Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 2730-2743

ECCOMAS Proceedia

COMPDYN 2021
8th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Streamed from Athens, Greece, 28 - 30 June 2021

ANALYTICAL INVESTIGATION OF THE TENSILE EXPERIMENTS TO PRISMS WITH VARYING LONGITUDINAL RATIO FOR STUDYING THE LATERAL BUCKLING OF R/C WALLS

Theodoros A. Chrysanidis[1], Vassilis P. Panoskaltsis[1]

[1] Demokritos University of Thrace
University Campus Xanthi-Kimmeria, P.C. 67100, Xanthi, Greece
theodoros_gr@yahoo.com, vpanoska@civil.duth.gr

Abstract

In the context of the present work, the influence of the longitudinal reinforcement ratio on the phenomenon of lateral buckling of reinforced concrete walls is examined. The present investigation is basically analytical but it contains experimental results of 6 test specimens published from the first author already. These specimens simulate only the extreme boundary edges of structural walls to study the basic mechanism of the transverse instability phenomenon. The elongation degree used for all six specimens is equal to 30‰. The geometric dimensions are the same for all specimens. What differentiates the specimens from each other is the longitudinal reinforcement ratio. More specifically, the longitudinal reinforcement ratios used are 1.79%, 2.68%, 3.18%, 3.68%, 4.02% and 4.19%. The loading stages for all specimens are as follows: (a) Uniaxial central tensile loading on each test specimen, (b) Uniaxial central compression loading on each specimen till its failure due to buckling. The present study focuses on the tensile loading stage only. Extreme tensile strain of 30‰ is used to take into account the cases of extreme seismic excitations. First, the experimental results from an already accepted publication are presented and afterwards they are followed by the numerical investigation of these 6 specimens using appropriate finite element software. Useful conclusions are drawn regarding the precision of the experimental tests investigating the influence of the longitudinal reinforcement ratio on the phenomenon of transverse buckling. These conclusions are substantiated both experimentally and analytically, as the results of the tensile experiments are compared with the corresponding results of the analytical investigation.

Keywords: Longitudinal reinforcement ratio, Lateral buckling, Seismic walls, Tensile load

ISSN:2623-3347 © 2021 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi: 10.7712/120121.8670.18669

1 INTRODUCTION

Engineers worldwide have been troubled for the structural behavior and soil-structure interaction for various types of structures [1]–[10]. Structural walls play an important role in the structures' behavior and safety against horizontal loads and especially against earthquake cyclic loading [11], [12]. It is well-known that the vast part of seismic loading is resisted by seismic walls in reinforced concrete structures [13]–[26]. One critical mode of failure which can appear during earthquake cyclic loading is the lateral buckling of R/C shear walls [27]–[36]. It has been observed that such type of failure is so critical that can lead to partial or total collapses of multi-storey reinforced concrete buildings [37]. This phenomenon can appear when the boundary edges of seismic walls have sustained a large size of tensile loading during the first semi-cycle of seismic loading and then are subjected to a compressive loading during the second semi-cycle of earthquake loading [38]–[41]. Transverse buckling appears when the cracks formed during the first stage of tensile loading have such a large width that makes it impossible to be closed during the second stage of compressive loading [42]–[50].

The present study uses experimental tests performed already by the first author trying to investigate the mechanical parameters affecting the transverse instability [51]. These specimens were all subjected to tensile strain equal to 30‰ but they had a different longitudinal reinforcement ratio. In the framework of the present work, the six specimens subjected to tensile loading are modelled using finite element software and the results of this analytical investigation are compared to the existing experimental results concerning the tensile loading stage. It is noted that the experiments have taken place in the Laboratory of Strength of Materials of Aristotle University of Thessaloniki and the analysis of the results has taken place in Demokritos University of Thrace.

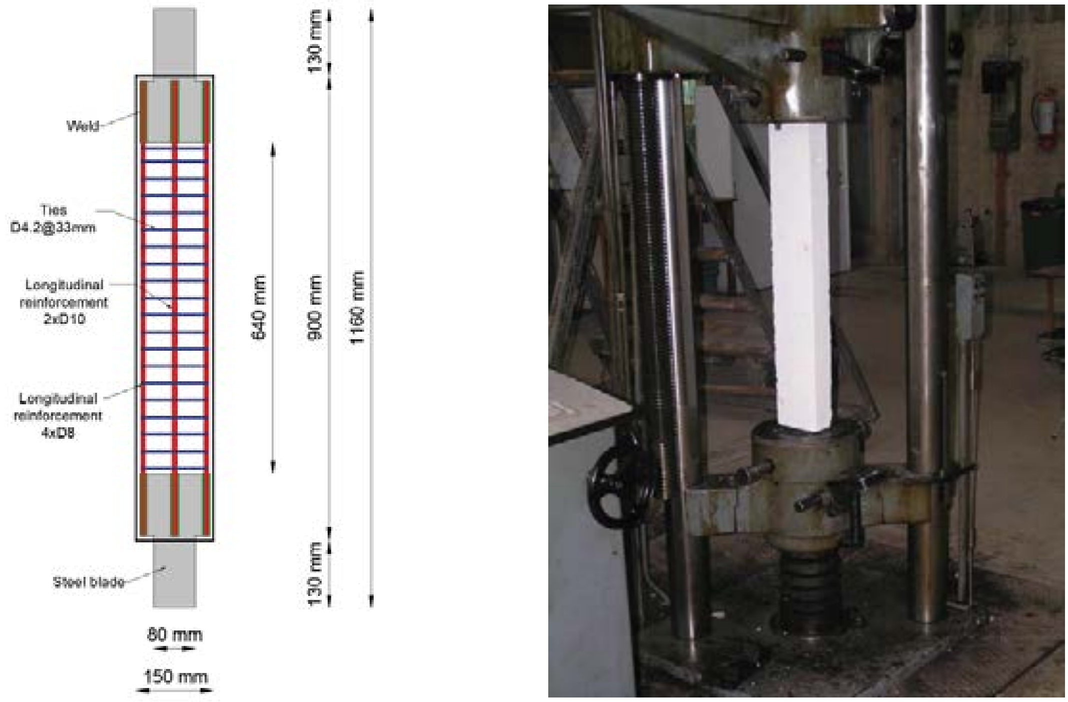
2 EXPERIMENTAL RESEARCH

2.1 Test specimen characteristics

The experimental investigation for the six test specimens has been described in detail by the first author already [51]. Figure 1a shows the geometrical characteristics of one of the six test specimens and more specifically the test specimen detailed with longitudinal reinforcement of 4 bars of 8 mm diameter and 2 bars of 10 mm diameter. Figure 1b displays the load test setup used for the application of the tensile loading. It is noted the fact that the tensile loading is the first stage of the two loading stages. In the framework of the present study, only the experimental results of the tensile loading stage are compared to the analytical ones. Table 1 shows the test specimens' characteristics.

