. The dimensions of the steel frames are 2184 mm (length) x 2540 mm (height), measured from center to center of the steel sections. The dimensions of the infill wall for each story are height 1016 mm, width 2057 mm and thickness 89 mm.

The columns consisted of W130X28 wide flange steel sections and the beams consisted of W200X19 wide flange steel sections. Partially-restrained connection consisted of a top, a seat angle and double web angles. The section of top and seat angles was L127X76X8X127 connecting the beam flanges to the column flange, and the section of web angles was L51X51X8X127 connecting beam web with column flanges. The total plastic moment of the partially-restrained connection, considering the effect of axial force from the diagonal compression strut in the infill wall, was 28 kNm, approximately 55% of the plastic moment of the steel beam. The RC infill wall was assumed to transfer 100% of the seismic story shear. Both the horizontal and vertical reinforcement ratios were 0.51% achieved by arranged two curtains of 6 mm smooth bars spaced at 140 mm. Prefabricated reinforcing cages were placed around the entire perimeter of each infill panel in the specimen with 6 mm smooth bars [7]. The confining cage was an effective way to delay primary types of concrete cracking around the shear connectors due to the limited thickness of the infill wall. For integral action between steel frame and RC infill wall, headed studs are provided along the perimeter of the infill wall. The shear connectors along the column-infill interface were the same as that along the beam-infill interface placed at 102 mm. The bottom beam of the specimen is welded to the foundation plate with continuous fillet welds.

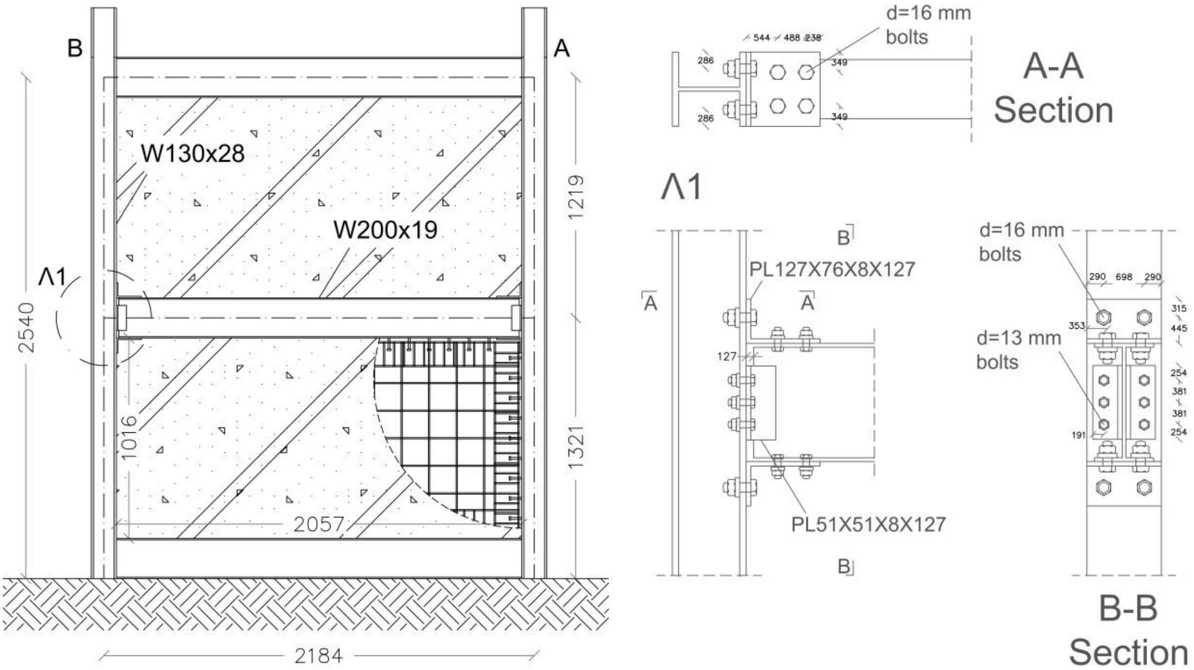

Fig 2: PRSRCW a) Specimen dimensions, b) PR connection detail (units: mm)

The cyclic loading history (*Fig. 4α*) was modified according to the SAC protocol [12] with a total of 25 cycles, divided into 9 loading groups depending on the displacement range of loading. Each group has three loading cycles (0.05%, 0.2%, 0.35%, 0.50%, and 0.75%)

except for the last two groups, which have two loading cycles (1%, 1.75%). The total drift was measured between the centerlines of the bottom and top girders [7].

