Al-Nahrain Journal for Engineering Sciences (NJES) Vol.20 No.1, 2017 pp.206 - 213

Cracking Control due to Early Thermal Movement of Watertight Continuous RC Members

Hussam K. Risan
Civil Eng. Dep., Al-Nahrain University, Baghdad, Iraq
dr.hussamrisan@gmail.com

Abstract

Action of applied external loads, early thermal by hydration of cement in reinforced concrete (RC) structures, creep and shrinkage and seasonal effects due to environmental conditions are the main causes of inducing cracks in RC members. Most Design Codes of RC structures have underestimated the distribution steel requirements based on stating nominal or minimum requirements for early thermal and moisture movement especially in watertight continuous constructions. Three dimensional finite element analysis for a verification problem was carried out on a continuous reinforced concrete members with different bar diameter subjected to different applied temperatures values which represent the early-age and seasonal effects. The results of this analysis were compared with the available BS Code equations for crack control for early thermal movements. The comparison between the Code equation and finite element analysis was met in a good agreement. The resulted data was used to study parametrically the crack characteristics in terms of crack width and spacing of RC members in term of the effects of three different construction exposures (Class A, B and C), three values of temperatures with three different bar size diameter (10mm, 12, 16) for each one. The present work was indicated as the bar diameter increases, the required steel ratio increases proportionality to match the assumed crack width. So, to get the minimum steel ratio this is the target. It must use smallest bar diameter. But unfortunately this is limited by minimum practical bar spacing. The overall of present study was indicated that the continuous construction required high steel area especially for class A exposure.

Keywords: Watertight; Continuous Construction; Crack Width and Spacing; Early Thermal Movement; Immature Concrete.

Introduction

Distribution strains due to early thermal by hydration of cement frequently occur in RC structures transversely to the main structural load direction as a result of thermal and moisture movements and, if uncontrolled, can give risk to unwanted cracks. Most publications in this subject have deal roughly with the distribution steel Requirements by just using so called minimum steel ratio which is often inadequate especially in a watertight continuous construction. The ACI Code (**ACI 209.2R-08, 2008** and **ACI 350M-06, 2006**) specifies a minimum percentage of thermal and shrinkage reinforcement for member up to 300 thick and a fixed minimum quantity of steel for thicker sections. Australian Code specifies an absolute minimum of 0.4% and a larger value for fully restrained concrete which varies between 0.48% and 1.28% depending on bar size. BS Code (**BS 8007, 2003**) deals with the subject in some extend details as reviewed here.

Cracks are initiated in unloaded reinforced concrete members due to either by heat of hydration of cement in early age of RC members accompanied with creep and shrinkage or by environmental conditions. The effects of heat of hydration with time can be predicted from any typical temperature curve of freshly placed concrete (**Anchor R. D. 1992**). It is depicted that the high peak temperatures can be generated within 24 to 36 hours of placing concrete, and the heat is then dissipated to the surroundings. By the sixth day, the temperature is usually backed to normal. Peak temperatures are increased with high cement content, with use of more reactive cements, when timber forms are used, and when placing and ambient temperatures are high. They are also increased as section thickness increases up to a limit of a bout 2m (**Huges, B. P. and Mahmood, A. T. 1988**). After reaching peak temperatures, the hardened mass cools and contracts. Relatively thin members cool to ambient within two or three days after removal of formwork, but thick sections cool at only a few degrees per day. If contraction is restrained, cracking may occur (this is known as early-age effects thermal movement) and the induced strain is given as:

$$\varepsilon_1 = \frac{\alpha}{2} T_1 \qquad \ldots (1)$$

where:

$\alpha =$ Coefficient of thermal expansion of mature concrete (reduced by a half to allow for Early high creep effects in immature concrete);

$T_1 =$ Temperature fall from hydration peak to ambient.

In addition, the long-term effects (this is known as seasonal effects thermal movement) of mean seasonal variations of temperature must be considered and the additional strain will be:

$$\varepsilon_2 = \frac{\alpha}{2} T_2 \qquad \dots (2)$$

$\alpha =$ Coefficient of thermal expansion of mature concrete (reduced by a half to allow for bond effects in mature concrete);

$T_2 =$ Fall in mean seasonal temperature.