N/A	Specimen	Dimensions (cm)	Longitudinal reinforcement	Transverse reinforcement	Longitudinal reinforcement ratio (%)	Elongation degree (‰)
1	S-1.79-4Ø8	15x7.5x76	4xD8	D4.2@33 mm	1.79	30.00
2	S-2.68-6Ø8	15x7.5x76	6xD8	D4.2@33 mm	2.68	30.00
3	S-3.19-4Ø8+2Ø10	15x7.5x76	4xD8+2xD10	D4.2@33 mm	3.18	30.00
4	S-3.68-4Ø10+2Ø8	15x7.5x76	4xD10+2xD8	D4.2@33 mm	3.68	30.00
5	S-4.02-4Ø12	15x7.5x76	4xD12	D4.2@33 mm	4.02	30.00
6	S-4.19-6Ø10	15x7.5x76	6xD10	D4.2@33 mm	4.19	30.00

Table 1: Dimensions of the test specimens.



(a) **(b)**

Figure 1: (a) Vertical reinforcement layout (Reinforcement differs for each specimen. Example shows a typical longitudinal reinforcement 4xD8+2xD10.), (b) Test setup for tensile loading.

2.2 Materials

Materials used and their characteristics were also described by the first author already [28]. Table 2 displays the concrete mechanical properties and Table 3 the steel characteristics.

N/A	Specimen	Concrete cube resistance (28 days) (MPa)	Concrete cube resistance (Compression test day) (MPa)	Concrete cylinder resistance (Compression test day) (MPa)
1	S-1.79-4Ø8	23.33	25.56	20.56
2	S-2.68-6Ø8	22.22	27.55	22.55
3	S-3.19-4Ø8+2Ø10	22.82	25.78	20.78
4	S-3.68-4Ø10+2Ø8	22.82	25.78	20.78
5	S-4.02-4Ø12	23.26	27.85	22.85
6	S-4.19-6Ø10	23.26	27.85	22.85

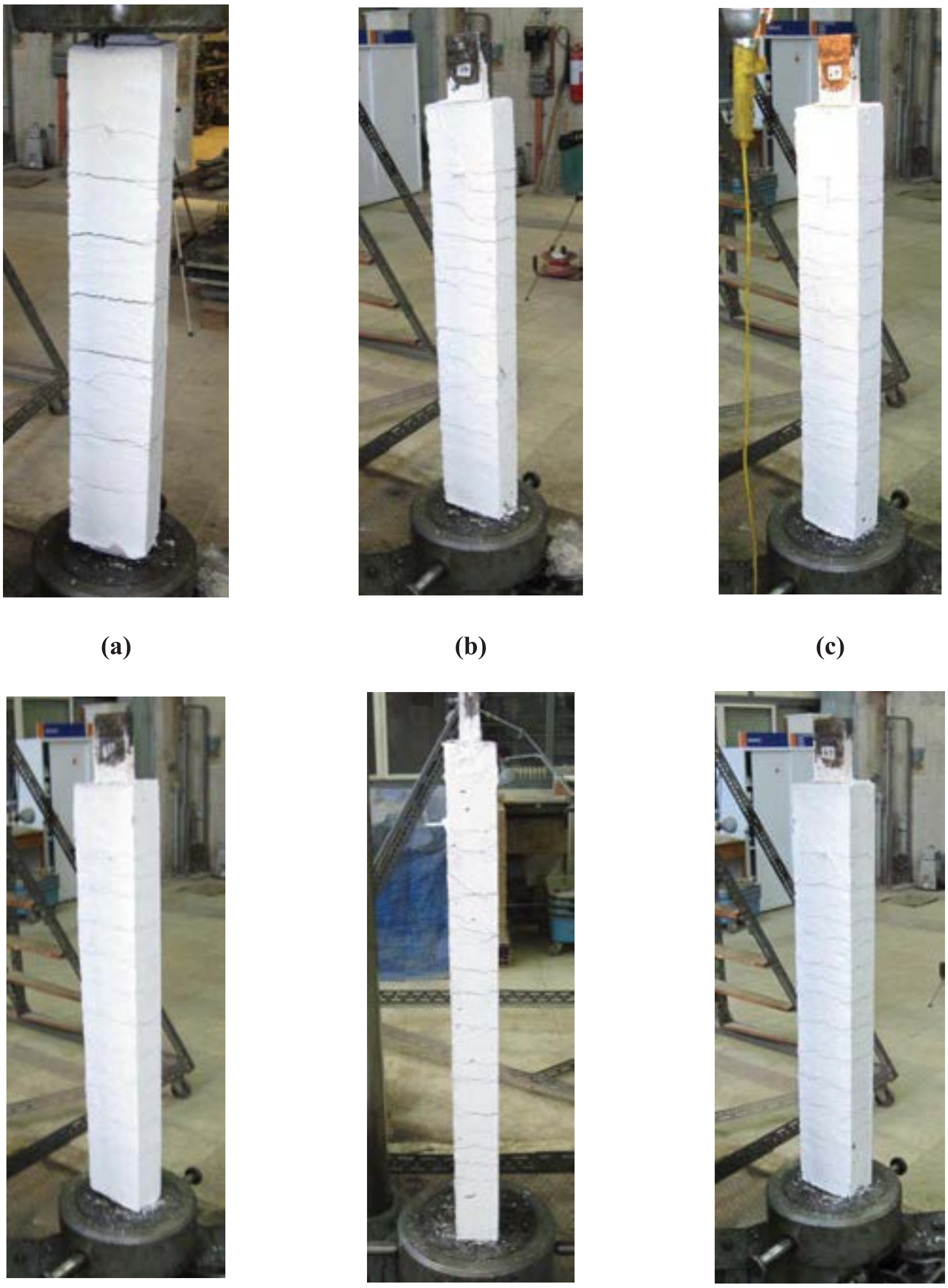
Table 2: Concrete mechanical properties.

Reinforcement	Yield strength (MPa)	Ultimate strength (MPa)
D8 (Longitudinal reinforcement)	603.77	743.10
D10 (Longitudinal reinforcement)	552.02	670.91
D12 (Longitudinal reinforcement)	560.27	666.43
D4.2 (Transverse ties)	552.02	670.91

Table 3: Reinforcement mechanical properties.

2.3 Experimental results

Each one of the six test specimens has been subjected to the same degree of elongation according to Table 1 and the results have been published by the first author already [51]. Figure 2 displays the shape of test specimens after the uniaxial tensile test has taken place. It is obvious that several cracks of different width have formed after the tensile loading according to the longitudinal reinforcement ratio that each specimen has.



