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CRACKING BEHAVIOR OF BASE RESTRAINED REINFORCED CONCRETE WALLS UNDER TEMPERATURE AND SHRINKAGE STRAINS

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Abstract: The issue of crack control in reinforced concrete members has been the subject of research for decades. However, crack formation still cause serious damages in reinforced concrete structures. This phenomenon is particularly of significance in structures the performance of which highly affected by the formation of wide cracks such as liquid containing structures. Most codes provide limited guidelines on amount of required reinforcement to control the crack width. The primary aim of this research is to study the minimum amount of reinforcement required to control the maximum crack width. The cracking behavior of reinforced walls subjected to volumetric deformations due to thermal and shrinkage strains is investigated using finite element method. A parametric study is performed to investigate the effects of wall geometry (length, height, length to height ratio, and thickness), concrete tensile strength, reinforcement ratio, and volumetric strain (climate) on crack width of reinforced concrete walls. For each of these effective parameters, the manner and the rate of impact on crack width are investigated. Based on valuable amount of data resulted from finite element analyses, a design recommendation is provided proposing a new procedure to determine the minimum reinforcement ratio needed to control shrinkage and temperature cracking in reinforced concrete walls.

1 INTRODUCTION

Concrete members start to crack as the tensile stress exceeds the tensile strength of concrete. Cracks in concrete may lead to severability problems such as leakage which, accordingly will result in corroded reinforcement that may jeopardise the structural strength and integrity Therefore, crack control has always been of concern especially in liquid containing structures (LCS) since it could affect their functionality.

Thermal and shrinkage cracks usually occur in reinforced concrete (RC) structures consisting of rigidly interconnected parts when a member is cast after the adjacent part is hardened. As fresh concrete undergoes volumetric deformations from the moment it is cast, developing strains are restrained by adjacent parts that have hardened previously. This restraint could cause stress development and consequently crack formation. RC members experience several narrower cracks as opposed to plain concrete which could fail due to development of a single wide crack that extends throughout the section.

Temperature and shrinkage cracking in RC members has been studied by several researchers in the last few decades. Stoffers (1978) studied shrinkage cracking in edge restrained RC walls. This research examined micro-concrete walls that were either constrained to remain straight or free to curve. Carlson and Reading (1988) investigated the stress conditions in different base restrained walls, with and without openings considering various degrees of restraint by performing experiments on models made of rubber. Al Rawi and Kheder (1990), Kheder et al. (1994) and Kheder (1997) performed experimental studies on the behavior of base restrained RC walls. They suggested a crack prediction formula based on the theory of restraint variation during the formation of cracks. They concluded that the length to height (L/H) ratio in addition to the wall height are the main factors influencing this type of cracking.

Harrison (1987) studied early age thermal cracking with a concentration on thermal contraction of concrete which could be the result of heat dissipation after cement hydration process. He developed a theory to estimate the crack width based on bond force between the reinforcement and the adjacent concrete. Gilbert (1992) and Nejadi and Gilbert (2004) presented an approach to determine the spacing, number and width of cracks in fully restrained concrete members under direct tension using principles of mechanics. They concluded that crack spacing and crack width in RC members could be highly variable even in identical specimens. Pettersson and Thelandersson (2001a, 2001b), used the finite element method (FEM) to simulate base restrained walls. They showed that the tensile strength of concrete has the most significant influence on the crack width. Thelandersson et al. (1998) studied the behavior of end restrained walls due to sudden and slow changes in temperature using a computer program. Micalleff et al. (2017) investigated the influence of early-age thermal contraction and long-term shrinkage on cracking in four edge-restrained RC walls on the basis of laboratory tests and nonlinear finite element (FE) analysis. They highlight the importance of considering the influence of wall aspect ratio and height in design equations for crack widths in base restrained walls.

This research aim to clarify the influence of different factors that could affect the cracking behavior of base restrained RC walls under temperature and shrinkage strains. Finally, a design guide is proposed for required reinforcement ratio to maintain the crack width to an acceptable limit.

2 FINITE ELEMENT MODELING

In a restrained member, thermal and shrinkage strain causes increase in tensile stress which could exceed the tensile strength of concrete and develop cracks. These tensile strains can reach 1000 με, while concrete usually resists only 100 με before the first crack formation. Once the first crack is formed, the stresses will be transferred to the reinforcement from the concrete. Thus, there will be zero stress in the concrete at the crack location and tensile stresses start to develop in steel. As the stresses further increase, more cracks form and therefore the stresses are redistributed again. By developing further cracks, the steel stress at the location of the first crack is reduced and even its width could decrease. This procedure will last until the tensile stresses become stable in the member.