The total thermal contraction strain must be considered is:

$$\varepsilon_{tc} = \frac{\alpha}{2}\left(T_1 + T_2\right) \qquad \dots (3)$$

As concrete further dries out, more contraction happened as a drying shrinkage effect. The drying shrinkage figure around 0.04% (**Westbrook R. 1988**) which is depends on the section mass or thickness. In thin member which is not greater 300 mm thickness, it is expected less than 50% of drying shrinkage will take place in the first three months from concrete starting age, and continue over a year before it has reached its full extent. While in thick sections, drying shrinkage will extend for a period of years. An expansion amounting to around two-thirds of the drying shrinkage happened due to practical re-saturation process of the concrete. So, the contraction strains due to moisture movements do not usually exceed the strain capacity of the concrete and may be ignored unless aggregate of high shrinkage value are used.

Research Significance

There are many options for controlling cracking and mainly can be classified as continuous construction, semi-continuous construction and jointed construction. An attempt here was made to study the behavior and characteristics of early thermal movement and cracking control of watertight continuous reinforced concrete construction. Finite element analysis for continuous RC construction was made to validate the BS Code equations which are must used for solving crack control problems. Bar diameter and spacing, steel ratio, crack width and type of construction exposures were parametrically studied for watertight continuous RC wall members.

Distribution Of Cracks

Providing reinforcement in RC members usually controls the cracking due to both early-age and seasonal effects so that the overall contracting strain given in equation 3 is distributed in any RC members between reinforcement and movement joints, so that the crack widths are within acceptable value. The controlling early thermal cracking problem has no single design solution. The engineer may design to have closely spaced movement joints with a low ratio of reinforcement, or a widely spaced joints with a high ratio of reinforcement. The final design is dependent on the structure size, construction method and economics. The crack distribution in term of spacing and width is captured in two main headings which are based on stress equilibrium and strain condition.

Critical steel ratio

The strength of the steel at yield will be less than the ultimate tensile strength of concrete if a low steel ratio is used. Definitely the steel will yield when the crack initiates. Thus the crack will be wide and unrestrained (**Harrison T. A. 1991**). The critical steel ratio ρ_{cr} can be defined by equating the yield force in the steel with the tensile force in the concrete as:

$$\rho_{cr} = \frac{f_{ct}}{f_y} \qquad \dots (4)$$

where:

$f_{ct} =$ Concrete tensile strength in three days;

$f_y =$ Yield strength of steel.

Stress condition

To find the spacing of cracks, stress condition may be applied. Equating the bond force between the reinforcement and the surrounding concrete with the tensile force in the concrete within the width under consideration as (**Anchor R. D. 1992**):

$$f_b S \sum u_s = f_{ct} bh \qquad \dots. (5)$$

where:

$f_b =$ Average bond stress adjacent to a crack;

$S =$ Bond length necessary to develop cracking force which represents half the crack spacing;

$\sum u_s =$ Total perimeter of bars in the width considered.

Equation 5 is based on sufficient reinforcement is provided to control the cracking (i.e. the providing steel ratio is greater than the critical steel ratio given in equation 4). The maximum crack spacing $S_{\max}$ is obtained by rearrange equation 5 which yields (**Lee M. S.** and **Seo T. S. 2013**):

$$S_{\max} = 2S = \left(\frac{f_{ct}}{f_b}\right)\frac{\phi}{2\rho} \qquad \dots (6)$$

where:

$\phi =$ Diameter of steel bar;

$\rho =$ Providing steel ratio.

Strain condition

The total contraction strain, that is unrelieved by movement joints in the length of the member under consideration, determine the number and width of probable cracks. To find the crack width w, strain condition may be applied as:

$$S_{\max} = \frac{w}{\varepsilon_{tc}} = \frac{w}{\frac{1}{2}\alpha\left(T_1 + T_2\right)} \qquad \ldots (7)$$

Equating equation 6 and 7 yields:

$$\rho = \left(\frac{f_{ct}}{f_b}\right)\frac{\varepsilon_{tc}\phi}{2w} \qquad \ldots (8)$$

Watertight Considerations

From the preceding sections, it is clear that the most critical period in the life of a watertight structure occurs during the first few days. Tensile strength of the concrete is low, yet significant thermal contraction movements take place during this period, and restraints to this movement may therefore cause cracks to form. Design details can materially affect the restraints to movement, but specification limitations on the timing and sequence of concrete placing are important only during this critical initial period and only if reinforcement is continuous through joints (**Deacon R. C. 1978**).