(a) (b) (c)

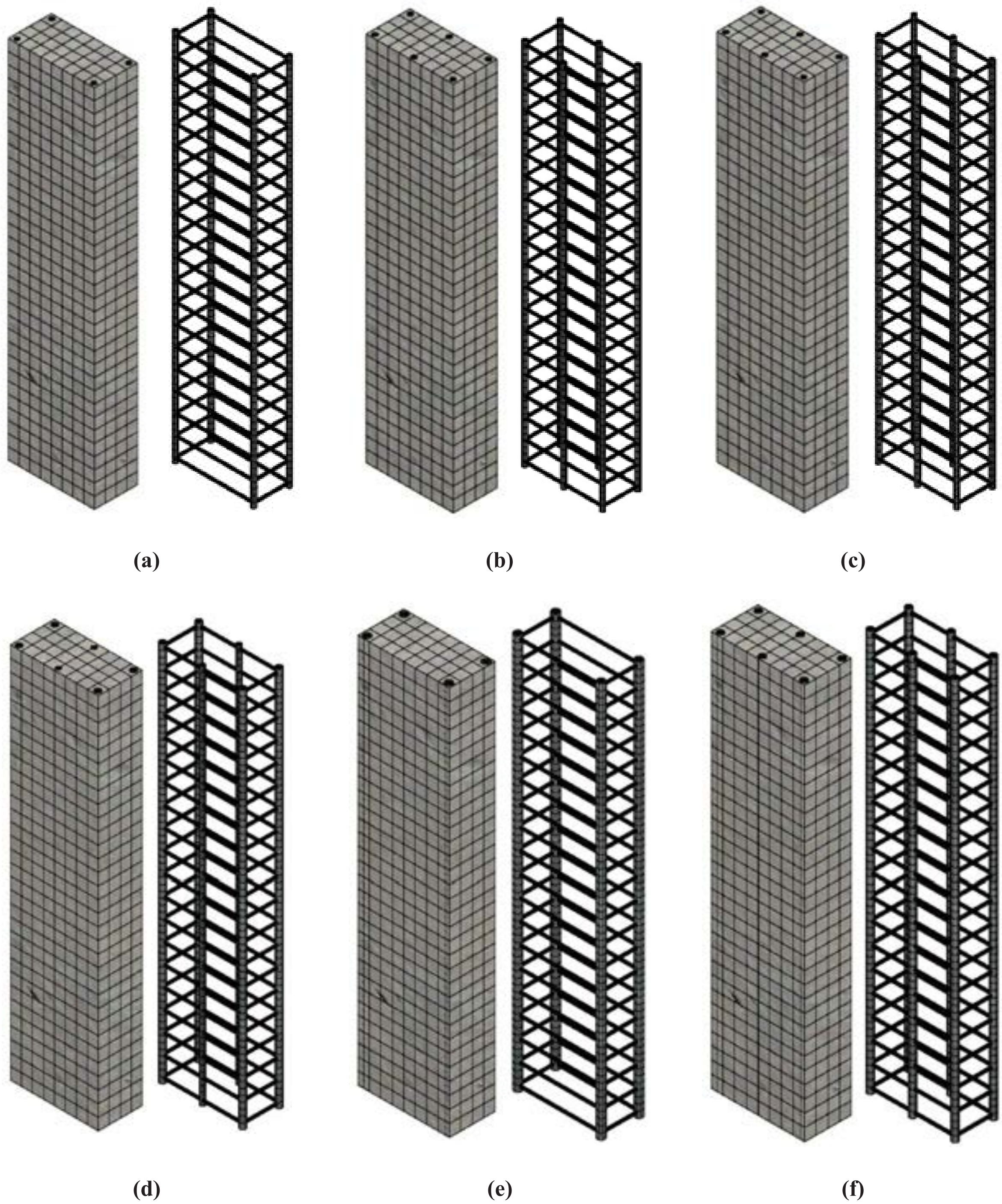
(d) (e) (f)

Figure 2: State of specimens after the end of the tensile experiment: (a) S-1.79-4Ø8, (b) S-2.68-6Ø8, (c) S-3.19-4Ø8+2Ø10, (d) S-3.68-4Ø10+2Ø8, (e) S-4.02-4Ø12, (f) S-4.19-6Ø10

3 ANALYTICAL RESEARCH

3.1 Modeling of test specimens

The analytical research has taken place using 3D elements to model specimens subjected only to tensile loading. Inelastic models are used both for concrete and steel. Figure 3 shows the 3D model both for the whole column section and its corresponding reinforcement steel.



(a) (b) (c)

(d) (e) (f)

Figure 3: 3D model for column and reinforcement for: (a) S-1.79-4Ø8, (b) S-2.68-6Ø8, (c) S-3.19-4Ø8+2Ø10, (d) S-3.68-4Ø10+2Ø8, (e) S-4.02-4Ø12, (f) S-4.19-6Ø10

3.2 Analytical results

Figure 4 displays the displacement along the column height after the end of the tensile loading test for all six test specimens. The displacement is zero at the fixed column base.

