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Buckling of Radially Loaded Concrete Cylinders in Fire Condition

A. T. Kassem [a*]

[a] *Civil Engineering Department, Faculty of Engineering, Beni-Suef University, Egypt.*

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Abstract

Concrete cylinders are commonly used in water treatment and sewerage plants, in the form of wells or basins. They are mainly subjected to axial compression resulting from soil lateral pressure and aqueous hydrostatic pressure, in case of the presence of a groundwater table; that is why they are mostly designed in the form of a circular hollow section. Concrete cylinders face a complicated case of loading in fire condition, as a result of material degradation in addition to thermally induced stresses. This paper studies buckling stability of that case where, a concrete cylinder is subjected to an internal fire load in addition to superimposed structural loads from the surrounding environment. The main objective of the research is to study buckling stability of concrete cylinders through identifying various structural and thermal parameters, controlling that behaviour. Finite element modelling using "Ansys 18.1" has been chosen as an approach to deal with the research problem. Twenty-five solid elements models have been prepared to study both thermal and structural behaviour of concrete cylinders in fire condition. Cylinder thickness, slenderness ratio, load ratio, and groundwater presence have been adopted as main research parameters to identify their effect on well's fire buckling endurance, in accordance with ISO 834 standard fire curve. A parametric study has been designed to study fire endurance vulnerability to cylinder thickness ranging from 50 mm up to 800 mm; diameter to thickness ratio [D/t] ranging from "10" up to "160"; full spectrum of structural load ratios; in addition to the presence of a surrounding groundwater. Outputs of the parametric study have been introduced in the form of figures, which could be used as preliminary design aids to identify buckling fire endurance as function of load ratio for various spectrums of thickness and slenderness ratios. Moreover, critical thicknesses and load ratios have been revealed.

Keywords: R.C.; Concrete Cylinders; Fire Endurance; Buckling; ISO 834.

1. Introduction

Concrete cylinders are widely used in various engineering applications, especially water treatment and sewerage facilities. The circular section has been adopted for two main reasons. The first is the type of loading, which is symmetric radial compression. The second is the modern improvement in construction technology through digging and circumferential concrete lining. Whatever the function of the cylinder is, most structures face the case of being internally empty; especially during construction. That is the case where a fire may burn up, putting into consideration that shuttering, or other combustible materials may present in the cylinder's internal space. The case becomes more complicated in case of presence of groundwater table, as concrete environment becomes hygrothermal [1]. Figure 1 represents a natural concrete cylinder surrounded by soil during filling stage, while Figure 2 shows a schematic diagram for the research problem in the form of a longitudinal section in a concrete cylinder subjected to an internal fire load.

* Corresponding author: abdelraouf_kassem@yahoo.com

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Figure 1. Cylindrical concrete well environment

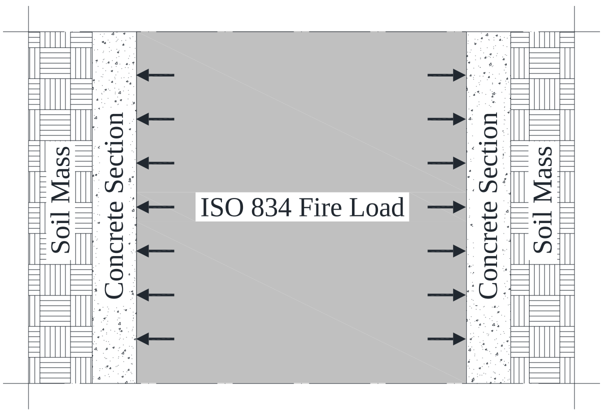


Figure 2. Cylindrical concrete well vertical section

This paper studies cylindrical concrete well's buckling instability, independently from structural crushing limit. The structural problem of cylinders buckling has first been introduced by Timoshenco [2], where buckling surface stress "P_{cr}^{tsh}" has been expressed by Equation 1.

$$P_{cr}^{tsh} = \frac{1}{4}\frac{E}{1-\upsilon^2}\frac{h^3}{a^3} \tag{1}$$

Where

E: is modulus of elasticity

ν: is Poisson's ratio

h: is cylinder thickness

a: is cylinder mid-radius

But that approach has assumed that cylinder's diameter is very large compared with its thickness, as discussed by Kumar et al. [3], that is why it is valid for thin cylinders only. Papadakis [4] introduced a modification to the theory of buckling of cylinders to enable its usage for thin and thick cylinders, as introduced in Equation 2, while Luzzi et al. [5] introduced formulation for thick cylinders subjected to both external pressure and a normal force. Figures 3 and 4 show problem parameters and free body diagram.

$$P_{cr}^{tsh} = \frac{E}{4}\left(\frac{h}{a}\right)^3 \frac{(1-\zeta)}{1+\frac{h}{2a}-\zeta\left(\frac{5}{16}+\frac{25}{96}\frac{h}{a}\right)}; \quad Where\ \zeta = \frac{4\frac{h^2}{a^2}}{4\frac{h^2}{a^2}+\frac{5}{1+\nu}} \tag{2}$$

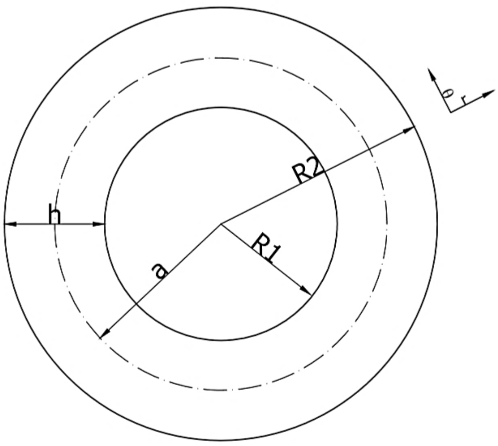


Figure 3. Cylindrical buckling parameters [3]

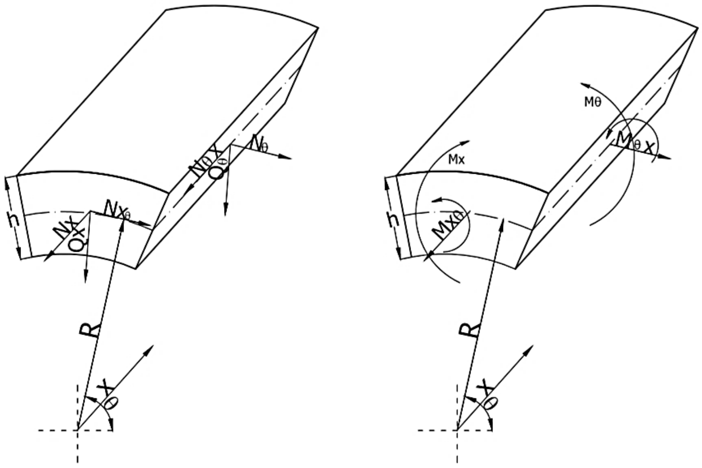


Figure 4. Cylindrical free body diagram [2]

Thermal analysis of the problem requires implementation of conduction, convection and radiation transient heat transfer analyses. Convection and radiation parameters take place at the internal surface of the cylinder, where the fire load exists. Conduction takes place through the cylinder thickness and from the cylinder outer surface to the surrounding soil. Moreover, convection heat transfer takes place at the interface between cylinder's outer surface and running subterranean water, if any. Transient thermal conduction within continuous masses could be expressed via Equation 3 [6].