The simulation of cracking behavior in RC structures requires nonlinear analysis that makes the FE model complex. The selected FE program ABAQUS (Hibbitt et al. 2004) is able to simulate the nonlinearity of RC behavior. Among provided constitutive models for analyzing concrete in ABAQUS, brittle cracking model is chosen for this study since it is mainly designated to concrete member under tension which is ideal for RC walls subjected to shrinkage and thermal strain. This model assumes a linear elastic behavior in compression and considers anisotropy that could be caused by crack development. A simple brittle failure criterion is available to allow the removal of elements from the mesh. It uses the Rankine criterion for detecting the initiation of crack therefore the concrete cracks when the maximum principal stress reaches the tensile strength of concrete. The crack forms in a way that its surface is normal to the direction of maximum tensile principal stress (Hibbitt et al. 2004). In addition to tension stiffening, post-cracked behavior has been defined to consider shear retention of RC. This behavior is based on the fact that after crack opening, the shear modulus at cracked surface reduces. Thus, shear stiffness could be defined based on the opening strain across the crack.

After the element failure occurs based on brittle cracking criterion, the element stress carrying capacity reduces to zero but the rebars start to contribute to carry stresses. By including a shear failure criterion in the rebar material, the progressive failure of under-reinforced concrete member could be modeled where concrete failures is followed by a ductile failure of reinforcement. An elastic-plastic constitutive model is defined for steel rebars considering a perfectly plastic behavior after the yield strain is exceeded. The smeared reinforcement model distributes the cross section of the reinforcement evenly among the concrete elements. Linear shell elements are chosen for simulating the walls. Performing the mesh sensitivity analysis proved that the proper mesh size for the walls is 200×200 mm. The steel reinforcement is provided in two layers in horizontal and vertical directions with a clear cover of 50 mm. The spacing between the bars is defined to be 200 mm for all cases. The walls are completely fixed to their base with zero degree of freedom. The total volumetric strain which is the summation of shrinkage and temperature strain is applied to the walls in form of a temperature drop.

2.1 Crack width

It worth mentioning that ABAQUS does not has the capability to determine the crack width directly. However, the results of FE analysis in ABAQUS can be used to estimate the reinforcement stress/strain, which then can be used to predict the crack width. For this purpose, an approach proposed by Frosch (1999) is used to determine the crack width. He proposed that the crack width has a direct relationship with steel strain and crack spacing as presented in the equation below:

[1] $$W_c = \varepsilon_s S_c$$

Where, W_C is the width of crack, εs is the strain in reinforcement and S_C is the spacing between cracks. This equation is also adapted in ACI 318-11 Code (2011) for calculating the crack width. Based on statistical data, Frosch also developed an equation for spacing between cracks (S_C) as presented below:

[2] $$S_c = \psi_s d^*$$

Where ψ_S is defined as crack spacing factor (1 for minimum crack spacing, 1.5 for average crack spacing and 2 for maximum crack spacing) and d* is called controlling cover distance. He calibrated the crack spacing factor value based on cracking in flexural members in his model. Here in this study, assuming that the crack width due to volume change is still proportionate to steel strain at the cracked location, this factor is adjusted based on the experimental results on RC walls. The crack spacing factor ψs is taken to be 1 after comparing the FE results with the case study. Controlling cover distance (d*) could be calculated using the following equation

[3] $$d^* = \sqrt{d_c^{\,2} + \left(\frac{S}{2}\right)^2}$$

Where S is the reinforcement spacing and dc is the concrete cover for reinforcement.

2.2 Case study and FE verification

In order to verify the selected FE model, the crack pattern and width of a previous case study is compared with the results of the simulated walls. The case study presents the crack width and pattern of some highway tunnel retaining walls (Kheder 1997). The crack width and spacing of the base restrained RC walls were recorded using monitoring devices. The selected wall for simulation is 2 m tall and 4 m long with a thickness of 500 mm and 0.2% reinforcement ratio subjected to a total of 1050 με shrinkage and temperature strain. The elastic modulus of concrete and steel are assumed to be 25000 MPa and 200000 MPa respectively. In the FE model, the rebars are defined in two horizontal and vertical layers. The calculated temperature and shrinkage strain in the case study is modeled by applying the equivalent temperature change to the walls using the following equation considering the coefficient of thermal expansion (α) of $10\text{x}10^{-6}\,^{\circ}\text{c}$.