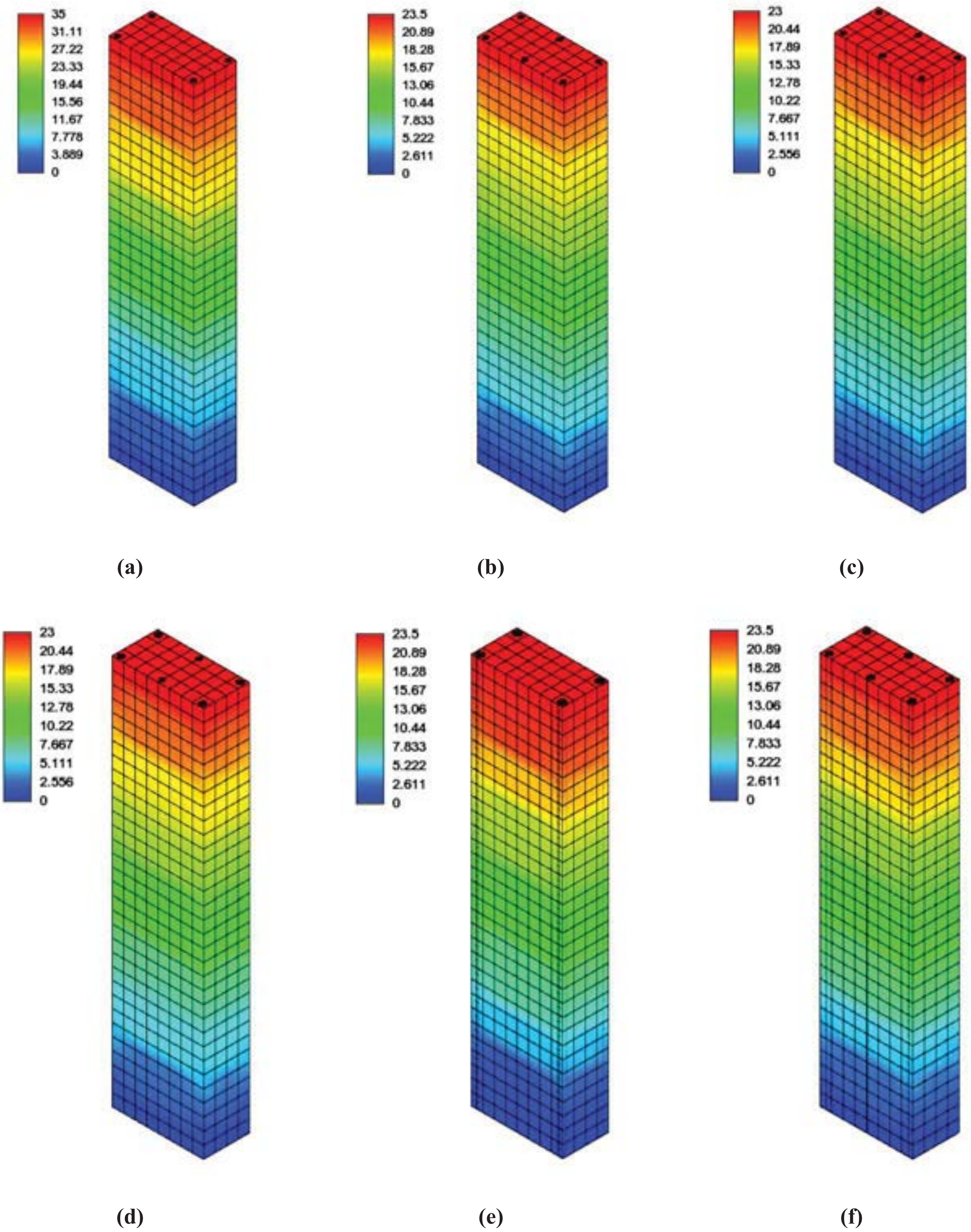


Figure 4: Displacement along the column axis at the end of the tensile test (mm): (a) S-1.79-4Ø8, (b) S-2.68-6Ø8, (c) S-3.19-4Ø8+2Ø10, (d) S-3.68-4Ø10+2Ø8, (e) S-4.02-4Ø12, (f) S-4.19-6Ø10

4 ANALYSIS OF RESULTS

4.1 Analytical versus experimental results

Figures 5-10 show the comparison between the experimental and the analytical diagrams of load versus elongation for specimens modeling the boundary edges of R/C walls.

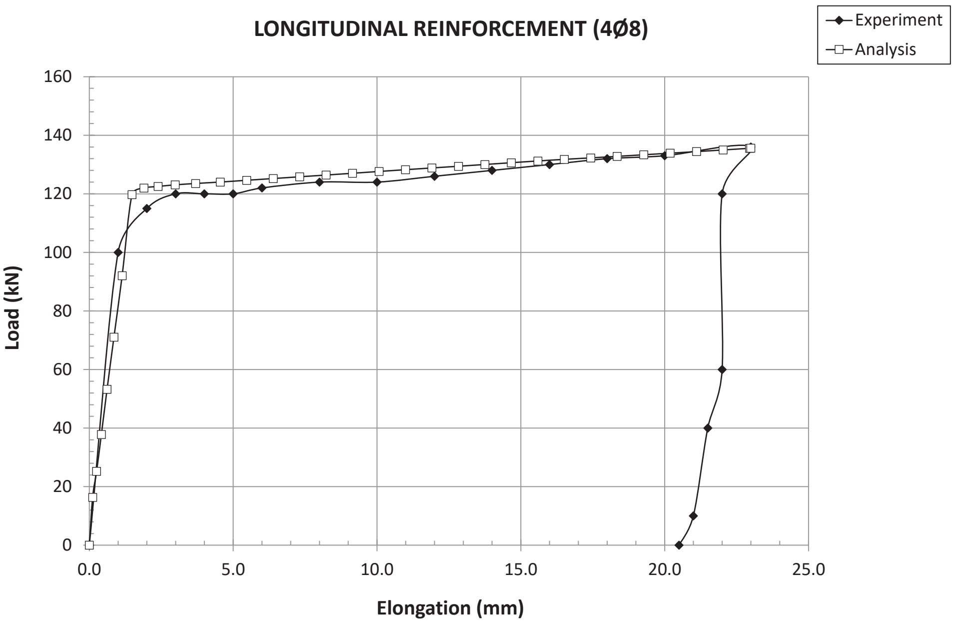


Figure 5: Load versus elongation diagram for specimen S-1.79-4Ø8.

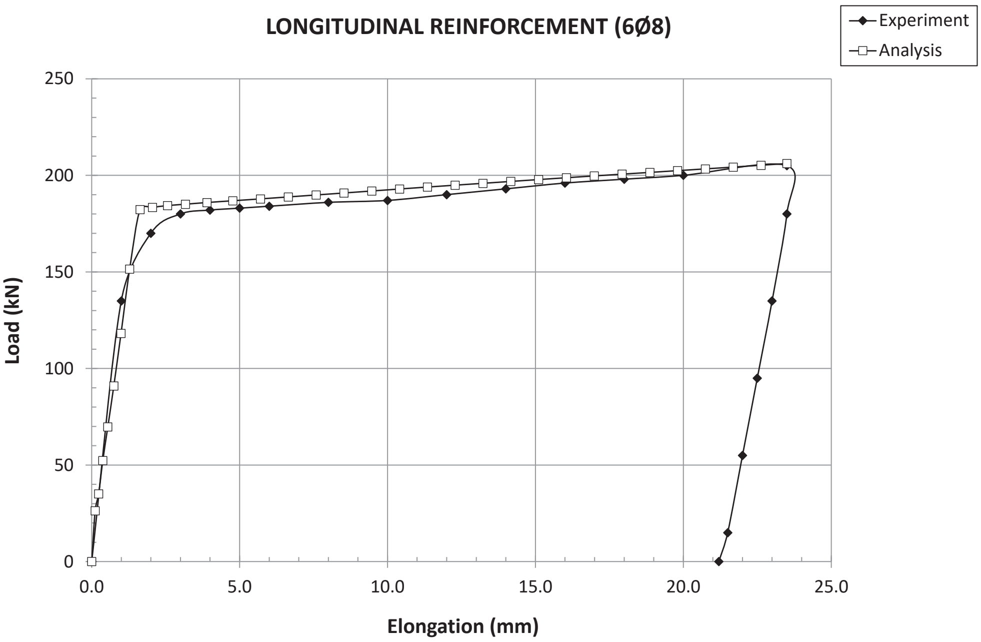


Figure 6: Load versus elongation diagram for specimen S-2.68-6Ø8.

