Proceedings of the 7^h World Congress on Civil, Structural, and Environmental Engineering (CSEE'22)
~~Lisbon, Portugal~~ Virtual Conference – April 10 – 12, 2022
Paper No. ICSECT 147
DOI: 10.11159/icsect22.147

Experimental Study on the Effect of Elongation Degree on the Cracking of Highly-Reinforced R/C Members

Theodoros Chrysanidis[1*], Nikolaos Alamanis[2], Grigorios Papageorgiou[3]
[1*]Aristotle University of Thessaloniki
54124, Thessaloniki, Greece
chrysanid@uth.gr
[2]University of Thessaly
41110, Larissa, Greece
alam@teilar.gr
[3]University of Thessaly
V. Griva 11, 41300, Karditsa, Greece
gpapageor@uth.gr

Abstract **-** The main objective of this research is to study the phenomenon of cracking in the R/C structural elements, in particular the columns and the walls, and more particularly in the extreme regions of the walls, namely the boundary columns. Various parameters of the phenomenon of cracking will be studied, e.g., load influence, tensile strain, etc. It has to be noted the fact that load application is a monotonic axial tensile loading that simulates the strain condition that takes place at the boundary edges of reinforced concrete seismic walls. Specifically, this type of loading simulates the tensile loading that takes place during the first semi-cycle of loading under seismic dynamic events. Experimental research takes place by the construction and use of a group of 4 experimental specimens subjected to different degrees of elongation. This test group examines the tensile parameter and how it affects the cracking. The test specimens in question are all reinforced with the same high longitudinal reinforcement ratio (3.68%) and subjected to tensile degrees 10‰, 20‰, 30‰ and 50‰. Significant conclusions are reached on cracking, e.g., its extent, the size of the cracks, their positions, minimum crack width, maximum crack width, average crack width, number of cracks, etc.

Keywords**:** Elongation Degree, Cracking, Structural Elements, Width, Highly-Reinforced

1. Introduction

Several international researchers have explored the phenomenon of cracking in reinforced concrete structures [1]–[5]. Although most of the given structures are typically reinforced in two directions, most studies carried out worldwide to investigate the behaviour of cracking have involved uniaxially strained reinforced concrete members with reinforcement in only one direction. To date there is not yet a widely established and accepted methodology for predicting cracking characteristics, e.g., crack widths and spacings between cracks [6]–[9]. In addition, most of the existing research conducted has been strictly limited to the state of the stabilized crack pattern only and does not involve cracking behaviour and crack characteristics deep in the yield region [10], [11]. It has to be noted the fact that cracking can occur in several situations, e.g., transverse buckling of R/C structural walls or retaining walls under cyclic seismic loading [12]–[18], phenomena appearing due to soil-structure interaction [19]–[23], etc. The cost of repairing the cracking and the possible resulting corrosion to the reinforcement bars is something which needs to be taken into account by consulting engineers, too [24]–[29]. Furthermore, cracking can reduce the load-bearing capacity of R/C members [6], [7], [9].

In the framework of the current study, an experimental program has been conducted involving reinforced concrete members detailed in two directions using longitudinal rebars and transverse reinforcement in the form of ties. This is a common construction practice used, in at least, the vast majority of concrete structures. As per the results outlined within this work, cracking behaviour and the crack characteristics are discussed. Afterwards, the aforementioned experimental results are analysed and the results of the analysis given in the form of diagrams are discussed. Useful conclusions concerning cracking under different degrees of elongation are derived.

2. Experimental Program

The current experimental program consists of four test specimens. The thickness of each specimen is 7.5 cm and the length of the cross-section is 15 cm. The ratio between the length and the thickness of the cross-sectional area is equal to 2, which is a typical ratio for constructing reinforced concrete columns. The total height of the test specimen is equal to 90 cm. Each of the four specimens is subjected to a uniaxial central tensile loading. The main test element is between the metal plates and its height is 64 cm (Figure 1). A universal testing machine was used to apply the load. For example, for specimen CH-30, the nominal degree of elongation is 30.00‰. Figure 2 displays the experimental configuration for imposing the central tensile load. The rate of loading was slow, of the order of 4 mm/min, so no result was affected by the influence of the strain rate [30]–[36].