The consequences of cracks must be kept in their true perspective. Large uncontrolled full-depth cracks will cause leakage, will be difficult to seal and will be a persistent problem throughout the life of structure. Fine cracks controlled by sufficient reinforcement and less than about 0.2mm in width to be self-sealing and of little significance. All reinforced concrete structures crack to some extent, the aim in designing and constructing watertight structures is to control any cracks which form to a limiting width of 0.1 to 0.2mm.

Verification Problem Using Finite Element Method

Long specimen with relatively small cross-sectional dimension is made containing one steel bar at center with different diameter (10mm, 12 and 16) as shown in Figure 1, and the ends of the reinforcement are held to prevent any movement. If experimental done for this problem it is expected after a few days it will be found that fine lateral crack are present. Depending on the relation between the quantity of reinforcement, the bar size, and cross-sectional area of concrete, either a few wide cracks, or a large number of fine cracks will form. The cracks are induced by the resistance of the reinforcement to the strains in the concrete caused by chemical hydration of the cement in the concrete mix.

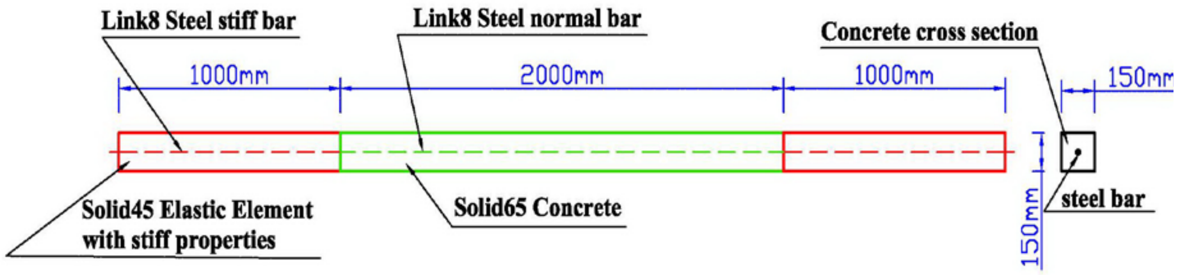


Figure 1: Verification problem geometry.-

In the present work, this problem is solved using finite element method (ANSYS) (**Madenci E. and Guven I. 2006**). The types of element, real constants and elements properties used in this analysis are presented in Table 1. Stiff element is used at both ends of the concrete as well as steel bar ends to overcome the problem of stress concentration at these points. The properties used for stiff elements in term of either cross sectional area or/ and modulus of elasticity is assumed as a huge values. The properties of the concrete element under consideration are assumed as immature concrete properties. The tensile strength of the immature concrete is equivalent to the tensile strength of three days of concrete age. While, the coefficient of thermal expansion of immature concrete is assumed half of mature concrete one. The 25 mm element size is used through the meshing processing as shown in Figure 2. The both ends of the volume block and steel reinforcement element were prevented from any movement as shown in Figure 3 which represents the boundary condition of one end. The other end is identical to the first one. The applied temperature is subjected to all nodes as a uniform nodal temperature which gradually increased from zero to 50 ^{o}C. The crack width and spacing founded from the finite element method are compared with the code equations (8) in Table 2 and Figures form 4 to 7 for different level of temperatures. Table 2 shows an acceptable agreement between the finite element model and the Code equations.

Table 1: Types of element, real constants and material properties.

Element Type	Constant and/or Property	Value (Unit)
Solid65 Concrete	Modulus of Elasticity of Concrete	24000 (MPa)
	Poisson's Ratio of Concrete	0.2
	Thermal Expansion of Concrete	6x10^{-6} (1/^{o}C)
	Standard Stress Strain Curve of Concrete, $f'c$	28 (MPa)
	Tensile Strength of Concrete at 3 days	1.6 (MPa)
Solid45 Elastic element with stiff properties	Modulus of Elasticity	200000 (MPa)
	Poisson's Ratio	0.3
	Thermal Expansion	6x10^{-6} (1/^{o}C)
Link8 Steel bar	Area	79, 201, 113 (mm^2)
	Initial Strain	0
	Modulus of Elasticity	200000 (MPa)
	Poisson's Ratio	0.3
	Thermal Expansion	12x10^{-6} (1/^{o}C)
	Yield Strength of Steel	460 (MPa)
	Tangent Modulus	25 (MPa)
Link8 Steel stiff bar	Area	500 (mm^2)
	Initial Strain	0
	Modulus of Elasticity	2000000 (MPa)
	Poisson's Ratio	0.3
	Thermal Expansion	12x10^{-6} (1/^{o}C)