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+q^{\bullet}=\rho c\frac{\partial T}{\partial \tau} \quad (3)$$

Where

$\dot{q}$: is the power generated per unit volume (w/m^3)

ρ: is the material density (kg / m^3)

T: is point temperature

c: is the material specific heat (J/kg.^{o}C)

τ: is time (sec.)

x: is distance

Single sided transient thermal heat transfer could be used to evaluate temperature distribution within the concrete mass, as a function of time, as expressed in Equation 4 [7].

$$C_c\frac{dT_c}{dt}=kA\frac{dT}{dx}-hA(T_s-T_a) \quad (4)$$

Where

C_c: is the specific heat

h: is the convection heat transfer coefficient

t: is time

T_s: is surface temperature

k_c: is the thermal conductivity

x: is distance through which heat flux propagate

A: is the area perpendicular to heat flux

T_a: is ambient temperature

Figure 5 shows a concrete cylinder's cross sections that summarize problem thermal boundary conditions for cases of dry and fully saturated soils.

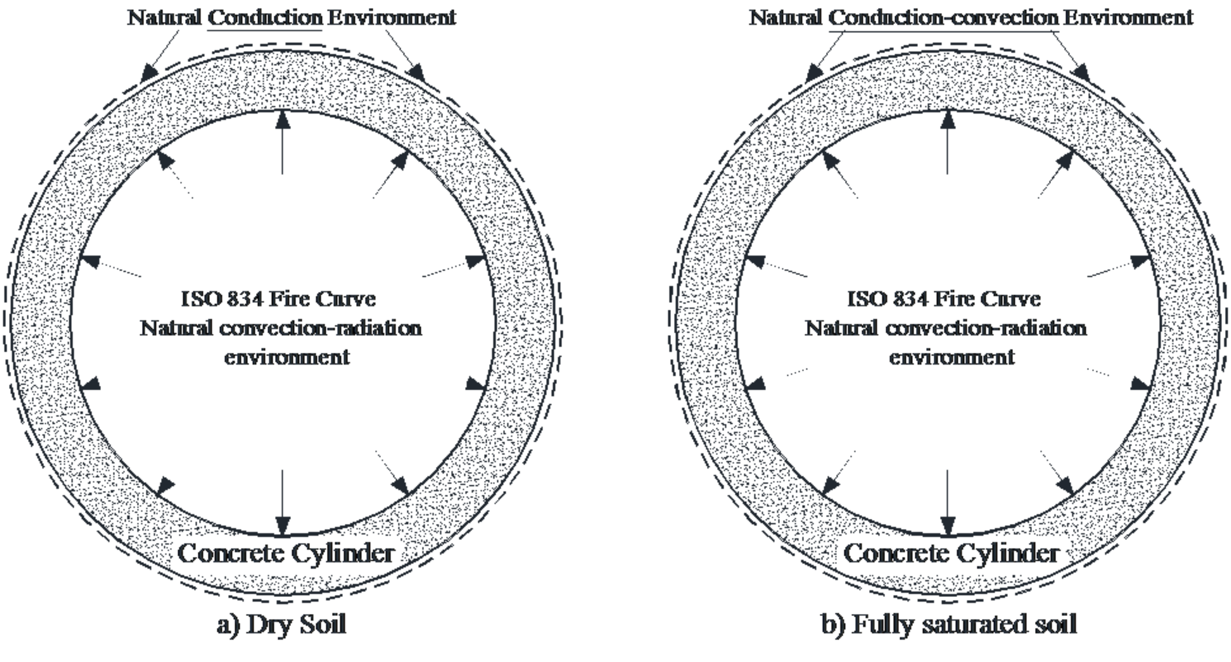
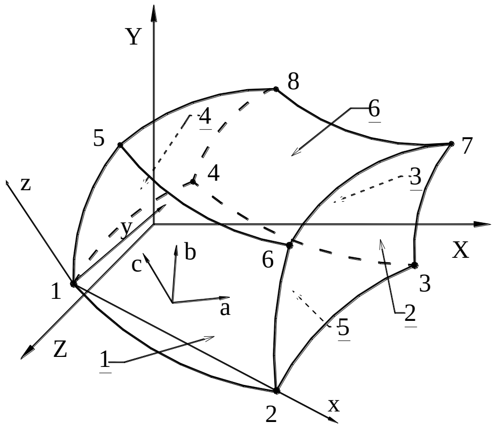


Figure 5. Problem thermal boundary conditions

2. Finite Element Model

Finite element modelling is a common fire engineering research tool due to complications accompanying experimental approaches, regarding facilities and limitations of achieving reliable data due to effect of temperature on installed instrumentation. Research problem is an interface problem between thermal and structural analyses, so element type has been chosen to fulfil both analysis types. Parameter regarding the two analyses approaches have been identified in accordance with the natural environment of the research problem. The thermal analysis has been performed considering an internal fire load in accordance with the ISO 834 [8] fire curve in conjunction with two external conditions. The first external condition is a dry soil environment, allowing the well external temperature to rise and transfer heat flux to the heated surrounding environment. The second external condition is a surrounding fully saturated soil environment, which retains well external temperature at the level of initial temperature. Both transient thermal and structural analyses have been accomplished using solid elements as shown in Figure 6. Solid elements have been meshed in a hex dominant form as shown in Figure 7 [9-19].



XYZ	Global Cartesian Coordinate System
xyz	Element Coordinate System
abc	Material Coordinate System
1,2,3,4,5,6	Face Numbers for Applying Loads

Figure 6. Solid element's configurations [9]

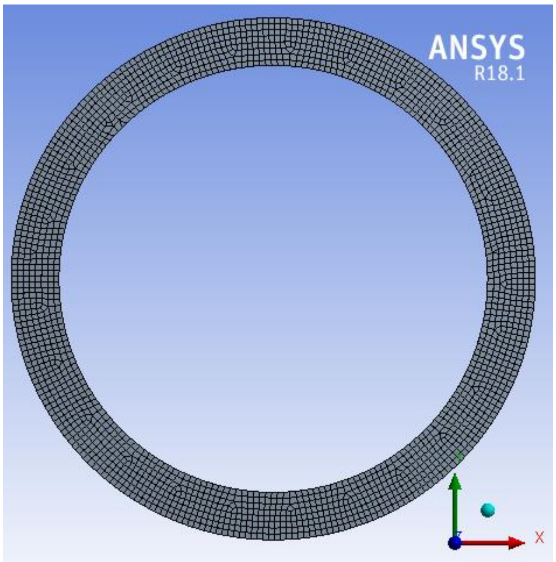


Figure 7. Solid elements mesh

The finite element analysis has been performed on three stages as shown in Figure 8. The first stage concerned transient thermal analysis. Outputs of thermal analysis, in the form of temperature profile across concrete cylinder as a function of time, have been saved in the model; for two main reasons. The first is determining temperature dependent material properties at each time step of the structural analysis. The second is applying the thermal load to the cylinder at each time step to determine resulting stresses, simultaneously with structural loading. Thermal outputs are then transferred to a static nonlinear analysis. Static nonlinear analysis used temperature curve as a thermal load in conjunction with radial compressive pressure as shown in Figure 9. Outputs of static analysis have been transferred to an Eigenvalue buckling module. Thermal and structural nonlinearities have been considered in accordance with Eurocode [9]. Figures 10 to 12 show material nonlinearities regarding structural and thermal parameters.