[4] $$\Delta T = \varepsilon_V / \alpha$$

Where, ε_v is the total volumetric strain and ΔT is the equivalent temperature change. Therefore the equivalent temperature drop of 105 ˚C is applied to the simulated wall. The concrete is assumed to behave linearly until it reaches its tensile strength of 3 MPa after which a linear descending stress strain behavior has been defined for it until it reaches the ultimate strain. The strain contour of the FE model for the selected walls is presented in Figure 1 along with the cracking pattern observed in the case study for the same wall. The developed cracks in the simulated FE model could be recognized in the strain contour presented in the figure. The widths of cracks are calculated based on the steel strain collected from the analysis and by using Equation 1 for crack width. The widest crack in the wall according to the experiment and FE model is 0.480 mm and 0.529 mm respectively. It can be seen in Figure 1 that not only the crack widths are in the same range but also the overall crack pattern of the FE model is in good agreement with the case study. Therefore, it can be concluded that the proposed FE model is capable of simulating the base restrained RC walls under restrained volumetric changes.

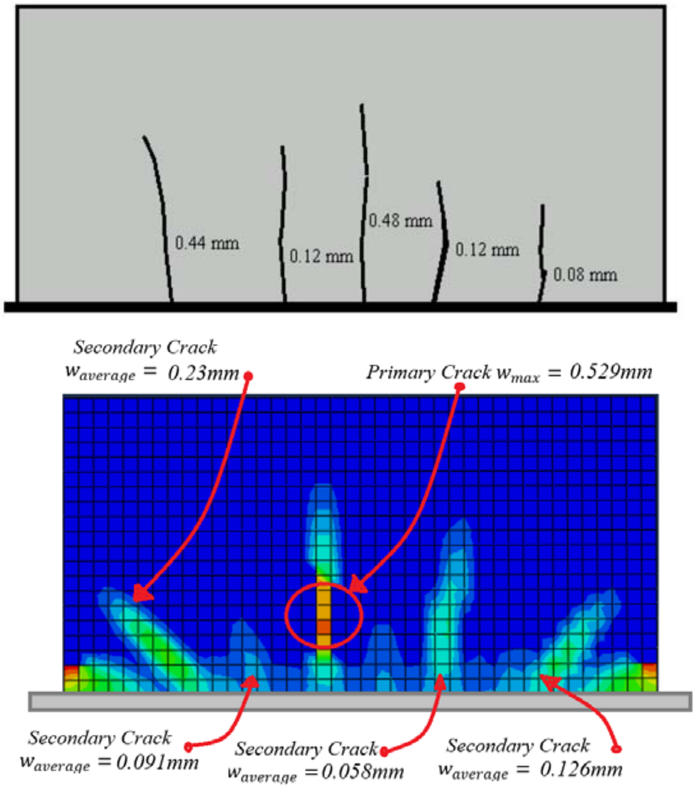


Figure 1. Comparison of the crack pattern and width with experimental study

2.3 Temperature and shrinkage strain

In the case of parametric study, reasonable value for shrinkage and thermal strain are required since it affects the crack width of structures. To determine the total thermal strain, the maximum and minimum concrete temperatures need to be estimated. Thereafter, the thermal strain could be calculated by multiplying the total temperature change by the coefficient of expansion. The hydration temperature is not considered as the highest temperature since the concrete undergoes compressive stresses due to thermal hydration. Therefore, the maximum temperature would be the highest ambient temperature while casting which is taken to be 30℃ assuming concrete is poured during the summer in a climate like Canada. In case of LCS, the temperature of water rarely goes below 0℃ and that prevents the concrete temperature to drop below 0℃ in the winter. Thus, considering a maximum temperature of 30℃ and a minimum of 0℃ the total temperature change could be taken as 30℃ which is equivalent to a volumetric strain of 300 με assuming the thermal coefficient of expansion (α) to be 10×10^{-6}℃. The shrinkage strain is calculated using the procedure proposed by ACI 209 (ACI 209.2R-08). It is calculated for different wall dimensions and an average value of 300 με is considered. Therefore, the total thermal and shrinkage strain is assumed to be equal to 600 με for the RC.