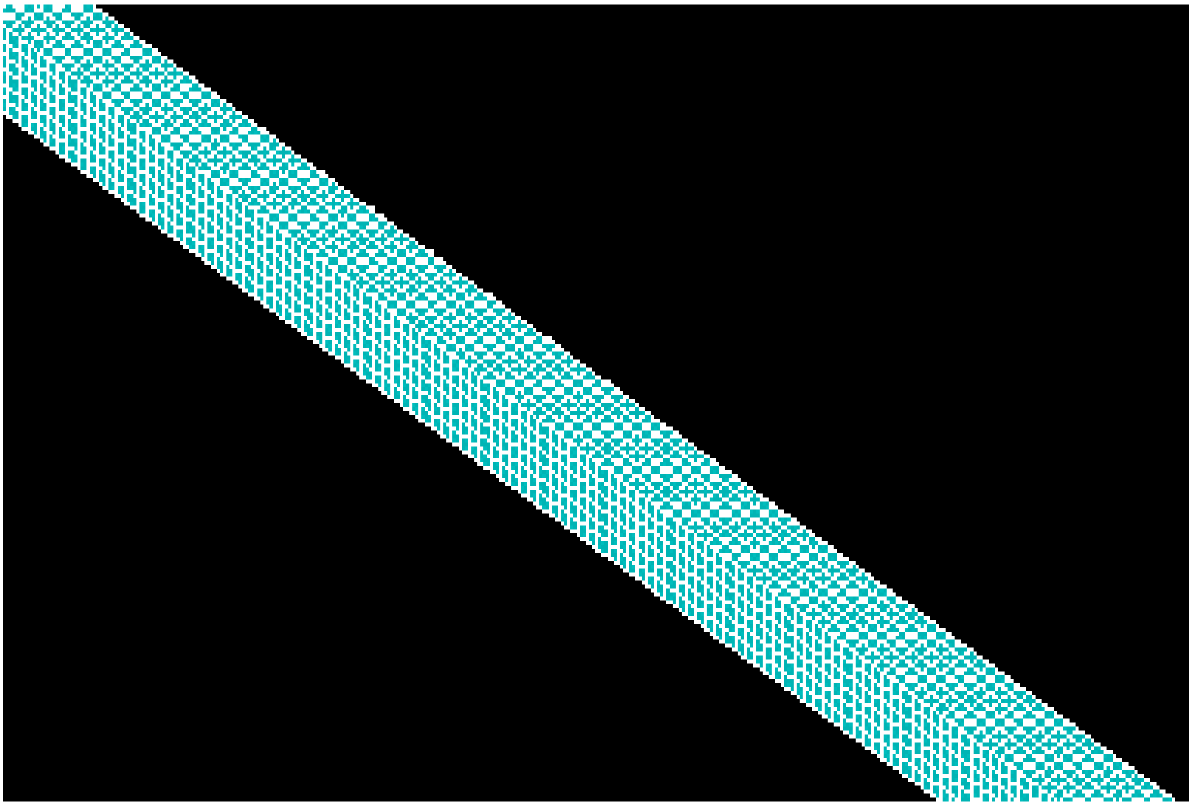


Figure 2: Problem discretization.