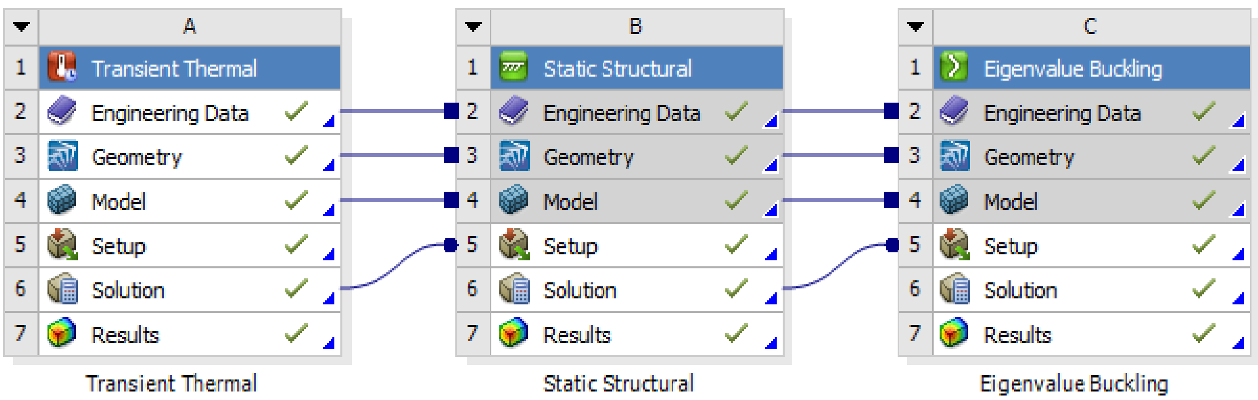


Figure 8. Finite element analysis stages

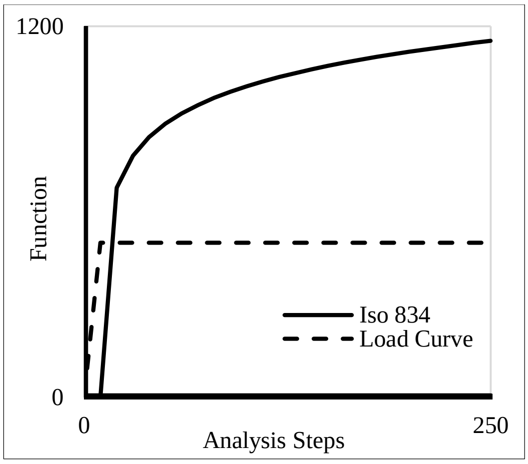


Figure 9. Structural-thermal load curve

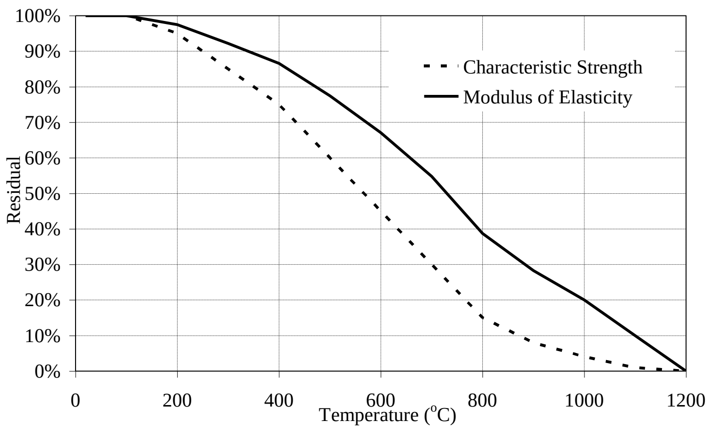


Figure 10. Concrete structural properties at elevated temperature

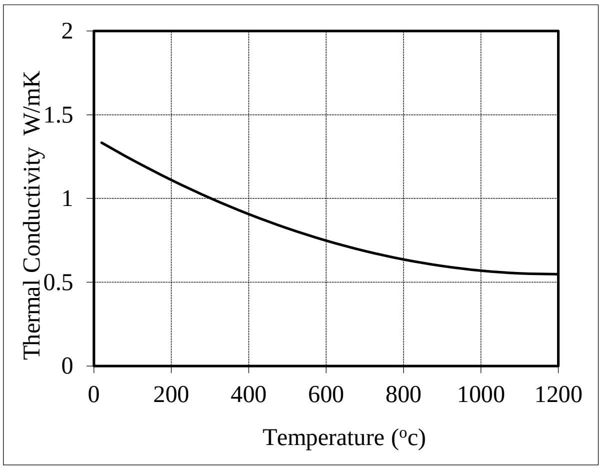


Figure 11. Concrete Thermal Conductivity at elevated temperature

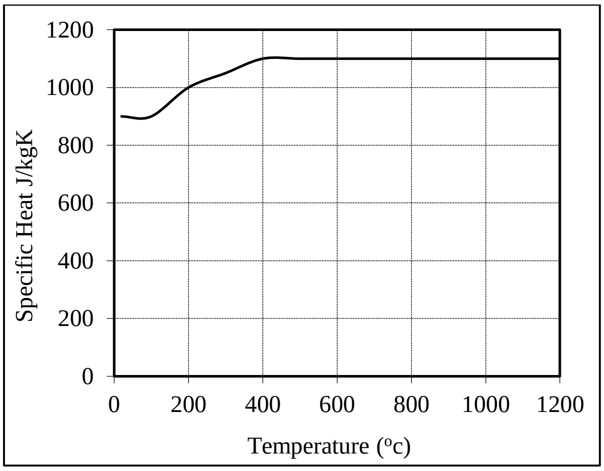


Figure 12. Concrete Specific Heat at Elevated Temperature

Verification of finite element model has been performed for structural and thermal parameters separately. Structural verification has been performed based on comparing buckling load generated from the finite element model with theoretical approach presented by Papadakis [4], as shown in Figures 13 to 17. Thermal verification has been performed by comparing outputs of finite element model with design charts available in the Eurocode [9], as shown in Figure 18.

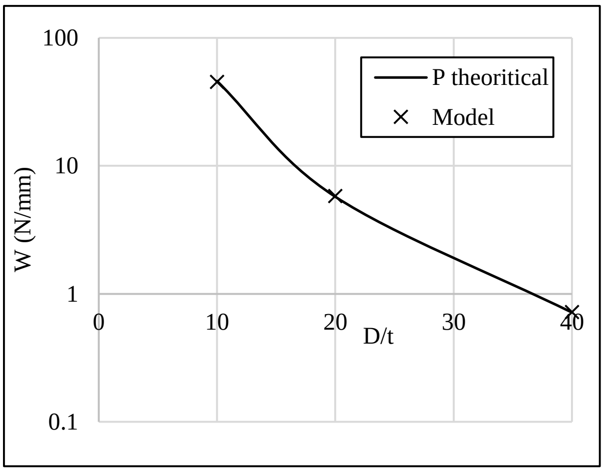


Figure 13. Buckling F.E. verification (Φ = 2000 mm)

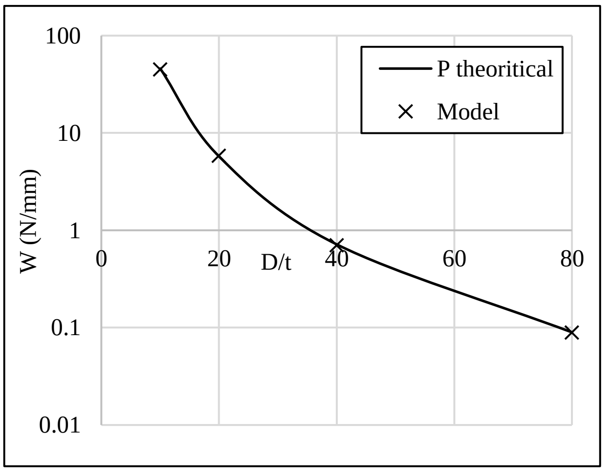


Figure 14. Buckling F.E. verification (Φ = 4000 mm)