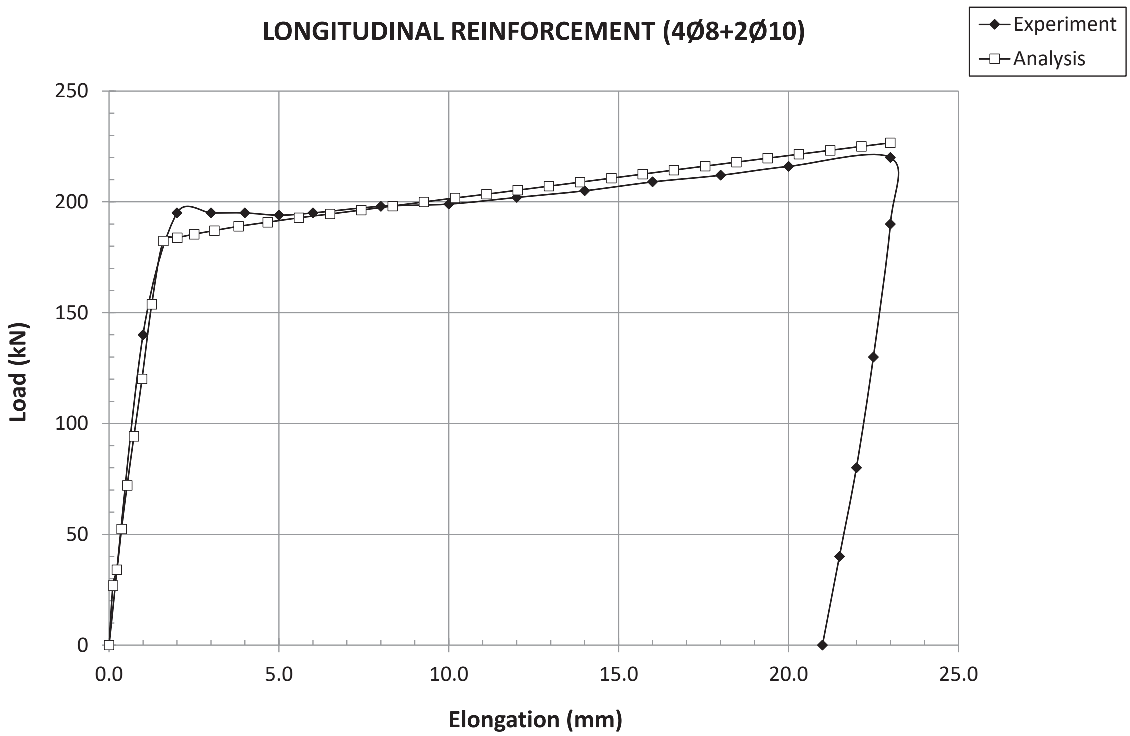


Figure 7: Load versus elongation diagram for specimen S-3.19-4Ø8+2Ø10.

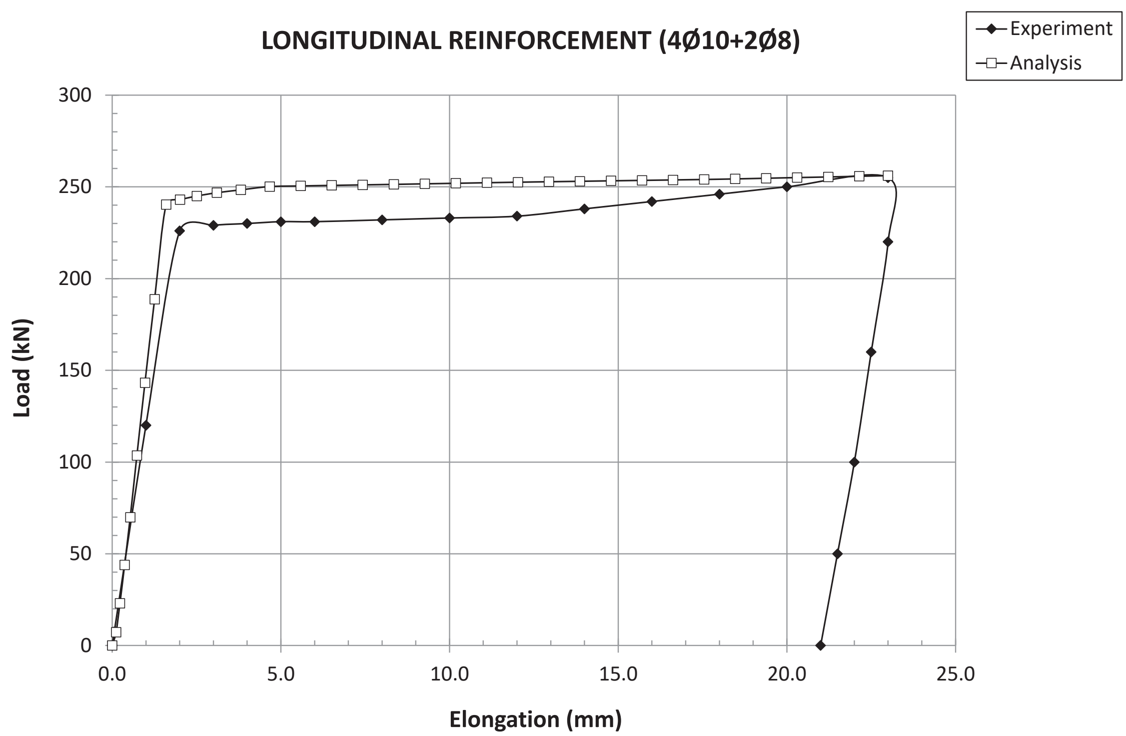


Figure 8: Load versus elongation diagram for specimen S-3.68-4Ø10+2Ø8.