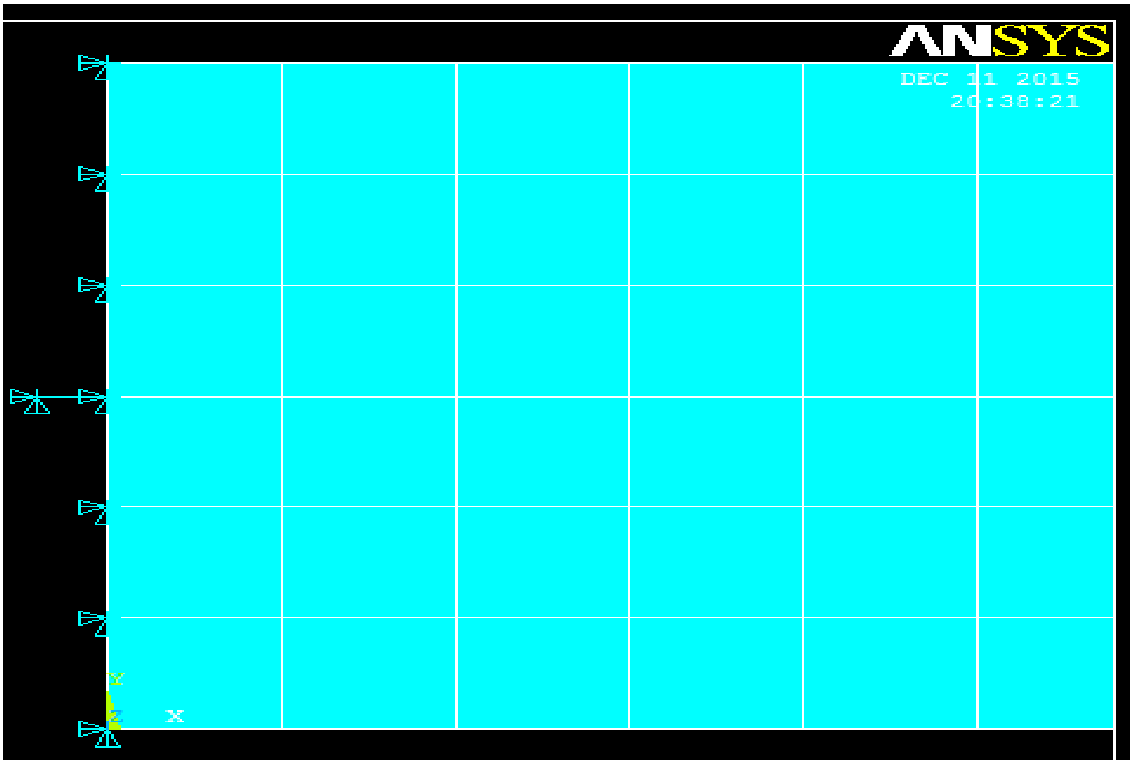
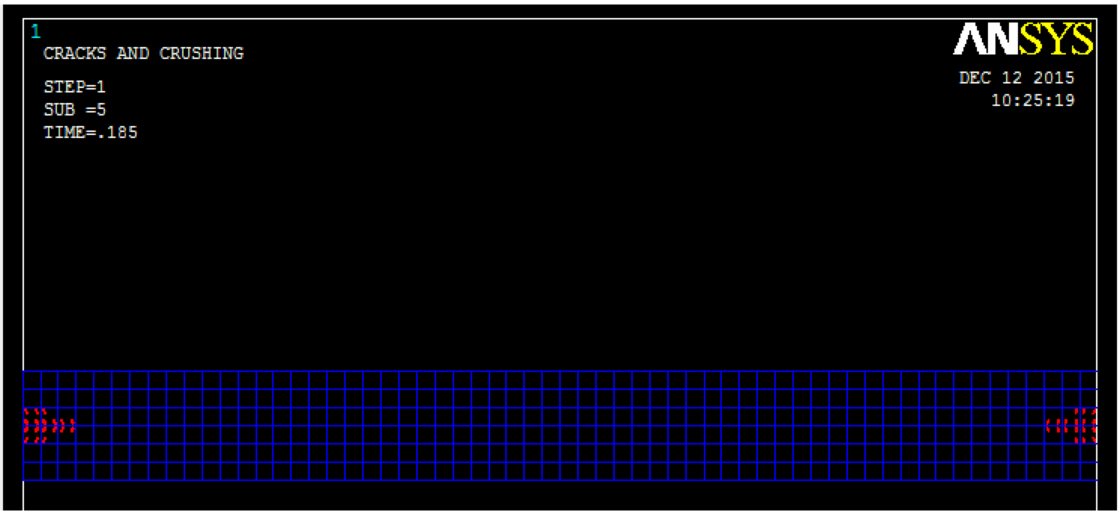


Figure 3: Support conditions.