4. MODEL DESCRIPTION

The present study utilized the finite element program ANSYS version 15 [13]. A three dimensional finite element model has been developed to simulate the geometric and material nonlinear behaviour of the PRSRCW. The whole height of the composite wall has been modeled. The composite wall is modeled using solid elements.

The following assumptions were made in the finite element model:

- Model included both material (steel, concrete) and geometric nonlinearities [14].
- Shear stud connectors and steel reinforcement were modeled as discrete elements.

The analysis performed is geometrically nonlinear with stress stiffening, large deflections and small strains characteristics. ANSYS uses the Newton-Raphson method as an incremental-iterative solution process. Both the normal and the tangential stiffness matrix are updated after iteration. The convergence procedure is force-based and thus considered absolute [14]. The 3D finite element model for the PRSRCW is shown in *Fig. 3*. In *table 1,* the steel material properties are reported.

Location	**Beam web**	**Column web**	**Column flange**	**Top & Seat angles**	**Web angles**	**Φ6**
Yield strength (MPa)	370	314	310	364	282	431
Ultimate strength (MPa)	553	513	479	533	461	612
Modulus of elasticity (GPa)	210	210	210	200	200	210

Table 1: Steel material properties

Concrete: The concrete is assumed to be homogeneous and initially isotropic. The uniaxial compressive stress-strain curve is based on the *Modified Hognestad* model (Hognestad, 1951) [15]. The numerical expressions by Desayi and Krisnan (1964) [16], Eq. (1), Eq. (2), were used along with Eq. (3) to construct the multilinear isotropic stress-strain curve for concrete in this study. The 28-day characteristic compressive strength was 24 MPa, the tangent modulus of elasticity determined at 23.4 GPa and the Poisson ratio for the concrete has been assumed as 0.2. The multi-linear isotropic stress-strain curve was used to help with the convergence of the nonlinear solution algorithm.

Stress at any strain :
$$f = \frac{E_C \bullet \varepsilon}{1+\left(\frac{\varepsilon}{\varepsilon_0}\right)^2} \tag{1}$$

Strain at the ultimate compressive strength :
$$\varepsilon_o = \frac{2 \bullet f_C}{E_C} \tag{2}$$

Elastic modulus :
$$E = \frac{f}{\varepsilon} \tag{3}$$

Frame Steel: The constitutive material law selected for the frame steel has been bi-linear elastoplastic-strain hardening using the von Mises stress yield criterion. Steel has been assumed to be homogenous. The density of steel has been determined at 7850 Kgr/m^3. Nonlinear stress-strain curves of steel were incorporated in the model using ANSYS' Bilinear Kinematic Hardening option. The real stress-strain curves were approximated by a series of straight lines [17]. The Poisson ratio for steel has been assumed as 0.3 [14].

Steel reinforcement: The constitutive law assumed was isotropic and the yield was also defined as isotropic (von Mises yield criterion), based on a perfect elastic-plastic model identical in tension and compression.