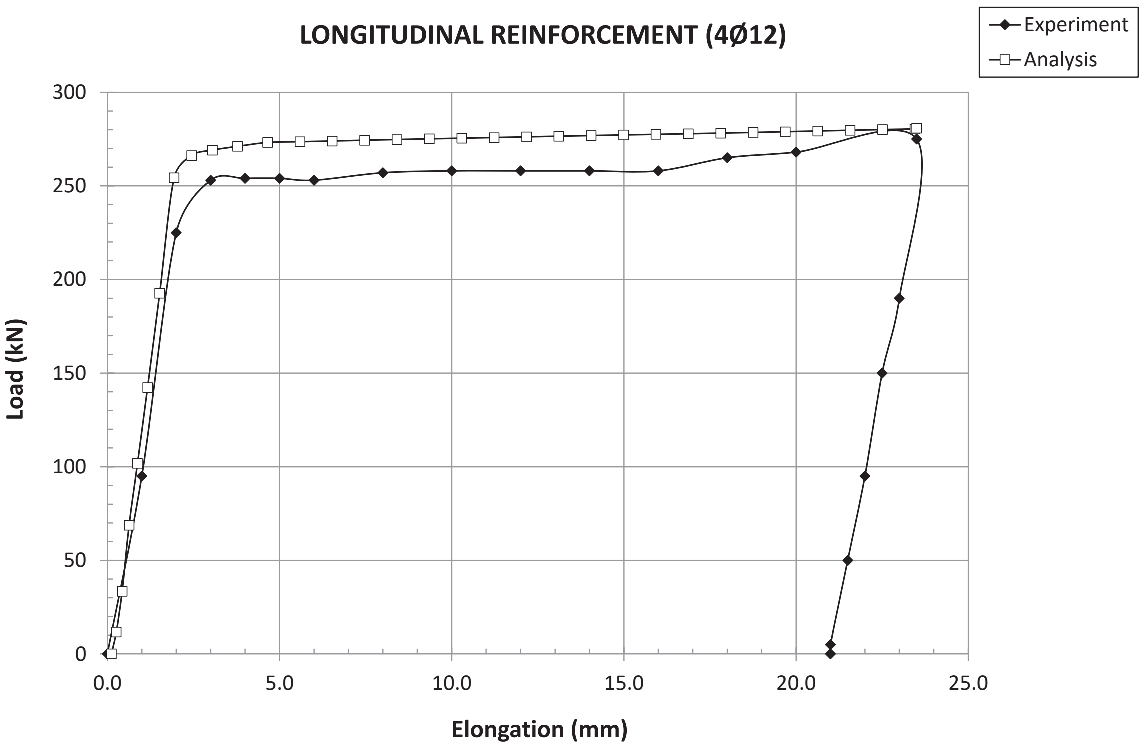


Figure 9: Load versus elongation diagram for specimen S-4.02-4Ø12.

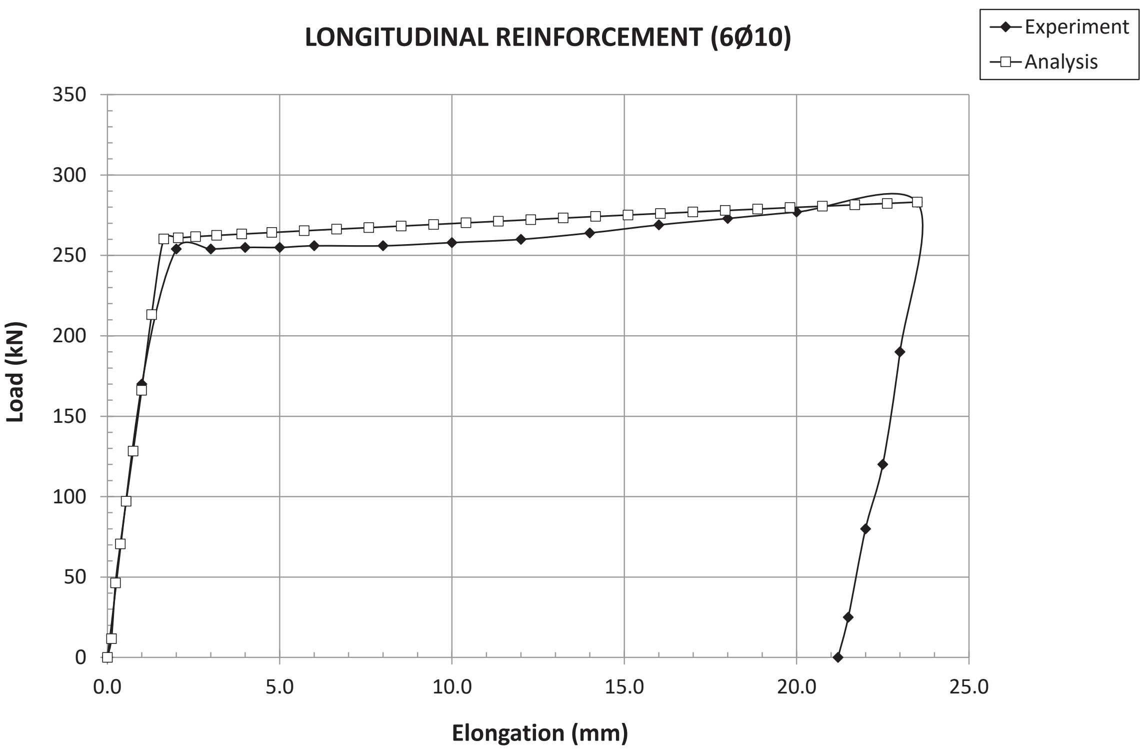


Figure 10: Load versus elongation diagram for specimen S-4.19-6Ø10.

4.2 Analysis of results

The analysis of the previous results leads to the following:

1. Figure 4 shows that the vertical displacement is zero at the base of the prisms since the base is rigid. The maximum vertical displacement is found towards the upper part of the specimens where the tensile load is applied. The same phenomenon at the tensile experiments, too.
2. It is obvious that there is a very good correlation between the experimental and the analytical results for all test specimens (Figures 5-10). This very good correlation can be noticed both for the elastic and the plastic branch, as well as for the point of yield.
3. The 640 mm effective length of the test specimens is the one which has been modelled only since this is the length in which the tensile elongation appears (Figure 1).

5 CONCLUSIONS

The conclusions resulted from the tensile experiments and the relevant analytical procedures concerning the behavior of the extreme edges of R/C walls are:

1. There is a very good correlation between the experimental results and the analytical results concerning the tensile loading. This very good correlation has to do with the elastic branch, the yielding point and the plastic branch for all six specimens.
2. The longitudinal reinforcement ratio is a significant mechanical parameter that affects the behavior of the extreme edges of seismic walls and its investigation has to be applied in the proper and right way following a correct procedure. The good convergence between the experimental and the numerical results proves that the procedure applied, probably, follows the correct methodology.
3. A future research could and should model the whole test specimen and not only the effective length in order to simulate even more precisely the experimental behavior.

REFERENCES

[1] N. Alamanis, “Influence of random soil strength properties on the earthquake vulnerability of slopes with embedded oil and natural gas pipelines,” *Energy Systems*, 2020, doi: 10.1007/s12667-020-00394-9.

[2] N. Alamanis and P. Dakoulas, “Investigation on the effect of spatial variability of soil properties on permanent seismic displacements of slopes in load,” in *14th Baltic Sea Geotechnical Conference 2020*, 2020.