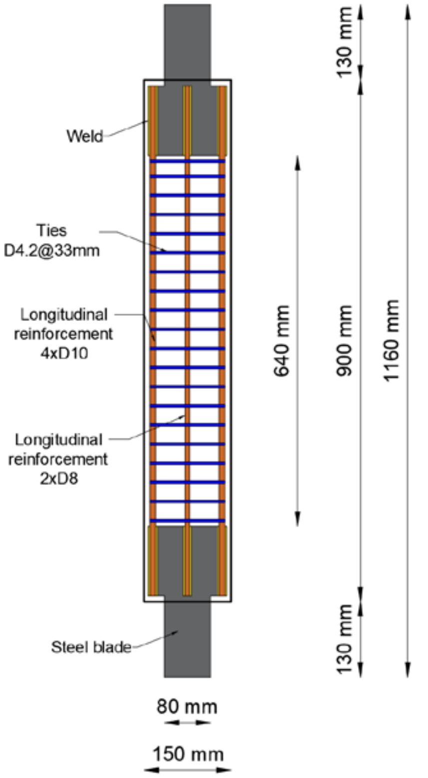

Figure 1: Vertical reinforcement layout for specimens.

Figure 2: Loading test configuration.

Table 1 shows the geometrical and detailing characteristics of all four specimens. All four segments tested here have been worked on in two directions through deformed bars in terms of reinforcement. The reinforcement of each specimen simulates a typical reinforcement found in the reinforced concrete columns of typical construction buildings or in the confined boundaries of reinforced concrete seismic walls. The construction scale used to simulate typical columns or typical confined boundaries was equal to 1:3, commonly used for research purposes worldwide [37], [38].

The number of longitudinal bars is equal to six. Four bars with 10 mm diameter and two bars with 8 mm diameter. The longitudinal reinforcement ratio is equal to 3.68%. The transverse reinforcement consists of transverse ties placed along the height of the prism. The centre-to-centre distance between two ties is about 3.3 cm and the diameter of each tie is 4.2 mm. The only variable differentiating specimens from each other is the elongation degree. The nominal degree of elongation takes values equal to 10.00‰, 20.00‰, 30.00‰ and 50.00‰. It is well known that in real constructions, tensile strains up to 30.00‰ have been observed [39], [40]. Also, modern seismic and concrete codes have provisions allowing large tensile strains for reinforcement bars [41]–[45]. These are the reasons why such large tensile strains were chosen to be applied to the elements. There is also, of course, the research interest itself, in examining what happens to cracking characteristics strained to such extents and their behaviour when such large strains are observed.

Table 1: Properties of prism specimens

N/A	Specimen name	Length (cm)	Thickness (cm)	Effective height (cm)	Longitudinal reinforcement	Longitudinal reinforcement ratio [ρ_l] (%)	Transverse reinforcement	Nominal tensile strain (‰)
1	CH-10	15	7.5	64	4xD10 + 2xD8	3.68	D4.2@33 mm	10.00
2	CH-20	15	7.5	64	4xD10 + 2xD8	3.68	D4.2@33 mm	20.00
3	CH-30	15	7.5	64	4xD10 + 2xD8	3.68	D4.2@33 mm	30.00
4	CH-50	15	7.5	64	4xD10 + 2xD8	3.68	D4.2@33 mm	50.00

3. Results and Discussion

3.1. Experimental Findings

After conducting the tensile experiments, different cracking formations and eventually cracking characteristics were noticed for each specimen. Figure 3 shows the state of each specimen after the end of the uniaxial tensile test. Cracks of small width are obvious for specimens with low degrees of tensile strain (10‰ and 20‰), while cracks of moderate and large width are present for specimens strained under larger degrees of elongation (30‰ and 50‰). It is apparent that the final cracking formation differs between the specimens, depending on the tensile strain they have sustained.