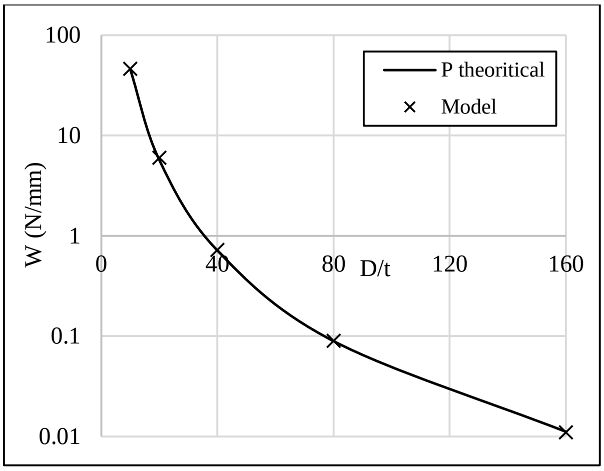


Figure 15. Buckling F.E. verification (Φ = 8000 mm)

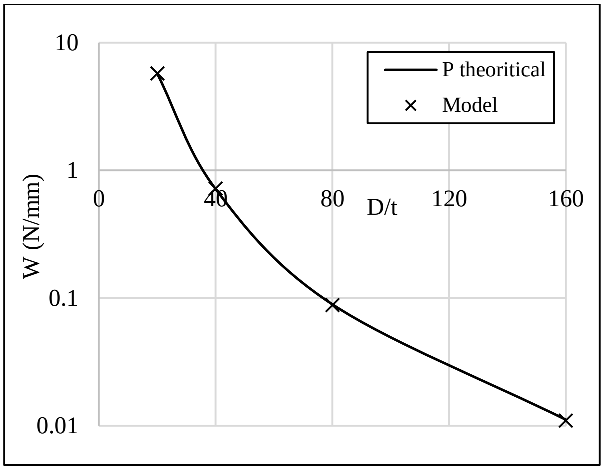


Figure 16. Buckling F.E. verification (Φ =16000 mm)

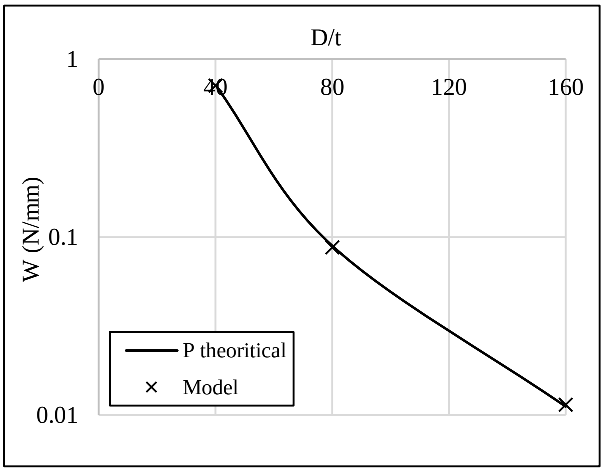


Figure 17. Buckling F.E. verification (Φ =32000 mm)

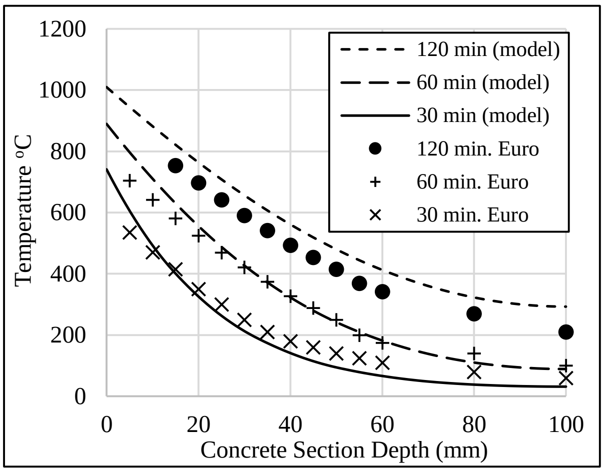


Figure 18. Thermal F.E. verification (t=100 mm)

Once verification had been performed model has been used to deal with both thermal and structural branches of the problem. Figures 19 shows an example of thermal outputs, in the form of temperature distribution across concrete section, while Figure 20 shows an example of structural outputs, in the form of buckling deformations through cylinder's cross section.

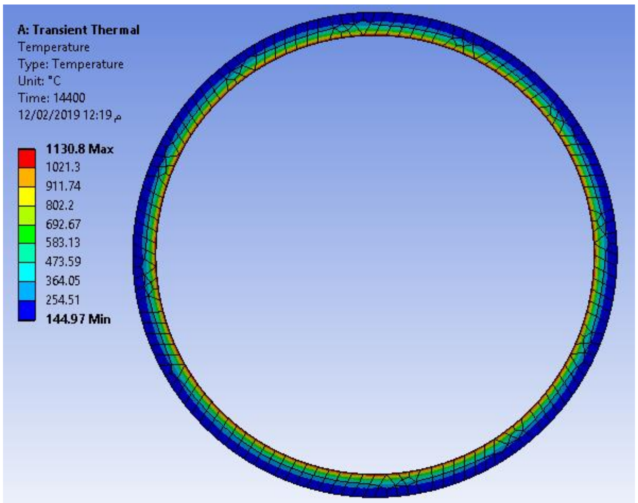


Figure 19a. Temp. distribution for Φ 4000 mm and thickness 200 mm @ 240 min.

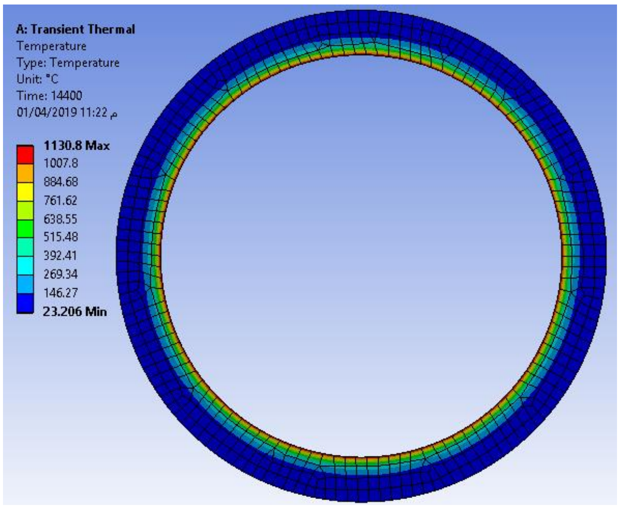


Figure 19b. Temp. distribution for Φ 4000 mm and thickness 400 mm @ 240 min.