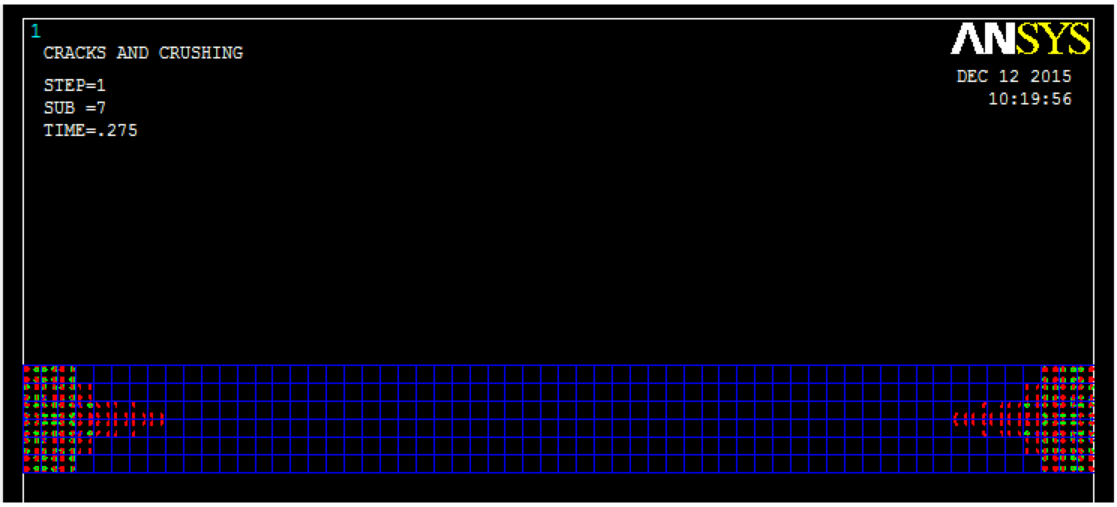
Table 2. Crack width and spacing.

ANSYS Time	Temperature °C	Crack Width Mm	Crack Spacing (ANSYS) mm	Crack Spacing (Code Equations) mm
0.1850	9.25	0.05	1550	1801
0.2750	13.75	0.05	1350	1212
0.3650	18.25	0.05	1050	913
0.4325	21.625	0.05	750	770
0.4887	24.435	0.05	600	682
0.5562	27.81	0.04	300	479
0.6406	32.03	0.03	200	312
0.7418	37.09	0.02	150	179
0.8937	44.685	0.01	75	74
1.0000	50	0.01	50	33



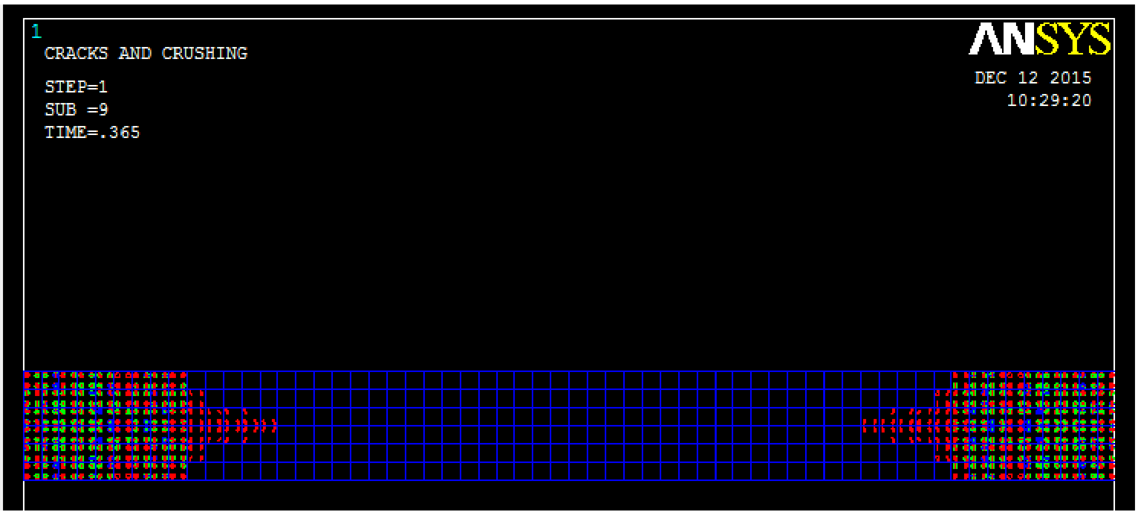
```
CRACKS AND CRUSHING

STEP=1
SUB =5
TIME=.185
```

Figure 4: Cracks at time equal 0.185.