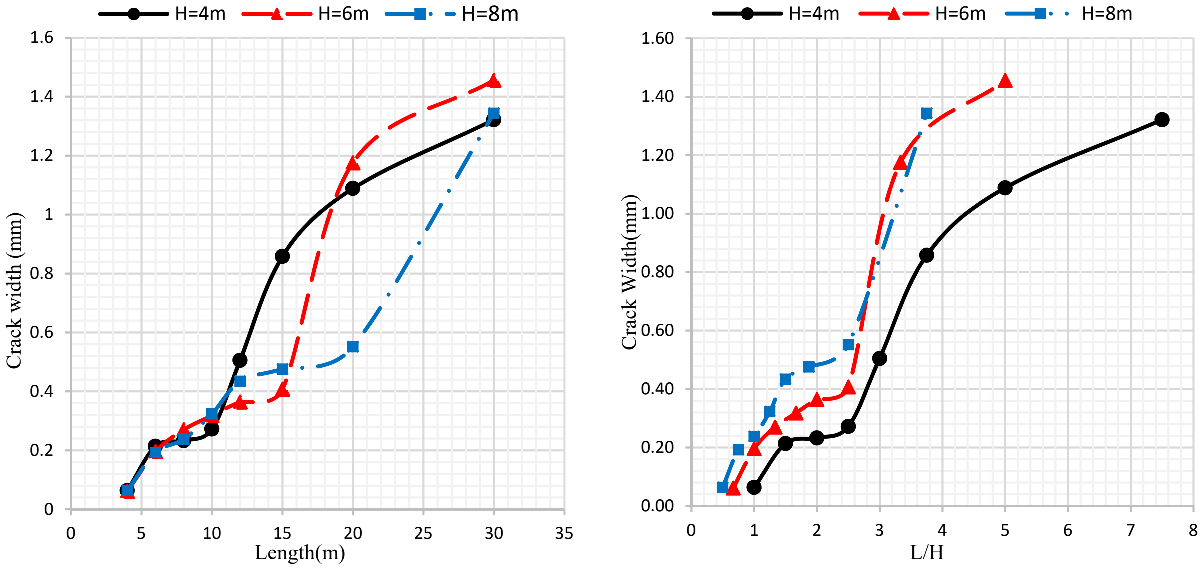
3 PARAMETRIC STUDY

3.1 Effect of wall geometry

The influence of length, height, length/height (L/H) ratio, and thickness of wall is evaluated using simulation of various RC walls. For this purpose, the RC walls simulated in three different heights (4 m, 6 m, and 8 m) and thicknesses (300 mm, 500 mm, and 700 mm) and different lengths varying from 4m to 40m.