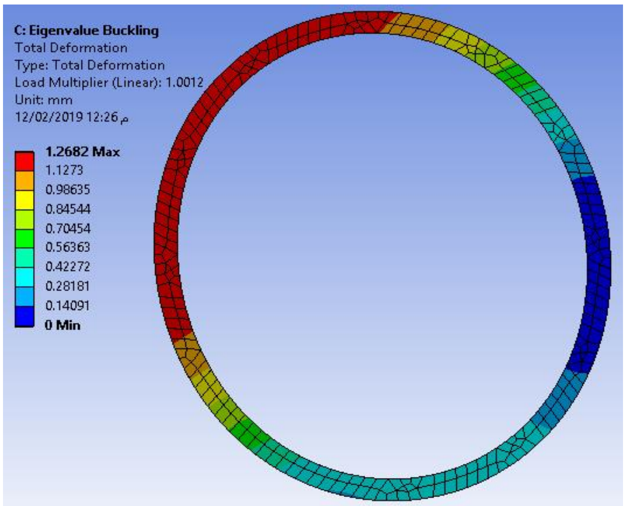


Figure 20a. Buckling deformation for Φ 4000 mm and thickness 200 mm

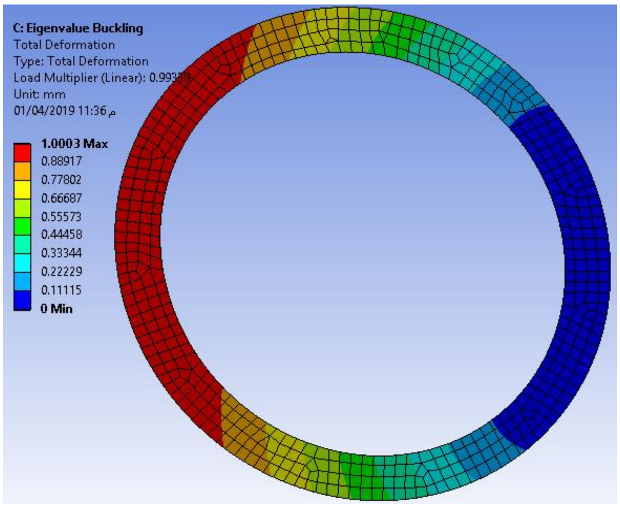


Figure 20b. Buckling deformation for Φ 4000 mm and thickness 400 mm

3. Parametric Study

A parametric study has been performed to identify the role of various parameters on buckling load of concrete cylinders, in fire condition. Cylinder thickness (t), slenderness ratio (D/t), and load ratio have been considered as structural parameters. While soil moisture content (dry or fully saturated) has been considered as a thermal parameter. Twenty-five different finite element models have been prepared. Table 1 shows details of various models, concerning studied parameters.

Table 1. Details of parametric study models

		Cylinder diameter (mm)				
	D/t	**2000**	**4000**	**8000**	**16000**	**32000**
Thickness (mm)	50	40	80	160		
	100	20	40	80	160	
	200	10	20	40	80	160
	400		10	20	40	80
	800			10	20	40

(grey shading) Means an additional model for saturated soil has been prepared

Outputs of the thermal analysis through various concrete sections thicknesses as a function of time have been consolidated in Figures 21 to 28. The case of surrounding saturated soil has been considered for concrete cylinders of thickness 50, 100 and 200 mm, because thicker cylinders outside temperature did not rise more than initial temperature till 240 minutes of fire exposure.

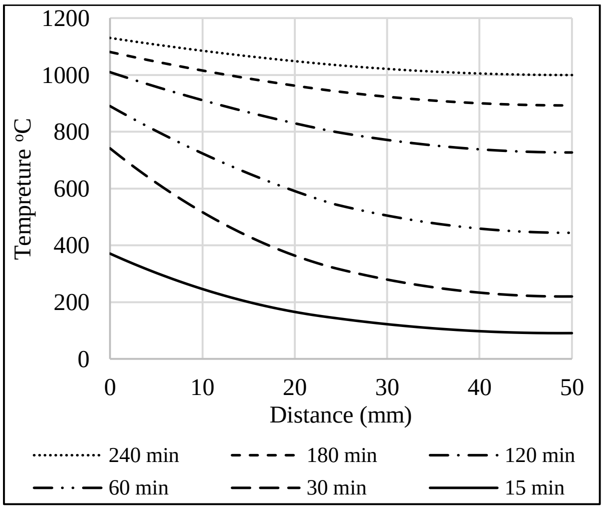


Figure 21. Temp. distribution for 50 mm thick concrete (dry soil)

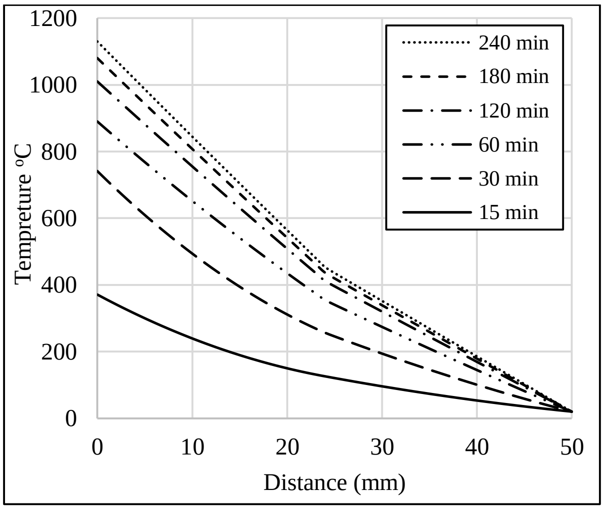


Figure 22. Temp. distribution for 50 mm thick concrete (saturated soil)

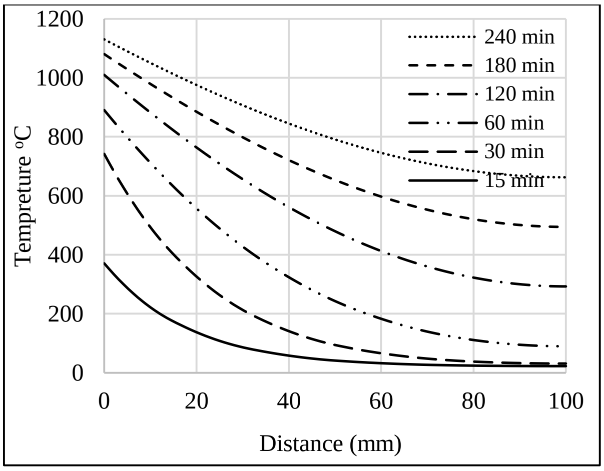


Figure 23. Temp. distribution for 100 mm thick concrete (dry soil)

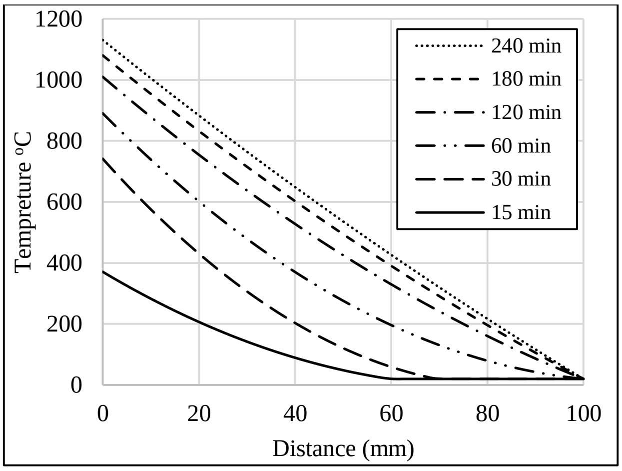


Figure 24. Temp. distribution for 100 mm thick concrete (saturated soil)

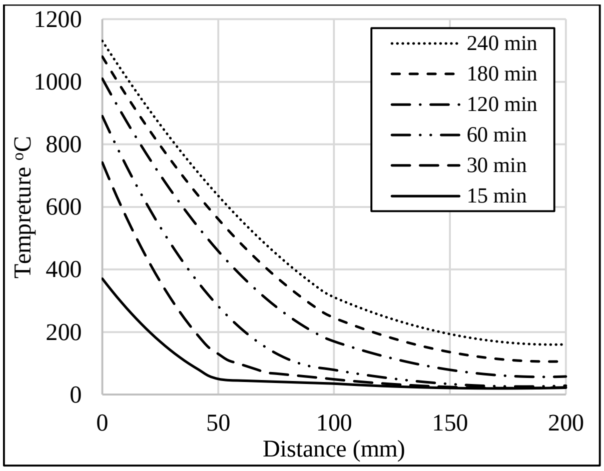


Figure 25. Temp. distribution for 200 mm thick concrete (dry soil)