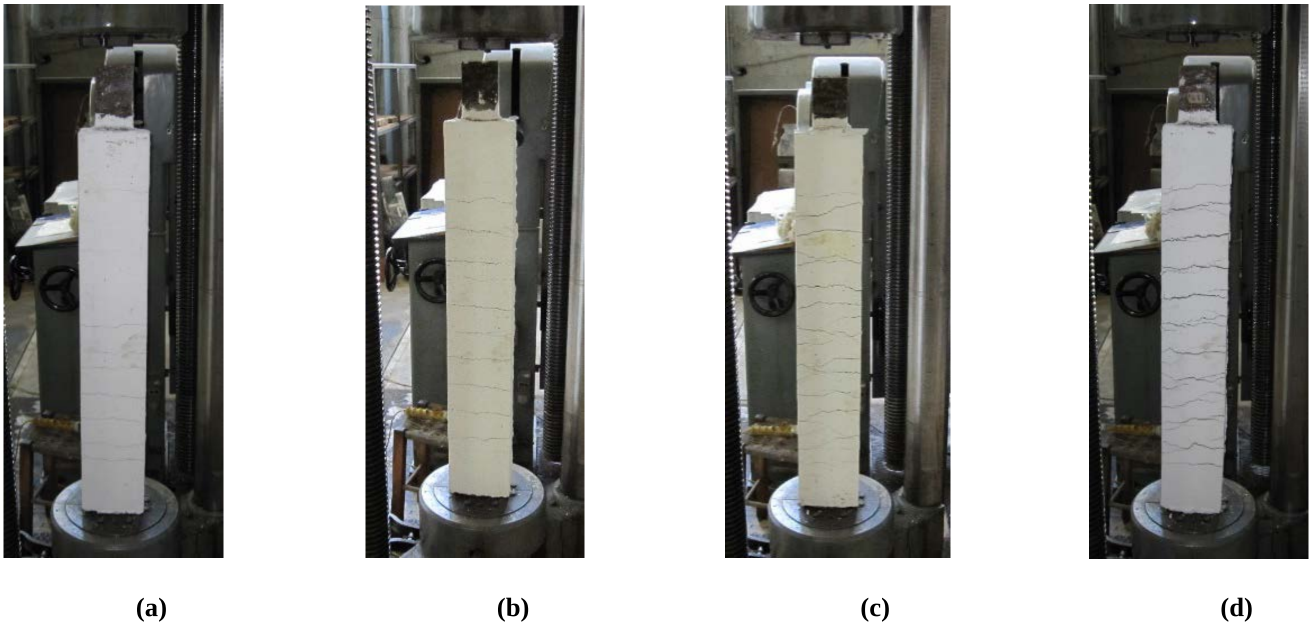

Figure 3: Specimens after the uniaxial tensile test: (a) CH-10, (b) CH-20, (c) CH-30, (d) CH-50.

3.2. Analysis of Experimental Findings

The results of the analysis of the test findings for all segments are brought together in the following table and Table 2 presents the width characteristics of the cracks. Figure 4 displays the variation of the crack width characteristics. Figure 5 – Figure 8 use column charts to display the results for the same type of cracking characteristics, e.g., maximum width, average width, etc.

Table 2: Crack width characteristics.

N/A	Specimen	Number of cracks [N]	Minimum crack width [W_{min}] (mm)	Maximum crack width [W_{max}] (mm)	Average crack width [W_{ave}] (mm)	W_{min}/W_{ave}	W_{max}/W_{ave}	W_{max}/W_{min}
1	CH-10	10	0.2	0.8	0.580	0.34	1.38	4.00
2	CH-20	12	0.2	1.4	0.917	0.22	1.53	7.00
3	CH-30	14	0.6	1.9	1.279	0.47	1.49	3.17
4	CH-50	14	1.2	3.2	2.321	0.52	1.38	2.67