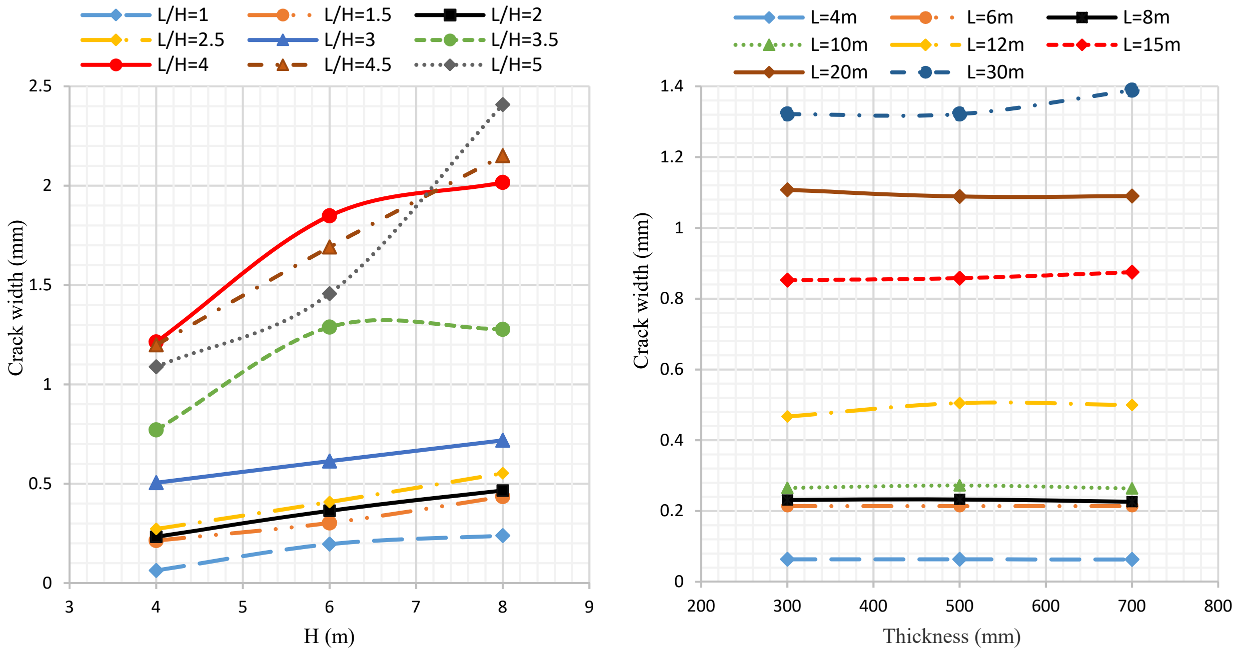
To investigate the effects of wall dimensions, other effective parameters keep constant. The applied volumetric strain is 600 με with a reinforcement ratio of 0.3%. The steel yield strength is 400 MPa and concrete tensile strength is assumed to be 3 MPa. The maximum crack width is calculated using Equation (1), having the maximum steel strain value from the FE analysis. Needless to say, the location of the maximum strained element may change depending on the geometry of the walls and randomness is expected to some extent when comparing the crack widths values. Figure 2 (a) shows the effect of wall length on the crack width having different heights with a constant wall thickness of 500 mm for all cases. It demonstrates that the maximum crack widths for the 24 modeled walls can vary between 0.06 mm and 1.45 mm. It can be seen that longer walls experience wider cracks. The lowest crack width occurs in the walls with 4m length and 30×6 m (L=30 m and H=6m) wall seems to experience the widest crack. The height has negligible influence on crack width of walls when the length is up to 10 m and the walls with same height have approximately similar crack widths. However, beyond 10 m length, the crack width increase irregularly.

Figure 2 (b) demonstrates the influence of L/H ratio on the width of cracks. The L/H ratio varies between 1 and 7.5 considering different heights. For example, at the L/H = 5, the length of the walls are 20 m, 30 m and 40 m for 4 m, 6 m and 8 m tall walls respectively. The walls with higher L/H ratio experience wider cracks. Taking the effect of height on the crack width into account, it appears that having the same L/H ratio, taller walls are prone to form wider cracks. This effect is shown more clearly in Figure 2 (c) which presents the crack width versus wall height with constant L/H ratios. It shows that for walls having the same L/H ratios, wider cracks develop in taller walls. These results are in agreement with previous experimental studies on base restrained RC walls. Based on experimental tests, Kheder (1997) and Kheder et al. (1994) concluded that wider cracks develop in walls with higher L/H ratio since they have higher restraint factors. They also observed that when L/H is constant, higher walls experience wider cracks. The effect of the wall thickness is presented in Figure 2 (d) on 4 m high walls. It is shown that the wall thickness has almost negligible influence on the crack width as there seems to be very little difference in crack width values.



(a) Crack width vs. wall length

(b) Crack width vs. L/H



(c) Crack width vs. wall height

(d) Crack width vs. wall thickness

Figure 2. Effect of the wall length, L/H ratio, height and thickness on the crack width

3.2 Effect of climate condition

The applied volumetric strain which is the summation of shrinkage strain and thermal strain due to temperature drop is another parameter that could affect the crack width of RC walls. It mainly depends on the climate in which the concrete is cast. To investigate the effect of this factor, three different values of ultimate volumetric strain are considered to represent three different climate conditions. The ultimate volumetric strain for cold and humid climate is considered to be 600 με as explained earlier. For hot and dry climate, the total volumetric strain is calculated to be about 900 με assuming a temperature variation of 40℃ and relative humidity of 20%. For a tropical climate assuming temperature drop of 15℃ and relative humidity of 90%, the shrinkage and thermal strain is computed to be about 300 με. Figure 3 shows the crack width versus the applied volumetric strain with different wall lengths while the rest of parameters are kept constant (i.e. H = 4 m, Thickness=500mm, ρ = 0.3%). As a general pattern, wider cracks form in walls under higher volumetric strain irrespective of the wall length. Therefore, as the climate change from hot/dry to cold/humid and tropical weather, the maximum crack width is increased in the walls with same length. It is also clear that, in a same volumetric strain the wall with a greater length experience larger crack width. Moreover, it is observed that the crack width of simulated walls could increase up to 1.45 mm in hot/dry climate while it does not exceed 1.1 mm and 0.90 mm in cold/humid and tropical weather respectively.