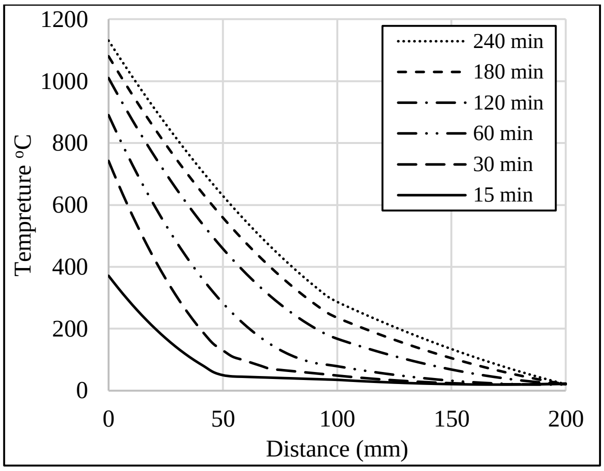


Figure 26. Temp. distribution for 200 mm thick concrete (saturated soil)

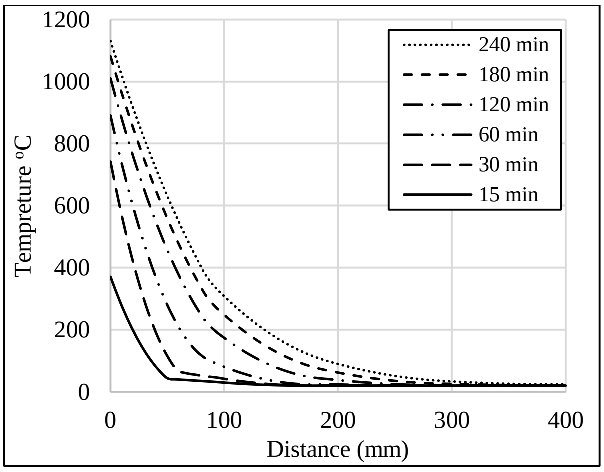


Figure 27. Temp. distribution for 400 mm thick concrete (dry soil)

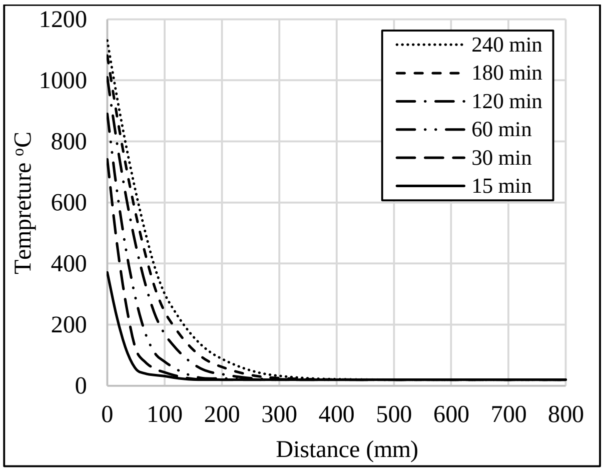


Figure 28. Temp. distribution for 800 mm thick concrete (dry soil)

It could be noticed that in case of slim cylinders temperature distribution is about to be linear throughout the section in case of saturated soil, while about to be uniform throughout the section in case of dry surrounding soil. This refers to the high thermal exchange rate between concrete surface and surrounding soil, in case of wet than dry surrounding environment. Temperature distribution pattern changes significantly for thick cylinders as temperature distribution is about to be bi-linear. This could be understood as a result of the high thermal capacity of thick concrete cylinders, relative to the testing interval. A thickness of order 150mm to 250 mm represents the interface between the two patterns, for fire exposure less than 240 minutes. Outputs of thermal analysis show, to what extent temperature distribution varies for different cases. This variation in the form of temperature values and distribution through the cross section will play a significant role regarding buckling load capacity and fire endurance. This takes place in both the forms of distribution of material degraded properties, in addition to stress distribution pattern resulting from the transient expansion pattern of cylinder's tracks.

Load ratio is mostly presented in design codes as a limiting criterion for structural elements to sustain a specific fire endurance. Since fire endurance is the most significant parameter, regarding structural reliability, it has been plotted versus load ratio for different thicknesses of the same slenderness ratio in Figures 29 to 32, for the case of dry soil. Slenderness ratio has been consistent to identify effects of concrete wall thickness independently.

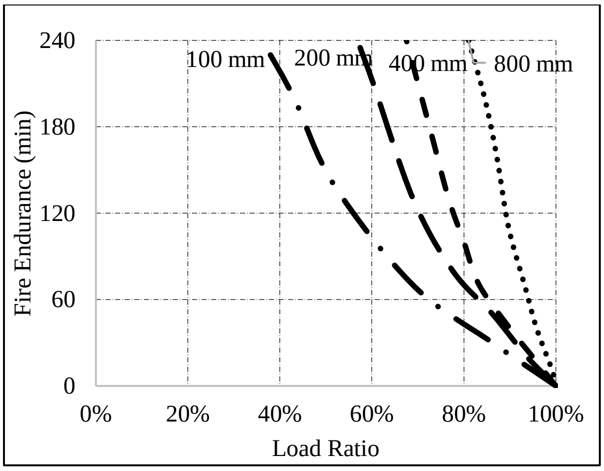


Figure 29. Fire endurance versus load ratio for (D/t=20, dry soil)

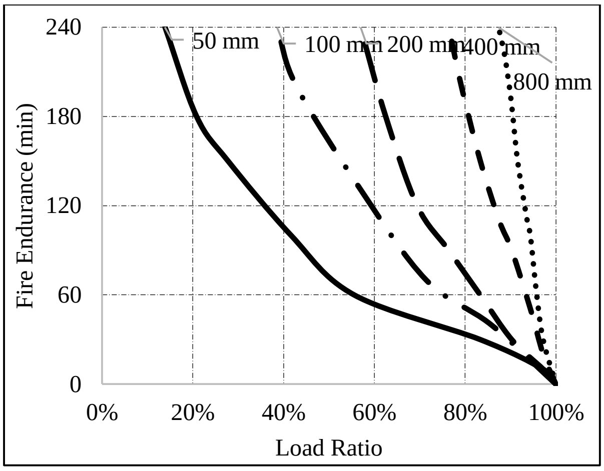


Figure 30. Fire endurance versus load ratio for (D/t=40, dry soil)

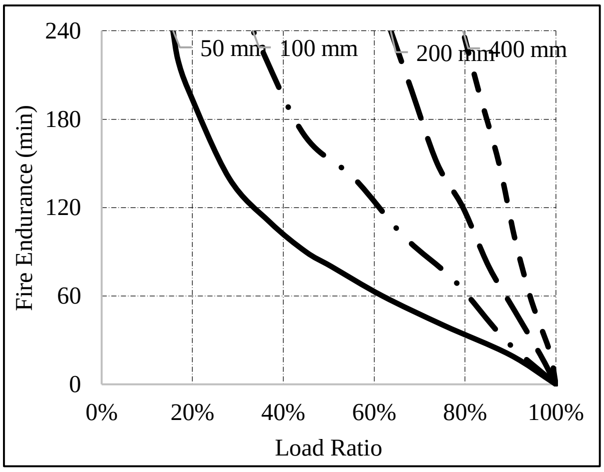


Figure 31. Fire endurance versus load ratio for (D/t=80, dry soil)

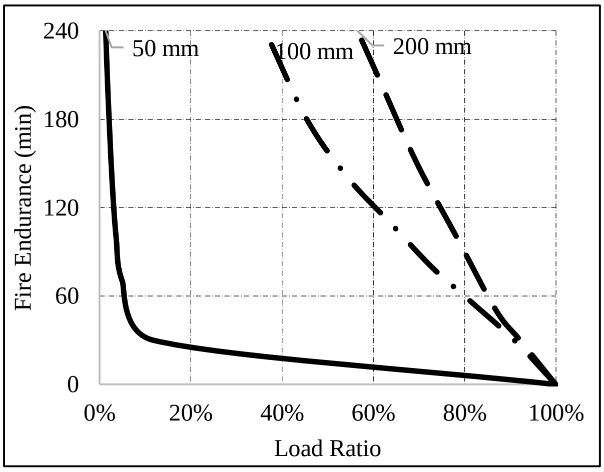


Figure 32. Fire endurance versus load ratio for (D/t=160, dry soil)

It could be noticed that fire endurance degradation versus load ratio is more linear for thick cylinders and nearer to behave non-linearly for thin cylinders. Referring to temperature distributions within various sections and concrete modulus of elasticity degradation, as a function of temperature, it could be concluded that the linearity takes place in thick sections, because temperature does not rise extensively; and consequently, concrete modulus of elasticity was in-affected significantly. This means that, the combined effect of material degradation and thermal expansion did not take place and load ratio was the paramount parameter affecting fire endurance. On the other hand, non-linearity takes place in thin sections, where temperature rises dramatically, and the combined effect of material degradation and thermal expansion affects fire endurance. It could also be seen that the band width of buckling load ratios of the same fire endurances converges for thick cylinders. This could be attributed to the fact that, only a thin shell of the internal surface of the cylinders heats up; leading to minor effects on thick cylinders behavior than thin ones.