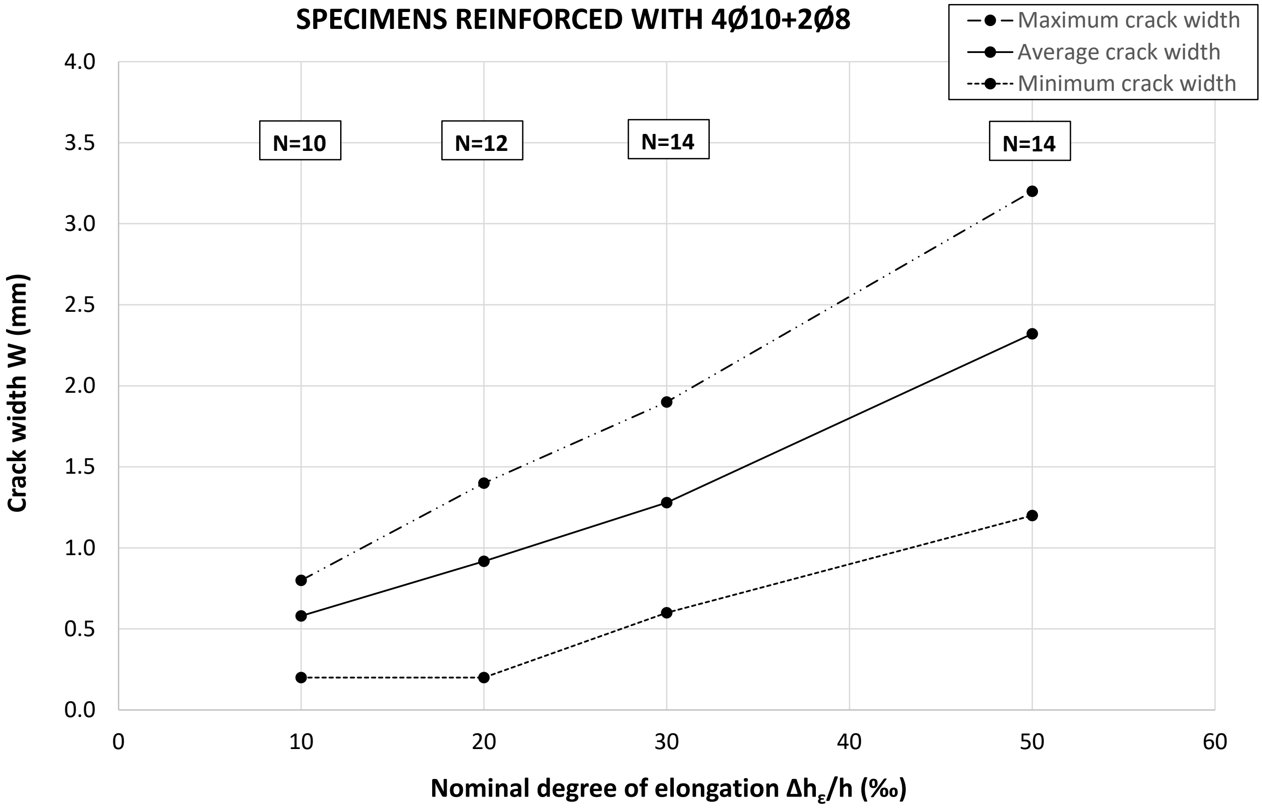

Figure 4: Variation of crack width relative to the degree of elongation.

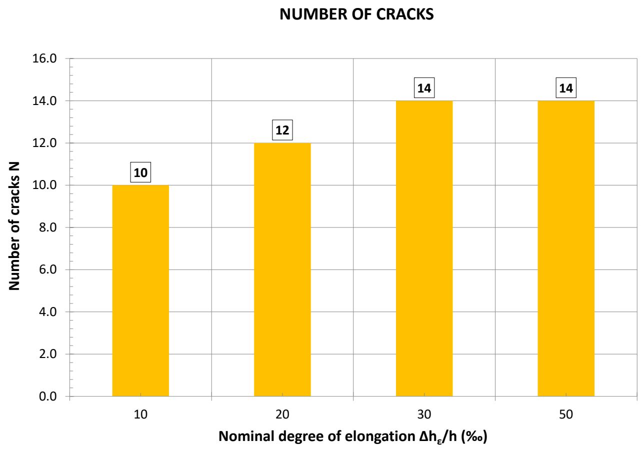

Figure 5: Column chart of number of cracks regarding the elongation degree.

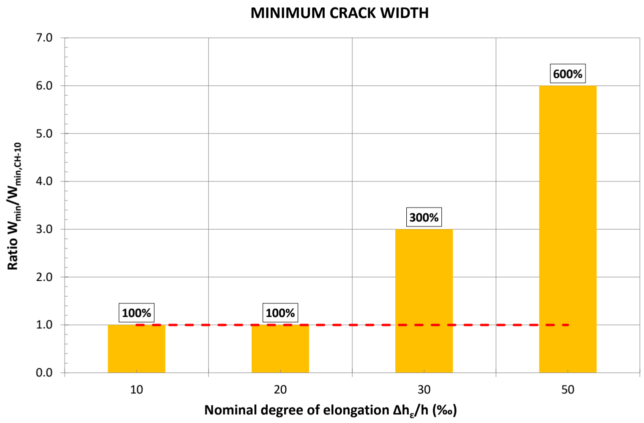

Figure 6: Column chart of minimum crack width as a percentage of the minimum crack width of the reference specimen.