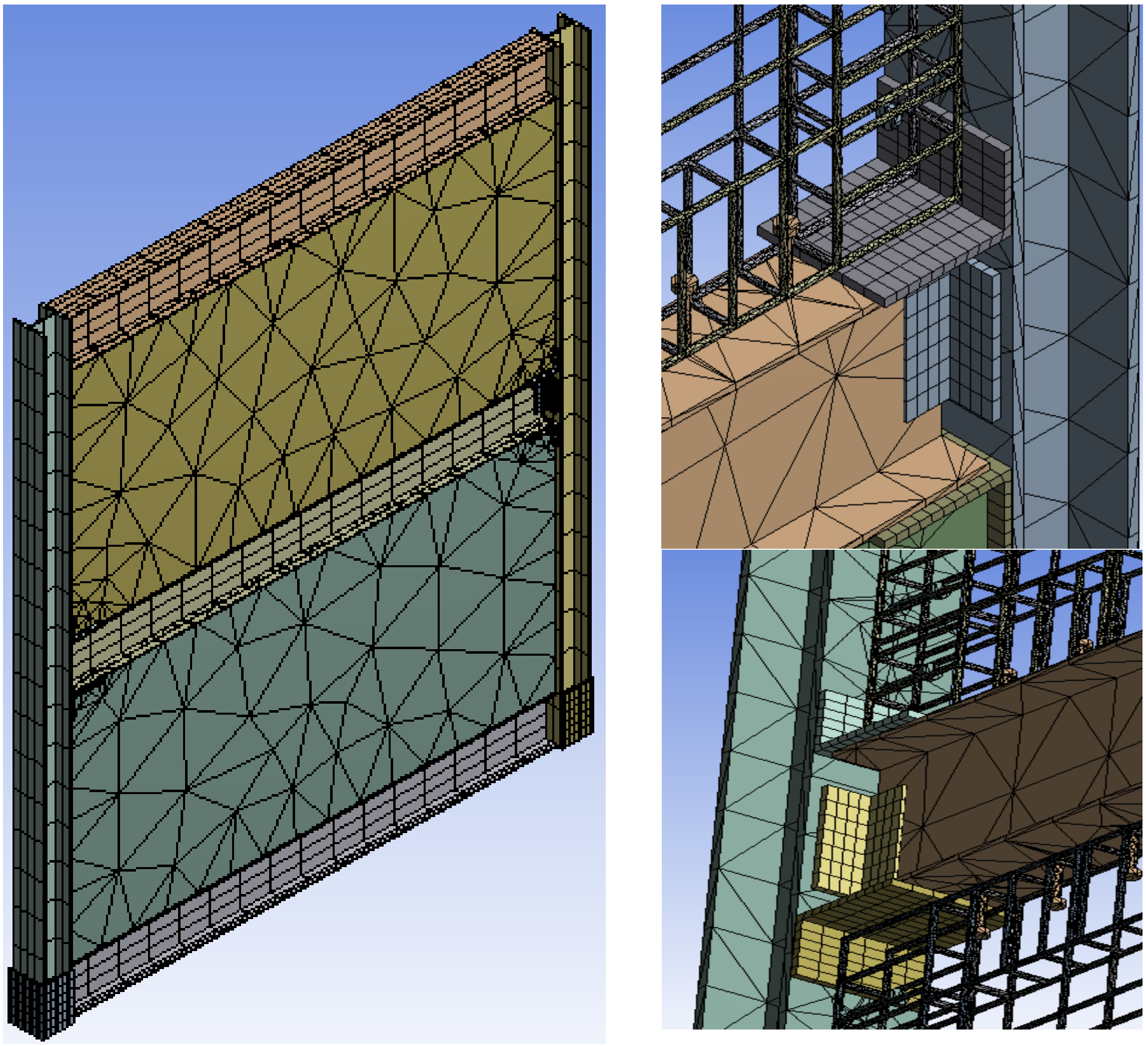

Fig 3: PRSRCW Finite element model

5. COMPARISON - CONCLUSIONS

The finite element simulation aimed to validate the model developed in this work, through a comparison with experimental [7] and numerical [7] results from the international literature. In this comparison, it was concluded that it is possible to represent fairly well the behaviour of PRSRCW through computational modeling.

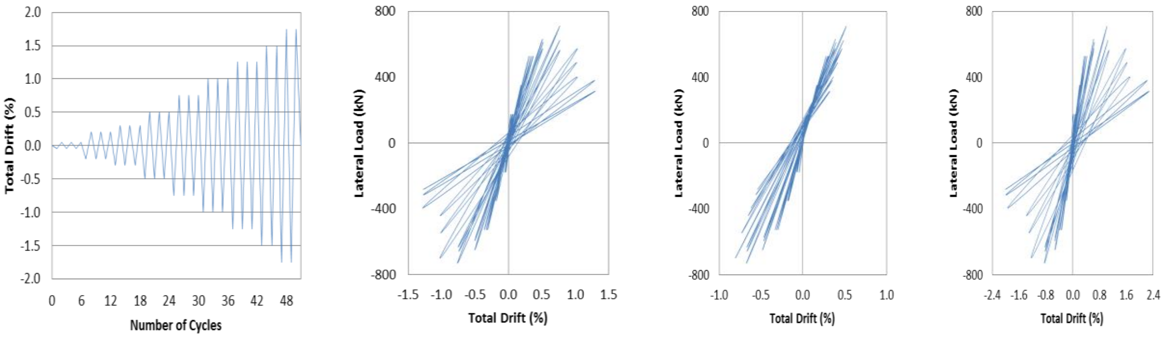

Fig 4: a) Cyclic displacement history, b) Total Drift VS lateral load, c) First story interstory drift, d) Second story interstory drift