[3] N. Alamanis and P. Dakoulas, “Effect of spatial variability of soil properties on the stability and permanent seismic displacements of highway slopes,” in *The 17th European Conference on Soil Mechanics and Geotechnical Engineering*, 2019.

[4] N. Alamanis and P. Dakoulas, “Effect of the spatial variability of soil properties on the seismic vulnerability of slopes with embedded oil and natural gas pipelines,” in *6th International Conference on “Energy, Sustainability and Climate Change” (ESCC 2019)*, 2019.

[5] N. Alamanis and P. Dakoulas, “Vulnerability of soil slopes against seismic damage based on the effect of spatial variability of soil properties on the development of permanent seismic displacements,” in *International Conference on Research in Engineering, Technology and Science*, 2019.

[6] A. Mouratidis, C. Daniilidou, and G. Papageorgiou, "Evaluation of pavement maintenance and strengthening techniques," in *Bituminous Mixtures and Pavements VII, Proceedings of the 7th International Conference on Bituminous Mixtures and Pavements (ICONFBMP 2019)*, 2019, pp. 516–523.

[7] N. Alamanis, G. Papageorgiou, P. Chantzopoulou, and I. Chouliaras, "Investigation on the influence of permeability coefficient k of the soil mass on construction settlements. Cases of infrastructure settlements in Greece," *Wseas Transactions on Environment and Development*, vol. 15, pp. 95–105, 2019.

[8] G. Papageorgiou, N. Alamanis, I. Chouliaras, and P. Kapsali, "Decision making for designing infrastructure projects: The case of the city of Larissa, Greece," *Journal of Engineering and Architecture*, vol. 7, no. 1, pp. 115–125, 2019, doi: 10.15640/jea.v7n1a13.

[9] G. Papageorgiou and A. Mouratidis, "Defining threshold values for pavement surface characteristics," *Proceedings of the Institution of Civil Engineers (ICE) - Transport*, vol. 168, no. 3, pp. 223–230, 2015, doi: 10.1680/tran.12.00028.

[10] G. Papageorgiou and A. Mouratidis, "A mathematical approach to define threshold values of pavement characteristics," *Structure and Infrastructure Engineering*, vol. 10, no. 5, pp. 568–576, 2014.

[11] K. Christidis and K. Trezos, "Experimental investigation of existing non-conforming RC shear walls," *Engineering Structures*, vol. 140, no., pp. 26–38, 2017, doi: https://doi.org/10.1016/j.engstruct.2017.02.063.

[12] T. Terzioglu, K. Orakcal, and L. M. Massone, "Cyclic lateral load behavior of squat reinforced concrete walls," *Engineering Structures*, vol. 160, 2018, doi: 10.1016/j.engstruct.2018.01.024.

[13] J. W. Wallace, "Performance-Based Design of Tall Reinforced Concrete Core Wall Buildings," *Geotechnical, Geological and Earthquake Engineering*, vol. 17, pp. 279–307, 2010, doi: 10.1007/978-90-481-9544-2_12.

[14] R. Serrette and D. P. Nolan, "Reversed Cyclic Performance of Shear Walls with Wood Panels Attached to Cold-Formed Steel with Pins," *Journal of Structural Engineering*, vol. 135, no. 8, pp. 959–967, 2009, doi: 10.1061/(asce)st.1943-541x.0000037.

[15] H. S. Lee and D. W. Ko, "Seismic response characteristics of high-rise RC wall buildings having different irregularities in lower stories," *Engineering Structures*, vol. 29, no. 11, pp. 3149–3167, 2007, doi: 10.1016/j.engstruct.2007.02.014.

[16] X. Lu and Y. Chen, "Modeling of Coupled Shear Walls and Its Experimental Verification," *Journal of Structural Engineering*, vol. 131, no. 1, pp. 75–84, 2004, doi: 10.1061/(asce)0733-9445(2005)131:1(75).

[17] M. Hassan and S. El-Tawil, "Inelastic dynamic behavior of hybrid coupled walls," *ASCE Journal of Structural Engineering*, vol. 130, no. 2, pp. 285–296, 2004, doi: 10.1061/40616(281)83.

[18] L. M. Massone and J. W. Wallace, "Load-Deformation Responses of Slender Reinforced Concrete Walls," *ACI Structural Journal*, vol. 101, no. 1, pp. 103–113, 2004.

[19] P. Riva, A. Meda, and E. Giuriani, "Cyclic behaviour of a full scale RC structural

wall," *Engineering Structures*, vol. 25, no. 6, pp. 835–845, 2003, doi: 10.1016/S0141-0296(03)00020-8.

[20] A. Rutenberg, "The seismic shear of ductile cantilever wall systems in multistorey structures," *Earthquake Engineering and Structural Dynamics*, vol. 33, no. 7, pp. 881–896, 2004, doi: 10.1002/eqe.384.

[21] Y. Chiou, Y. Mo, F. Hsiao, Y. Liou, and M. Sheu, "Experimental and analytical studies on large-scale reinforced concrete framed shear walls," *Symposium Paper*, vol. 211, no., pp. 201–222, 2003.

[22] T. A. Duffey, C. R. Farrar, and A. Goldman, "Low-Rise Shear Wall Ultimate Drift Limits," *Earthquake Spectra*, vol. 10, no. 4. pp. 655–674, 2003, doi: 10.1193/1.1585792.

[23] Y. L. Mo, J. Zhong, and T. T. C. Hsu, "Seismic simulation of RC wall-type structures," *Engineering Structures*, vol. 30, no. 11, pp. 3167–3175, 2008, doi: 10.1016/j.engstruct.2008.04.033.

[24] I. Ghorbani-Renani, N. Velev, R. Tremblay, D. Palermo, B. Massicotte, and P. Léger, "Modeling and testing influence of scaling effects on inelastic response of shear walls," *ACI Structural Journal*, vol. 106, no. 3, pp. 358–367, 2009.

[25] J. D. Aristizabal-Ocfaoa, "Seismic Behavior of Slender Coupled Wall Systems," *Journal of Structural Engineering*, vol. 113, no. 10, pp. 2221–2234, 2008, doi: 10.1061/(asce)0733-9445(1987)113:10(2221).

[26] P. Bisch and A. Coin, "Seismic behaviour of slightly reinforced concrete walls: Experiments and theoretical conclusions," *Bulletin of Earthquake Engineering*, vol. 5, no. 1, pp. 45–65, 2007, doi: 10.1007/s10518-006-9014-1.

[27] T. Chrysanidis, "Evaluation of Out-of-Plane Response of R/C Structural Wall Boundary Edges Detailed with Maximum Code-Prescribed Longitudinal Reinforcement Ratio," *International Journal of Concrete Structures and Materials*, vol. 14, no. 1. 2020, doi: 10.1186/s40069-019-0378-4.