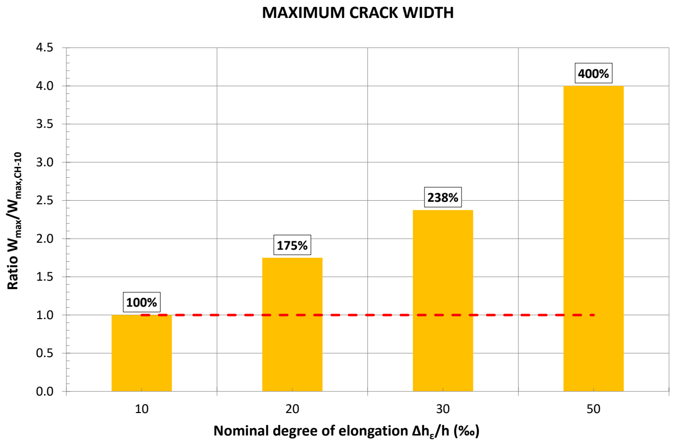

Figure 7: Column chart of maximum crack width as a percentage of the maximum crack width of the reference specimen.

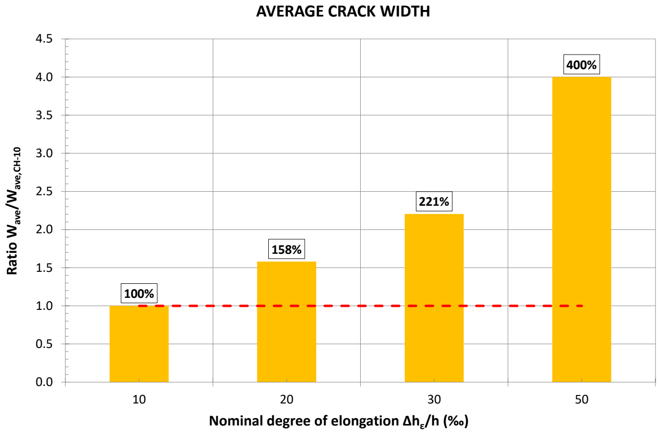

Figure 8: Column chart of average crack width as a percentage of the average crack width of the reference specimen.

The experimental findings of the test specimens were then analysed and evaluated:

1. Comparing the number of cracks formed according to the tensile strain applied, it is obvious that the number of cracks formed increases with the increase of the degree of elongation applied (Table 2, Figure 5). For a better understanding of this phenomenon, more experiments concerning different longitudinal reinforcement ratios and arrangements of rebars need to be performed.
2. Comparing the crack width with the degree of elongation applied, it can be seen that the width becomes larger as the elongation degree applied increases (Table 2, Figure 4). It is noteworthy that all types of crack width increase with the increment of the tensile degree – meaning the minimum, maximum and average crack width.
3. Specimen CH-10 is characterized as the reference specimen. It is noticeable that although the normalized elongation (20‰) is two times greater for specimen CH-20 compared to the elongation of the reference specimen (10‰), there is no increase for the minimum crack width which remains the same. However, for the specimen CH-50 the increase of

the minimum crack width is higher compared to the increment of the elongation degree applied; meaning six times larger minimum crack width whereas the degree of elongation is five times larger. No specific trend is displayed.

4. The increase of the average widths is smaller compared to the increase of normalized elongation, e.g., specimen CH-30 displays a 221% increase in average crack width for a 300% elongation increase compared to the reference specimen.
5. The damage state of specimens indicates that cracks appear at or near to the tie positions (Figure 3). Thus, the presence of steel ties helps and promotes the disorganization of concrete around them.

4. Conclusions

This paper looks at four specimens to investigate cracking formation and behaviour in terms of crack characteristics. The following conclusions are drawn:

1. The degree of tensile deformation holds a significant part in terms of the formation of cracks and their characteristics, e.g., the number of cracks formed and the width of cracks.
2. Higher degrees of elongation result in cracks with larger widths. Thus, the design of reinforced concrete structural components should take into account the degree of elongation because, as it is well known, large crack widths can lead to oxidization and deterioration of rebars and eventually affect structural safety.
3. The question arises whether the longitudinal ratio or whether the arrangement of rebars plays an essential role, too. Further research is needed on the subject using test specimens with different longitudinal reinforcement ratios and arrangements. This will help to check the impact that the mechanical factor of reinforcement ratio has.

References

[1] H. T. Hu and W. C. Schnobrich, “Nonlinear analysis of cracked reinforced concrete,” *ACI Structural Journal*, vol. 87, no. 2. pp. 199–207, 1990.