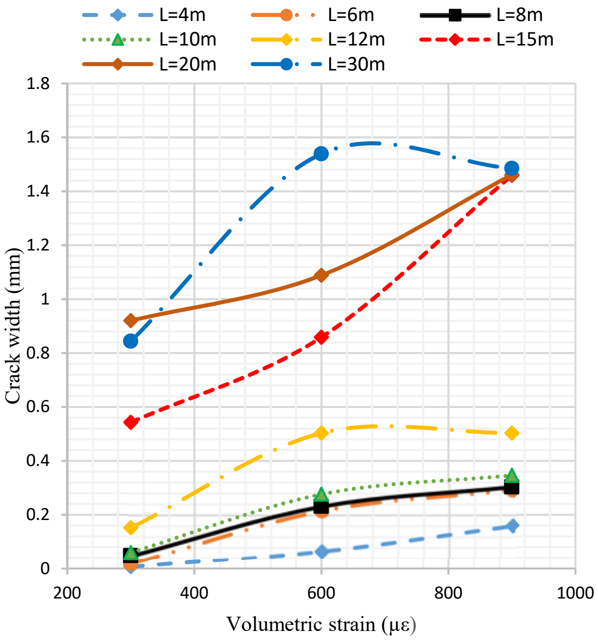


Figure 3. Effect of volumetric strain on crack width

3.3 Effect of reinforcement ratio

Usually, required reinforcement ratio is determined based on the total strain resulting from restrained volumetric deformation, which depends on the wall length and the amount of volumetric deformation (Kianoush, 2008). To investigate the effects of reinforcement ratio on crack width, a series of analysis have been run and the results are shown in Figure 4. Walls are modelled with steel ratios varying from 0.3% to 0.8% while the height is kept constant (4 m). The wall thickness is 500 mm and the applied volumetric strain is 600 με for all simulated walls.

The graph clearly demonstrate that increasing the steel percentage decreases the width of cracks. It can be seen that the effect of increasing the reinforcement ratio on reducing the crack width seems to gradually decrease. This is in agreement with results of the experimental study done by Al Rawi and Kheder (1990) which concluded that increasing steel ratio will decrease the crack spacing and width up to a certain point, and beyond that this effect will be minimal. Different reinforcement ratios do not significantly affect the crack width for the wall with length of 4 m. In this case, the crack width varies from 0.001 mm for 0.8% reinforcement ratio to 0.06 mm for 0.3% reinforcement ratio. This implies that 0.3% (reinforcement ratio) might be enough for this wall and higher amount of reinforcement could not meaningfully decrees the crack width. Similar trend is seen for the walls with 6, 8 and 10 m length as well and there is no significant reduction in crack width at higher reinforcement ratios. As the wall length increases, the effect of reinforcement ratio becomes more tangible. Crack width for the wall with 30 m length and 0.8% reinforcement ratio is 0.1 mm, while for the same wall with 0.7%, 0.6%, 0.5%, 0.4% and 0.3% is respectively 0.17mm, 0.44 mm, 0.69 mm, 0.94 mm and 1.32 mm. It can be concluded that, although an amount of 0.8% of reinforcement ratio is too conservative for walls with short lengths, it would control the crack width effectively for a 30m wall.

3.4 Effect of concrete tensile strength

Another contributing factor that could affect crack width is the concrete tensile strength. To investigate the effect of this factor, the RC walls are modeled with three values of concrete tensile strength. Figure 5 shows the influence of concrete tensile strength on width of cracks considering three different values for tensile strength (2.5, 3 and 3.5 MPa) with wall lengths varying from 4 m to 30m. The results show that wider cracks develop in walls made of stronger concrete. This could be explained by the fact that weaker concrete cracks under a lower stress/strain level and therefore it ends up with a larger number of narrower cracks. For RC walls up to 10 m length, the influence of concrete tensile strength on crack widths is negligible. However, as the length of wall increases and larger crack widths develop, the effects of concrete tensile strength on crack width become more considerable. The longest wall with 30 m length, experienced 1.55 mm and 1.06 mm crack width for concrete tensile strength of 3.5 and 2.5 MPa respectively.