- As the cyclic loading (*Fig. 4a*) was applied to the analytical PRSRCW model the following failure mode developed. During the early loading stage the concrete reached in the corners region, its maximum compressive strength. Also the steel reinforcing bars where gradually reaching their yield stress. As the cyclic loading continued to increase the shear connectors began to yield. During the 0.3% drift cycles, yielding of the steel frame occurred. With continued increase of the loading cycles the web angles of the partially restrained connections yielded. The model reached its maximum lateral strength with the concrete in the corner of each storey crush in multiple regions and a significant number of plastic hinges developed in the steel members. After the 1% drift cycles, the lateral strength dropped until the model obtained moderate ductility capacity.
- The composite wall under study has developed a ductile failure mode, as in the experimental analysis, due to the lack of significant fatigue fracture at the shear connectors.
- The deformation mode can be classified as the expected shear-dominated behaviour.
- The PRSRCW model reached its maximum lateral strength at 0.75% drift cycles with a value very close to the experimental specimen and more than twice than the one calculated according to the equivalent lateral force procedure [7].
- The proposed three-dimensional numerical model, for the type 1 composite shear wall (PRSRCW), is directly applicable to practice and can be used as an effective design tool for steel and composite structures.
- For future research: A comparison will be studied between a 3D finite element model with smeared reinforcement and one with discrete reinforcement. Evaluation of the model with more sophisticated nonlinear material laws for concrete and structural steel. Parametrical study of the model with different material properties.

6. REFERENCES

[1] EUROPEAN COMMITTEE FOR STANDARDIZATION “EN 1998-1: Eurocode 8: Design of structures for earthquake resistance-Part 1: General rules, seismic actions and rules for buildings”, 2004.

[2] HAJJAR, J.F. “Composite steel and concrete structural systems for seismic engineering”, *Journal of Constructional Steel Research*, Vol. 58, 2002, pp. 703-723.

[3] EUROPEAN COMMITTEE FOR STANDARDIZATION. “EN 1993-1-1:

Eurocode 3: Design of steel structures-Part 1-1: General rules and rules for buildings”, 2005.

[4] EUROPEAN COMMITTEE FOR STANDARDIZATION. “EN 1992-1-1: Eurocode 2: Design of concrete structures-Part 1-1: General rules and rules for buildings”, 2004.

[5] EUROPEAN COMMITTEE FOR STANDARDIZATION. “EN 1994-1-1: Eurocode 4: “Design of composite steel and concrete structures-Part 1-1: General rules and rules for buildings”, 2004.

[6] RAONGJANT W. and JING M. “Finite Element Analysis of Lightweight Reinforced Concrete Shear Walls with Different Web Reinforcement”, *The sixth PSU Eng. Conf.*, Songkhla, Thailand, 2008, pp. 61-67.

[7] TONG X. "Seismic Behavior of composite steel frame-reinforced concrete infill wall structural system”, *PhD Thesis*, Department of Civil Engineering, University of Minnesota, Minneapolis, MN, 2001.

[8] SHAHROOZ B.M., GONG B. and ARNOLD J. “Seismic behavior and design of composite coupling beam”, *Internal Report*, Department of Civil Engineering, University of Cincinnati, Cincinnati, OH; 1996.

[9] TONG X., SCHULTZ A.E. and HAJJAR J.F. “Prototype design and plastic analyses of steel frames with composite reinforced concrete infill walls”, *Report No. ST-99-02*, Department of Civil Engineering, University of Minnesota, Minneapolis, MN,2001.

[10] NATIONAL EARTHQUAKE HAZARD REDUCTION PROGRAM (NEHRP) “Recommended provisions for the development of seismic regulations for new buildings, Part I-provisions, Part 2-commentary”, Washington, DC: Building Seismic Safety Council, Federal Emergency Management Agency, 1994.

[11] NATIONAL EARTHQUAKE HAZARD REDUCTION PROGRAM (NEHRP) “Recommended provisions for the development of seismic regulations for new buildings, Part I-provisions. Part 2-commentary”. Washington, DC: Building Seismic Safety Council, Federal Emergency Management Agency, 1997.

[12] SAC JOINT VENTURE “Protocol for fabrication, inspection, testing, and documentation of beam-column connection tests and other experimental specimens”, Report No. SAC/BD-97/02, SAC joint venture, Sacramento, CA, 1997.