[2] Z. Shi, M. Suzuki, and M. Nakano, “Numerical Analysis of Multiple Discrete Cracks in Concrete Dams Using Extended Fictitious Crack Model,” *Journal of Structural Engineering*, vol. 129, no. 3, pp. 324–336, 2003, doi: 10.1061/(asce)0733-9445(2003)129:3(324).

[3] H. Mirzabozorg and M. Ghaemian, “Non-linear behavior of mass concrete in three-dimensional problems using a smeared crack approach,” *Earthquake Engineering and Structural Dynamics*, vol. 34, no. 3, pp. 247–269, 2005, doi: 10.1002/eqe.423.

[4] H. G. Sohn, Y. M. Lim, K. H. Yun, and G. H. Kim, “Monitoring crack changes in concrete structures,” *Computer-Aided Civil and Infrastructure Engineering*, vol. 20, no. 1, pp. 52–61, 2005, doi: 10.1111/j.1467-8667.2005.00376.x.

[5] M. M. Smadi and F. O. Slate, “Microcracking of high and normal strength concretes under short- and long-term loadings,” *ACI Materials Journal*, vol. 86, no. 2. pp. 117–127, 1989.

[6] T. Chrysanidis and V. Panoskaltsis, “Evaluation of cracking behavior of R/C vertical components reinforced with varying longitudinal reinforcement ratios,” in *Proceedings of the XI International Conference on Structural Dynamics (EURODYN 2020)*, 2020, pp. 3186–3197, doi: 10.47964/1120.9260.18887.

[7] T. Chrysanidis and V. Panoskaltsis, “Experimental investigation of the influence of tensile strain on the cracking of R/C vertical structural elements,” in *Proceedings of the XI International Conference on Structural Dynamics (EURODYN 2020)*, 2020, pp. 3174–3185, doi: 10.47964/1120.9259.18582.

[8] T. Chrysanidis and V. Panoskaltsis, “Does the degree of tensile strain have an impact on the cracking behavior of vertical structural elements?,” in *IOP Conference Series: Materials Science and Engineering, 2020 5th International Conference on Civil Engineering and Materials Science (ICCEMS 2020)*, 2020, vol. 897, doi: 10.1088/1757-899X/897/1/012004.

[9] I. Tegos, N. Giannakas, and T. Chrysanidis, “Serviceability cracking check of circular section piers,” *Bridge Structures*, vol. 7, no. 1, pp. 43–52, 2011, doi: 10.3233/BRS-2011-018.

[10] Wood Sharon, Wight James, and J. Moehle, “The 1985 Chile earthquake: Observations on earthquake-resistant construction in Vina del Mar,” Urbana, Illinois, U.S., 1987.

[11] M. Fintel, “Performance of Buildings With Shear Walls in Earthquakes of the Last Thirty Years,” *PCI Journal*, vol. 40,

no. 3. pp. 62–80, 2014, doi: 10.15554/pcij.05011995.62.80.

[12] T. Chrysanidis and V. Panoskaltsis, “Analytical investigation of the tensile experiments modeling the elongation degree of R/C walls for studying the lateral buckling phenomenon,” in *Proceedings of the 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2021)*, 2021, pp. 2718–2729, doi: https://doi.org/10.7712/120121.8669.18668.

[13] T. Chrysanidis and V. Panoskaltsis, “Analytical investigation of the tensile experiments to prisms with varying longitudinal ratio for studying the lateral buckling of R/C walls,” in *Proceedings of the 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2021)*, 2021, pp. 2730–2743, doi: https://doi.org/10.7712/120121.8670.18669.

[14] T. Mitkou and T. Chrysanidis, “R/C column modeling using ANSYS and loading rate and mesh method influence studies,” in *Proceedings of the 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2021)*, 2021, pp. 1063–1084, doi: https://doi.org/10.7712/120121.8546.19132.

[15] T. Chrysanidis and I. Tegos, “How does degree of elongation affect lateral buckling behavior of seismic walls?,” *American Academic and Scholarly Research Journal*, vol. 7, no. 4, pp. 266–272, 2015.

[16] T. Chrysanidis and I. Tegos, “The influence of the degree of elongation to the displacements of seismic walls with maximum code-prescribed reinforcement ratio,” *American Academic and Scholarly Research Journal*, vol. 7, no. 4, pp. 273–279, 2015.

[17] T. Chrysanidis and I. Tegos, “Does degree of elongation affect displacements of structural walls?,” *American Academic and Scholarly Research Journal*, vol. 6, no. 4, pp. 344–350, 2014.