[28] T. Chrysanidis, "Influence of elongation degree on transverse buckling of confined boundary regions of R/C seismic walls," *Construction and Building Materials*, vol. 211, pp. 703–720, Jun. 2019, doi: 10.1016/J.CONBUILDMAT.2019.03.271.

[29] T. Chrysanidis and I. Tegos, "Does reinforcement ratio affect displacements due to lateral buckling behavior of concrete walls?," *International Journal of Applied Engineering Research*, vol. 12, no. 3, pp. 382–388, 2017.

[30] T. Chrysanidis and I. Tegos, "Influence of elongation degree on out-of-plane buckling of R/C structural walls with a medium high reinforcement ratio," *International Journal of Civil Engineering and Technology*, vol. 7, no. 4, pp. 358–364, 2016.

[31] T. Chrysanidis and I. Tegos, "Size of seismic tensile strain and its influence on the displacements due to transverse buckling of ultra-highly reinforced structural walls," *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 23, pp. 13884–13890, 2016.

[32] T. Chrysanidis and I. Tegos, "Displacements and mode of failure of medium high reinforced walls due to transverse buckling," *International Journal of Engineering Development and Research*, vol. 4, no. 3, pp. 628–634, 2016.

[33] T. Chrysanidis, "Low Reinforced Shear Walls: Displacements and Failure Modes Due to Lateral Buckling," *International Journal of Science and Engineering Investigations*, vol. 5, no. 55, pp. 143–148, 2016.

[34] T. Chrysanidis, "Degree of Elongation of Maximum Code-Prescribed Reinforced Walls: Modes of Failure and Displacements of Lateral Buckling Phenomenon," *International Journal of Trend in Research and Development*, vol. 3, no. 4, pp. 435–440, 2016.

[35] T. Chrysanidis, "Size of seismic tensile strain and its influence on the lateral buckling of highly reinforced concrete walls," *IOSR Journal of Mechanical and Civil Engineering*, vol. 11, no. 1, pp. 18–22, 2014, doi: 10.9790/1684-11121822.

[36] T. Chrysanidis and I. Tegos, "Out-of-plane buckling of highly reinforced seismic walls: Displacements and mode of failure," *International Journal of Civil Engineering and Technology*, vol. 5, no. 6, pp. 101–107, 2014.

[37] C. Alarcon, M. Hube, R. Jünemann, and J. de la Llera, "Characteristics and displacement capacity of reinforced concrete walls in damaged buildings during 2010 Chile earthquake," *Bulletin of Earthquake Engineering*, vol. 13, pp. 1119–1139, 2015, doi: https://doi.org/10.1007/s10518-015-9727-0.

[38] A. Haro, M. Kowalsky, Y. Chai, and G. Lucier, "Boundary elements of special reinforced concrete walls tested under different loading paths," *Earthquake Spectra*, vol. 34, no. 3, pp. 1267–1288, 2018, doi: 10.1193/081617EQS160M.

[39] K. Herrick and M. Kowalsky, "Out-of-plane buckling of ductile reinforced structural walls due to in-plane loads," *Journal of Structural Engineering*, vol. 143, no. 3, pp. 1–15, 2016, doi: 10.1061/(asce)st.1943-541x.0001660.

[40] Y. Chai and S. Kunnath, "Minimum thickness for ductile RC structural walls," *Engineering Structures*, vol. 27, no. 7, pp. 1052–1063, Jun. 2005, doi: 10.1016/j.engstruct.2005.02.004.

[41] T. Welt, L. Massone, J. LaFave, D. Lehman, S. McCabe, and P. Polanco, "Confinement behavior of rectangular RC prisms simulating wall boundary elements," *Journal of Structural Engineering*, vol. 143, no. 4, pp. 1–12, 2017, doi: 10.1061/(asce)st.1943-541x.0001682.

[42] T. Chrysanidis and I. Tegos, "The influence of the degree of elongation to the ultimate strength and mode of failure of RC walls reinforced with the maximum code-prescribed longitudinal reinforcement ratio," in *Proceedings of the 2013 International Van Earthquake Symposium*, 2013.

[43] T. Chrysanidis and I. Tegos, "The influence of the degree of elongation of the longitudinal reinforcement of the high-reinforced end sections of ductile structural walls to their ultimate strength and mode of failure," in *Proceedings of the Vienna Congress on Recent Advances in Earthquake Engineering and Structural Dynamics (VEESD 2013)*, 2013.

[44] T. Chrysanidis and I. Tegos, "The influence of the longitudinal reinforcement ratio of R/C walls to their displacements due to failure of transverse instability under extreme seismic loads," in *Proceedings of the Vienna Congress on Recent Advances in Earthquake Engineering and Structural Dynamics (VEESD 2013)*, 2013.

[45] T. Chrysanidis and I. Tegos, "The influence of the degree of elongation of the ultra

high-reinforced end sections of R/C walls to their displacements and mode of failure," in *Proceedings of the 2013 International Van Earthquake Symposium*, 2013.

[46] T. Chrysanidis and I. Tegos, "The influence of the degree of elongation to the displacements and mode of failure of medium-reinforced ductile structural walls," in *Proceedings of the Engineering a Concrete Future: Technology, Modeling and Construction (fib Symposium 2013)*, 2013.

[47] T. Chrysanidis and I. Tegos, "The influence of ratio of the longitudinal reinforcement of the boundary edges of structural walls to the resistance against lateral instability of earthquake-resistant reinforced concrete structural walls," in *Proceedings of the 15th World Conference on Earthquake Engineering (15th WCEE 2012)*, 2012.

[48] T. Chrysanidis and I. Tegos, "The influence of tension strain of wall ends to their resistance against lateral instability for low-reinforced concrete walls," in *Proceedings of the 15th World Conference on Earthquake Engineering (15th WCEE 2012)*, 2012.

[49] T. Chrysanidis, "Evaluation of lateral buckling phenomenon using R/C prisms detailed with an ultra high reinforcement ratio," in *Emerging Trends in Engineering Research and Technology Vol. 3*, L. Salisu, Ed. London, UK: Book Publisher International, 2020, pp. 55–64.

[50] T. Chrysanidis and I. Tegos, "Can the diameter of longitudinal bars of extreme edges of R/C walls halt transverse buckling?," in *Emerging Trends in Engineering Research and Technology Vol. 3*, L. Salisu, Ed. London, UK: Book Publisher International, 2020, pp. 65–72.

[51] T. Chrysanidis, "The effect of longitudinal reinforcement ratio on the lateral buckling behavior of R/C walls modelled using prism elements," *Journal of Building Engineering*, vol. 42, no. 102456, 2021, doi: 10.1016/j.jobe.2021.102456.