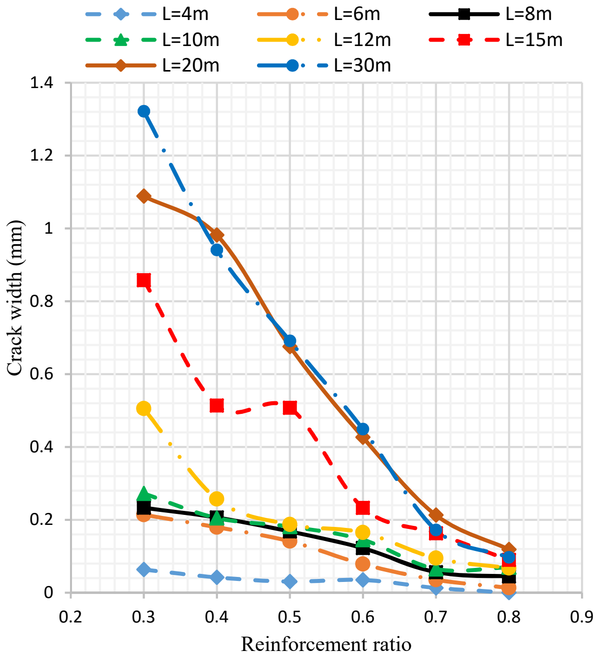


Figure 4. Effect of reinforcement ratio on crack width

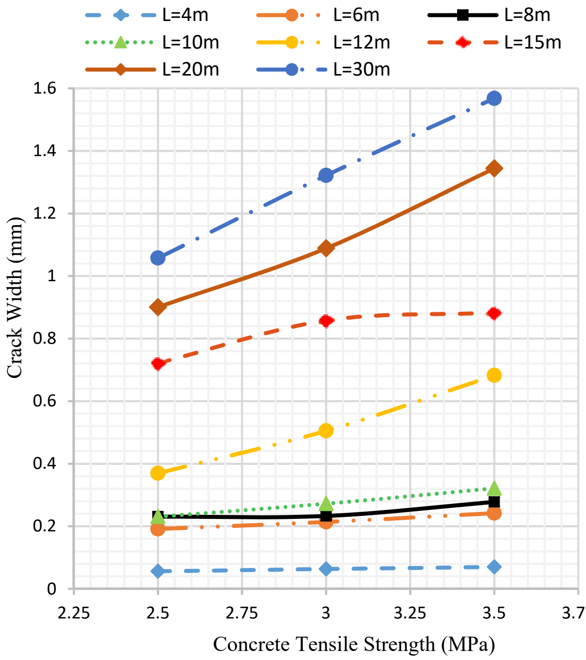


Figure 5. Effect of concrete tensile strength on crack width

4 PROPOSED MINIMUM REINFORCEMENT RATIO FOR RC WALLS

Based on the collected data for crack width of RC walls with various geometry, reinforcement ratio, concrete tensile strength and environmental situation, a procedure is proposed to determine the minimum required steel for RC walls. This minimum reinforcement ratio aims to limit the crack width to 0.1 mm for water retaining structure based on the ACI 224R-92 (2004). The proposed empirical formula is developed based on the FE results and considers the major parameters that affect the crack width as below:

[5] $\rho_{min} = 0.003\gamma_{L/H}\gamma_{H}\gamma_{cl}\gamma_{ft}$

Where, ρ_{min} is the minimum steel ratio and $\gamma_{L/H}$, γ_{H}, γ_{cl} and γ_{ft} are factors to account for L/H ratio, height, climate and concrete tensile strength respectively. Tables 1 presents the values for L/H, Height, and climate modification factors respectively and the concrete tensile strength factor could be computed using Equation 5 as below:

[6] $\gamma_{ft} = ft/3 \qquad (2<ft<4)(MPa)$

A series of FE analyses was performed to further examine the efficiency of the proposed procedure. For this purpose, RC walls simulated with lengths and heights varying from 2 to 32 m and 2 to 10 m respectively. Different values for the concrete tensile strength and different climate conditions are considered. Table 2 presents 15 examples of these modeled RC walls showing each parameter and the corresponding modification factors in addition to the computed minimum reinforcement ratios as per Equation 5. It shows that the crack width is kept below the 0.1 mm limit using the calculated reinforcement ratios.