[18] T. Chrysanidis and I. Tegos, “The influence of the diameter of the longitudinal reinforcement of RC walls to their displacements against lateral instability,” *American Academic and Scholarly Research Journal*, vol. 6, no. 4, pp. 351–359, 2014.

[19] 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.

[20] G. Papageorgiou, N. Alamanis, and N. Xafoulis, “Acceptable movements of road embankments,” *Electronic Journal of Structural Engineering*, vol. 20, no. 1, pp. 30–32, 2020.

[21] 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.

[22] N. Alamanis and P. Dakoulas, “Simulation of random soil properties by the Local Average Subdivision method and engineering applications,” *Energy Systems*, pp. 1–21, 2019, doi: 10.1007/s12667-019-00362-y.

[23] 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.

[24] P. Tselempi and T. Chrysanidis, “Differentiation of the construction cost of a fifteen-storey R/C building depending on the seismic hazard zone,” in *Proceedings of the 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2021)*, 2021, pp. 4520–4534, doi: https://doi.org/10.7712/120121.8804.19133.

[25] T.-E. Makris and T. Chrysanidis, “Does the seismicity of the area have an impact on the construction cost of the load-bearing structure of R/C buildings?,” in *Proceedings of the 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2021)*, 2021, pp. 4535–4546, doi: https://doi.org/10.7712/120121.8805.19134.

[26] P. Sioulas, T. Chrysanidis, N. Alamanis, and G. Papageorgiou, “Study of the influence of seismic action on the construction cost of the load-bearing structure of a ten-storey R/C building,” in *Proceedings of the 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2021)*, 2021, pp. 1712–1724, doi: https://doi.org/10.7712/120121.8593.18667.

[27] T. Chrysanidis, N. Alamanis, and G. Papageorgiou, “Investigation of the impact of seismic zone to the cost of

construction of a 5-storey R/C building," in *Proceedings of the 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2021)*, 2021, pp. 4272–4282, doi: https://doi.org/10.7712/120121.8784.19209.

[28] T. Chrysanidis, V. Panoskaltsis, and I. Tegos, "Parametrical cost analysis of an ultra high-rise building: Detailed design," *International Journal of Applied Engineering Research*, vol. 11, no. 18, pp. 9644–9650, 2016.

[29] T. Chrysanidis and I. Tegos, "Cost Comparison and Parametrical Investigation of the R/C Shear Wall Core of a Tall Building," *International Journal of Engineering Research and Technology*, vol. 5, no. 09, pp. 592–595, 2016.

[30] 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.

[31] T. Chrysanidis and I. Tegos, "Axial and transverse strengthening of R/C circular columns: Conventional and new type of steel and hybrid jackets using high-strength mortar," *Journal of Building Engineering*, vol. 30, no. January, p. 101236, 2020, doi: 10.1016/j.jobe.2020.101236.

[32] 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.

[33] 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.

[34] 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.

[35] 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.

[36] 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.

[37] G. G. Penelis and A. J. Kappos, *Earthquake-resistant Concrete Structures*. London, UK: E & F N SPON (Chapman & Hall), 1996.

[38] G. Penelis, K. Stylianidis, A. Kappos, and C. Ignatakis, *Reinforced Concrete Structures*. Thessaloniki, Greece: A.U.Th. Press, 1995.

[39] J. W. Wallace, "Behavior, design, and modeling of structural walls and coupling beams - Lessons from recent laboratory tests and earthquakes," *International Journal of Concrete Structures and Materials*, vol. 6, no. 1, pp. 3–18, Mar. 2012, doi: 10.1007/s40069-012-0001-4.

[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] Standards New Zealand, "NZS 3101:2006, Concrete structures standard: Part 1 – The design of concrete structures," Wellington, New Zealand, 2006.

[42] Canadian Standards Association, "CAN/CSA-A23.3-04, Design of Concrete Structures (Update No. 2 - July 2007)," Mississauga, Ontario, Canada, 2007.

[43] European Committee for Standardization, "EN 1998-1:2004, Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings," Brussels, Belgium, 2004.

[44] Ministry of Environment Planning and Public Works, "Greek Code for the Design and Construction of Concrete Works," Athens, Greece, 2000, p. . (In Greek).

[45] International Conference of Building Officials, "Uniform Building Code – Volume 2: Structural Engineering Design Provisions," Whittier, California, USA, 1997.