The presence of surrounding groundwater table has been investigated for sections, where temperature rise reached the external cylinder layer, within 240 minutes of fire exposure. The study of effect of soil moisture content on fire endurance showed that for the same fire endurance a concrete cylinder can sustain a higher load ratio in case of a saturated soil than dry soil. This phenomenon took place for cylinders of thickness 50 and 100 mm, as shown in Figures 33 and 34. Thick sections (200 mm and more) showed no difference in behaviour between saturated and dry soils. This could be attributed to that external temperature in thick sections did not rise than initial temperature, and consequently the almost behaved the same.

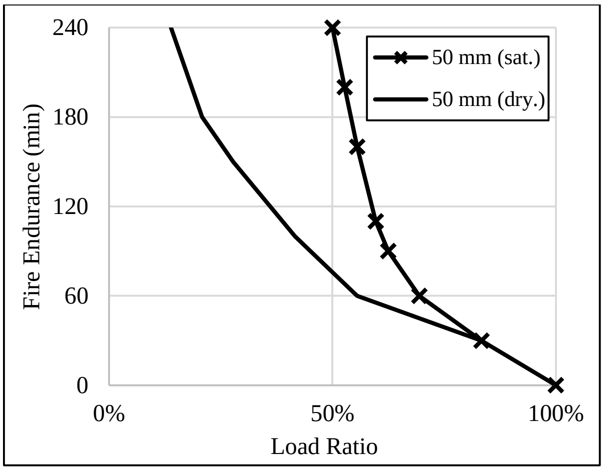


Figure 33. Effect of soil moisture content on fire endurance (D/t = 40, t = 50 mm)

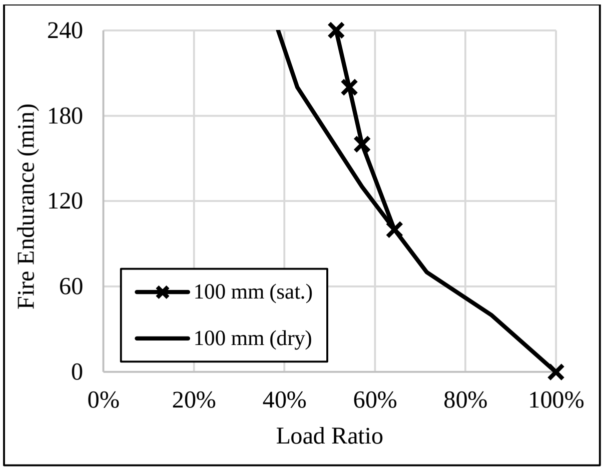


Figure 34. Effect of soil moisture content on fire endurance (D/t = 40, t = 100 mm)

It could also be noticed that the more the fire endurance the more the difference between buckling load ratio of saturated and dry soils, which is a reflection of the role of effective drop in concrete structural properties when exposed to a fire load for a long period. Very high load ratios resulted in the same fire endurance for the cases of dry and saturated soils. That is because just a minor degradation in modulus of elasticity could result in buckling failure, in case of heavily loaded cylinders. This minor degradation could take place in both dry and saturated soils, resulting in similar behaviour.

Thickness of concrete element is a very important parameter, affecting fire endurance. Thickness is mostly indicated by design codes and research recommendations to ensure a specific fire endurance. Figures 35 to 38, present fire endurance load ratio versus cylinder's thickness for different exposure intervals of the same slenderness ratio.

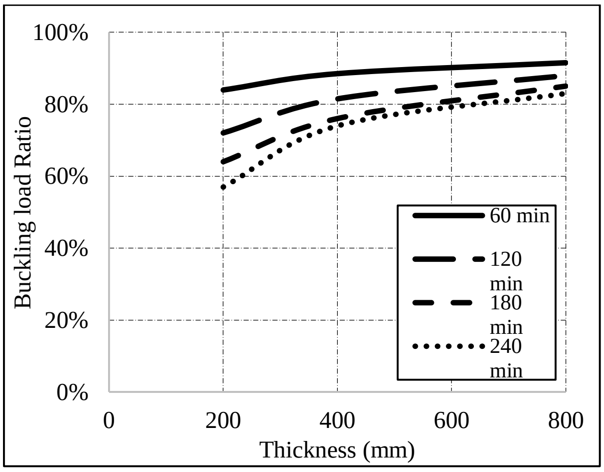


Figure 35. Effect of thickness on buckling load ratio (D/t=10)

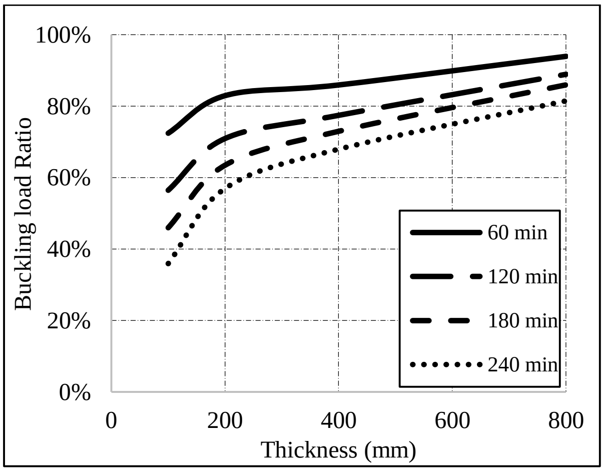


Figure 36. Effect of thickness on buckling load ratio (D/t=20)

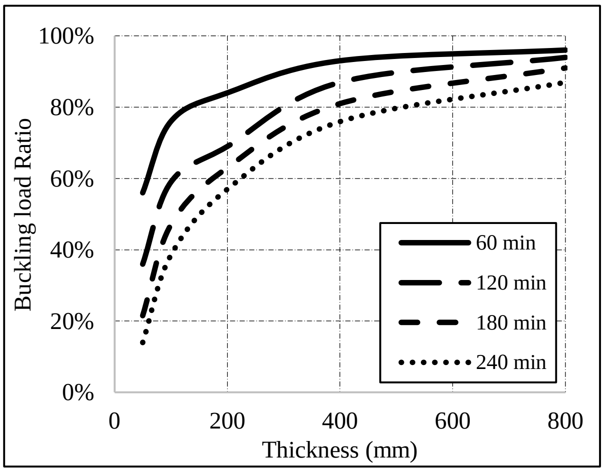


Figure 37. Effect of thickness on buckling load ratio (D/t=40)

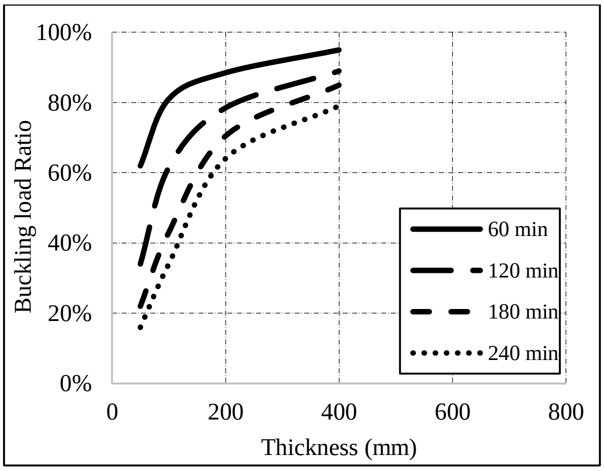


Figure 38. Effect of thickness on buckling load ratio (D/t=80)

It could be noticed that buckling ratio for concrete cylinders, subjected to fire load falls dramatically for thicknesses below 200 mm, this represents the thickness, where temperature rises significantly within the concrete section. In addition, temperature distribution in case of 200 mm thickness begins to show a bi-linear form. Bi-linear temperature distribution decreases buckling fire endurance significantly. This could be attributed to the combined effects of material degradation and additional stresses generated from the high difference in temperature between cylinder's internal and external surfaces.