[13] ANSYS “Version 15.0 Documentation”, ANSYS Inc, 2014.

[14] HOSSAIN, K.M. and WRIGHT, H.D. “Experimental and theoretical behaviour of composite walling under in- plane shear”, *Journal of Constructional Steel Research*, Vol. 60, 2004, pp. 59-83.

[15] HOGNESTAD E. “A study of combined bending and axial load in reinforced concrete members”, University of Illinois Engineering Experiment Station, Bulletin series No 399, 1951.

[16] DESAYI P. and KRISHNAN S. “Equation for the stress-strain curve for concrete”, *Journal of the American concrete institute*, Vol. 61, 1964, pp 345-350.

[17] CLUBLEY S., MOY S. and XIAO, R. “Shear strength of steel-concrete-steel composite panels. Part II–detailed numerical modeling of performance”, *Journal of Constructional Steel Research*, Vol. 59, 2003, pp. 795-808.

[18] AKHAND A.M., BADARUZZAMAN W.H.W. and WRIGHT, H.D. “Combined flexure and web crippling strength of a low- ductility high strength steel decking: experiment and a finite element model”, *Thin-Walled Structures*, Vol. 42, 2004, pp. 1067-1082.

[19] BATHE, K.-J. “Finite element procedures”, Prentice Hall, 1996.

ΜΕΤΑΛΛΙΚΑ ΠΛΑΙΣΙΑ ΜΕ ΕΣΩΤΕΡΙΚΟ ΤΟΙΧΩΜΑ ΟΠΛΙΣΜΕΝΟΥ ΣΚΥΡΟΔΕΜΑΤΟΣ. ΥΠΟΛΟΓΙΣΤΙΚΗ ΠΡΟΣΟΜΟΙΩΣΗ ΚΑΙ ΣΥΓΚΡΙΤΙΚΗ ΑΞΙΟΛΟΓΗΣΗ ΜΕ ΠΕΙΡΑΜΑΤΙΚΑ ΑΠΟΤΕΛΕΣΜΑΤΑ

Τζανετής Βογιατζής
Υποψήφιος Διδάκτορας
Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης
Θεσσαλονίκη, Ελλάδα
E-mail: tzanetisvoghiatzis@civil.auth.gr

Άρης Αβδελάς
Καθηγητής
Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης
Θεσσαλονίκη, Ελλάδα
E-mail: avdelas@civil.auth.gr

Θεμιστοκλής Τσαλκατίδης
Λέκτορας
Δημοκρίτειο Πανεπιστήμιο Θράκης
Ξάνθη, Ελλάδα
E-mail: ttsalkat@arch.duth.gr

ΠΕΡΙΛΗΨΗ

Τα σύμμικτα τοιχώματα, όταν έχουν σχεδιασθεί και μελετηθεί σωστά, εμφανίζουν διατμητική αντοχή και δυσκαμψία ανάλογη με τα τοιχώματα οπλισμένου σκυροδέματος. Η παρούσα εργασία αποσκοπεί στη διερεύνηση της μηχανικής συμπεριφοράς των σύμμικτων τοιχωμάτων, και συγκεκριμένα αυτών που κατασκευάζονται από μεταλλικό πλαίσιο με ημιάκαμπτες συνδέσεις που περιβάλλει περιμετρικά ενδιάμεσο στοιχείο από οπλισμένο σκυρόδεμα (PRSRCW). Το σύμμικτο αυτό σύστημα, που συνδυάζει τα πλεονεκτήματα των μεταλλικών πλαισίων και των τοιχείων οπλισμένου σκυροδέματος, κερδίζει καθημερινά την προτίμηση των μελετητών μηχανικών σε περιοχές με σημαντική σεισμική δραστηριότητα. Η σύμμικτη δράση επιτυγχάνεται με τη χρήση διατμητικών συνδέσμων, που συγκολλούνται στα μεταλλικά πλαίσια. Προκειμένου να διερευνηθούν οι μηχανικές ιδιότητες, η μορφή αστοχίας και η κατανομή των δυνάμεων υπό κυκλική καταπόνηση στα σύμμικτα τοιχώματα τύπου 1, κατασκευάστηκε τρισδιάστατο υπολογιστικό προσομοίωμα με χρήση πεπερασμένων στοιχείων. Τα υπολογιστικά αποτελέσματα αξιολογούνται κατόπιν σύγκρισης με αντίστοιχα πειραματικά, από τη διεθνή βιβλιογραφία.