Table 1. Modification factors for the proposed minimum reinforcement

L/H factor		Height factor		Climate factor	
L/H Categories	$\gamma_{L/H}$	Height Categories	γ_H	Climate Categories	γ_{cl}
L/H < 1.5	1.0	H < 2	0.8	Tropical (T)	0.8
1.5 ≤ L/H < 2	1.5	2 ≤ H < 4	0.9	Cold/Humid (C)	1.0
2 ≤ L/H < 3	2.0	4 ≤ H < 6	1.0	Hot/Dry (H)	1.2
3 ≤ LH < 4	2.5	6 ≤ H < 8	1.2		
L/H ≥ 4	3.0	H ≥ 8	1.4		

Table 2. Modelled walls with the proposed reinforcement ratio

Wall No.	L (m)	H (m)	L/H	Ft (MPa)	Climate	$\gamma_{L/H}$	γ_H	γ_{cl}	γ_{ft}	ρ_{min} (%)	Crack width (mm)
W1	2	2	1	3	H	1	0.9	1.2	1	0.32	0.07
W2	6	2	3	3.5	C	2.5	0.9	1	1.17	0.79	0.06
W3	6	4	1.5	2.2	T	1.5	1	0.8	0.73	0.26	0.06
W4	4	6	0.67	2.1	T	1	1.1	0.8	0.7	0.20	0.05
W5	10	8	1.25	2.8	H	1	1.2	1.2	0.93	0.47	0.06
W6	10	10	1	3	T	1	1.2	0.8	1	0.34	0.06
W7	15	4	3.75	3.8	C	2.5	1	1	1.27	0.95	0.08
W8	15	6	2.5	2.4	C	2	1.1.	1	0.8	0.58	0.06
W9	18	2	9	3.6	T	3	0.9	0.8	1.2	0.78	0.08
W10	20	8	2.5	3.1	H	2	1.2	1.2	1.03	1.04	0.07
W11	20	10	2	2.4	H	2	1.2	1.2	0.8	0.81	0.05
W12	24	4	6	3.4	H	3	1	1.2	1.13	1.22	0.09
W13	28	10	2.8	3.8	C	2	1.2	1	1.27	1.06	0.07
W14	29	6	4.38	3.2	H	3	1.1	1.2	1.07	1.38	0.06
W15	32	8	4	3	C	3	1.2	1	1	1.26	0.07

5 CONCLUSION

The cracking behavior of RC walls subjected to shrinkage and thermal strain was studied using FEM. The effect of wall dimensions, reinforcement ratio, climate (temperature variation and humidity), and concrete tensile strength on maximum crack width were investigated.

The results show that walls with higher L/H ratios and longer walls experience wider cracks and considering a constant L/H ratio, the crack width is larger in taller walls. Moreover, the wall thickness did not seem to have a major effect on the crack width for the range of wall thickness considered in this research. The climate in which the wall is cast was demonstrated to be of importance to this type of cracks. In fact, widest cracks develop in hot and dry climate due to the large volumetric strain as a result of high temperature variation and significant drying shrinkage strain. Walls exposed to cold and humid environment experience narrower cracks as they are subjected to lower volumetric strain while the narrowest cracks occurs in tropical zones with not much of temperature change and a very high humidity level. RC walls with reinforcement ratios ranging from 0.3% up to 0.8% were simulated and the results show that increasing the steel percentage could decrease the crack width significantly. However, as the wall length increases and the wall experience wider crack, the effect of reinforcement ratio on crack width becomes more tangible and higher reinforcement ratios control the crack width effectively. The concrete tensile strength is another factor that affect the crack width. Walls made of concrete with higher tensile strength showed wider cracks compared to the ones with lower strength since the latter experience larger number of narrower cracks as opposed to less but wider cracks. Based on the results of parametric analysis, a design recommendation is provided proposing a new procedure to determine the minimum reinforcement ratio required to control shrinkage and temperature cracking in RC walls.

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