Effects of slenderness ratio on buckling fire endurance has also been investigated. Figures 39 and 40 present slenderness ratio versus buckling load ratio for a 50 mm thick cylinder, in case of dry and saturated soils; while Figures 41 and 42 show effect of increasing cylinder's thickness, for the case of dry soil.

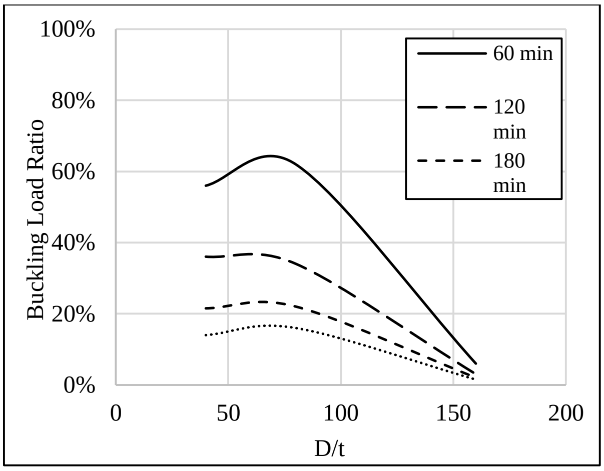


Figure 39. Effect of slenderness on buckling load ratio (t=50 mm, dry soil)

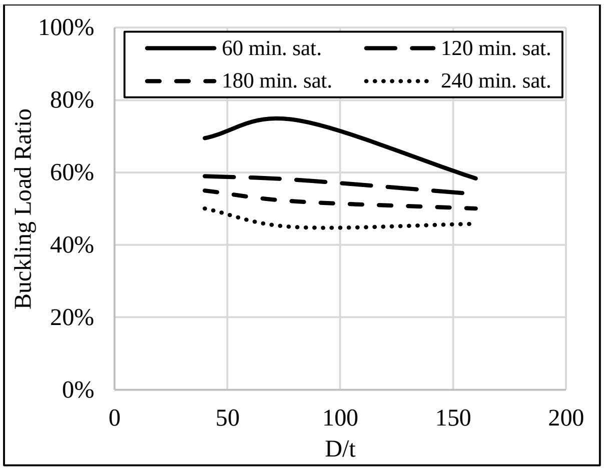


Figure 40. Effect of slenderness on buckling load ratio (t=50 mm, saturated soil)

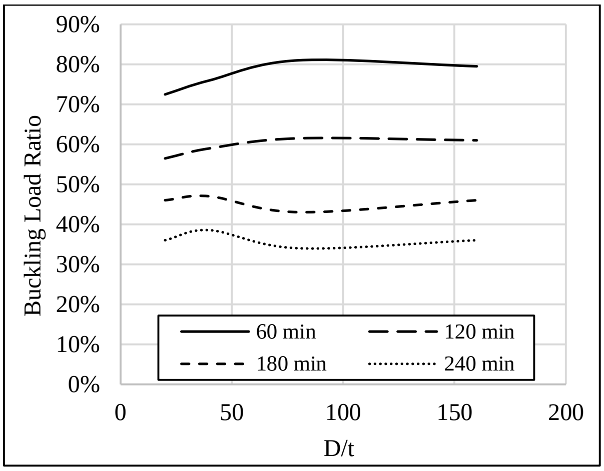


Figure 41. Effect of slenderness on buckling load ratio (t=100 mm, dry soil)

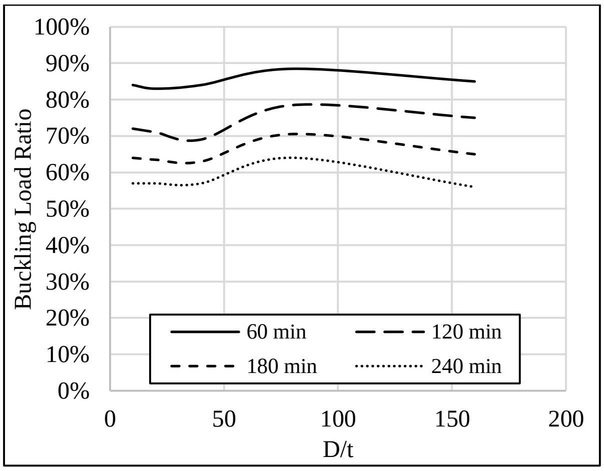


Figure 42. Effect of slenderness on buckling load ratio (t=200 mm, dry soil)

It could be noticed that buckling load ratio is not vulnerable to slenderness ratio, except for very thin cylinders in dry soil, this could be attributed to that for the same cylinder thickness, the same transient thermal distribution takes place; and consequently, the same material degradation that affects buckling load ratio take place. Very thin cylinders in dry soils showed a different behaviour because temperature in this case raised extensively leading to a high material degradation and thermally induced stresses; resulting in very large deformations; than other studied configurations.

4. Conclusion

Main research conclusions could be divided into thermal and thermal-structural conclusions. The first concerns temperature distribution within the concrete section, as a function of time for both cases of surrounding environment whether the concrete cylinder is located in a fully saturated of dry soil. It was found that, Temperature distribution within the first 240 minute of fire is highly vulnerable to soil saturation condition for concrete sections of thickness, not exceeding 200 mm and vice versa for sections exceeding 300 mm. In addition, temperature distribution within concrete sections with thickness of 50 mm order reaches steady state before 240 minutes for the case of dry soils. Moreover, temperature distribution within concrete sections with thickness of 100 mm order reaches steady state before 240 minutes for the case of fully saturated soils.

The paper could introduce figures be used to evaluate reduction in buckling fire endurance for a wide range of geometric configuration within the first four hours of fire exposure. Moreover, the study of thermal-structural behaviour of concrete cylinders resulted in some fruitful conclusions. A critical concrete thickness rounding about 200 mm has arisen, representing an interface between the behaviour of thin and thick cylinders. The increase in buckling fire endurance was found to be approximately linearly proportional to concrete section thickness exceeding 200 mm, but with a low rate. Concrete cylinder thickness was found to be the most significant parameter; regarding fire endurance, where the more the cylinder thickness the less the effect of fire exposure time on buckling failure load. In addition, extremely thin cylinder thickness showed improved fire endurance at load ratios less than 10%. Slenderness ratio was found to be an insignificant parameter regarding buckling fire endurance of concrete cylinders, subjected to radial compression. Soil saturation condition has also played a role, where it affected buckling failure load for concrete cylinders of thickness less than 200 mm, in the form of an increase in buckling load ratio for a specific fire endurance.

5. Conflicts of Interest

The authors declare no conflict of interest.

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