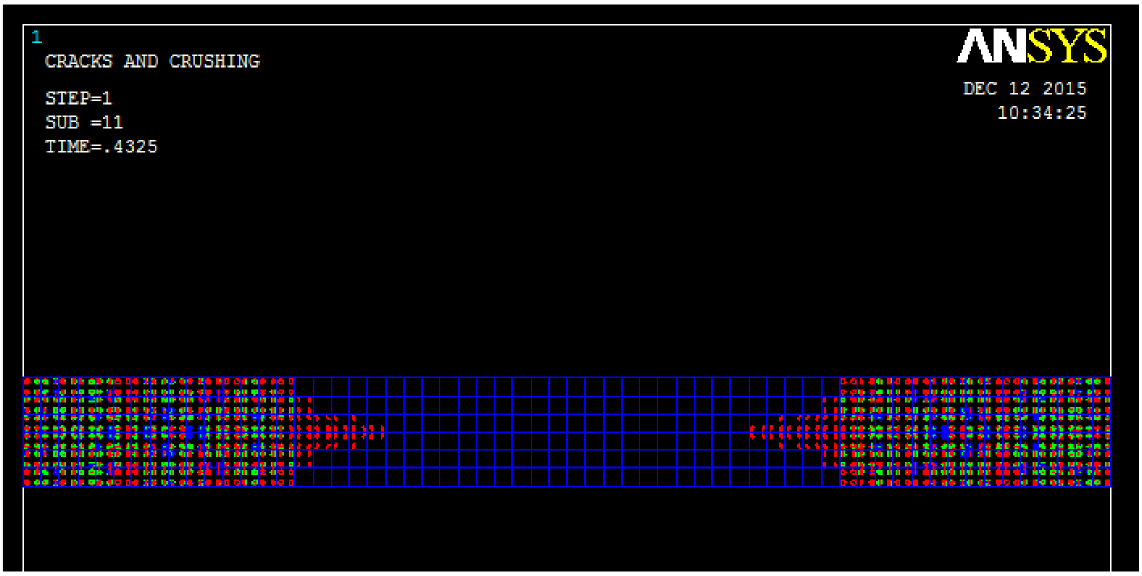
1
CRACKS AND CRUSHING
STEP=1
SUB =7
TIME=.275

Figure 5: Cracks at time equal 0.275.



1
CRACKS AND CRUSHING
STEP=1
SUB =9
TIME=.365

Figure 6: Cracks at time equal 0.365.



1
CRACKS AND CRUSHING
STEP=1
SUB =11
TIME=.4325

Figure 7: Cracks at time equal 0.4325.

Case Study

Reinforced concrete wall member of 0.25m thickness and 15m length with 2m height was used as a case study in this research throughout using equation 8. Three types of reinforcement bars were used $\phi 10$ mm, $\phi 12$ and $\phi 16$ subjected to three different values of applied temperatures 50 °C, 60 and 70 with three construction exposures class A(w = 0.1 mm), B(w = 0.2 mm) and C(w = 0.3 mm). The material properties and the real constants for both the concrete and rebar are having the same values for the verification problem above. The coefficient of thermal expansion of one half of the value for mature concrete was used to take into account the high creep strain in immature concrete for early-age effects and to take into account bond strength of mature concrete relative to immature concrete for seasonal effects. The results of the parametric study for the above parameters are collected and drawn in Figure 9. This figure is designed as a master chart for controlling the crack width and spacing in term of bar diameter, steel ratio and applied temperature. It is seen clearly concludes from this figure that high steel ratio required in different perspective values as either the crack width decreases or as the bar diameter increases. When the applied temperature increases led also to high steel ratio. The change in steel ratio is very sensitive with the crack width. The figure is also stated as the applied temperature increases due to heat of hydration in the concrete, the crack spacing decreases with a constant value for bar diameter, crack width and steel ratio.

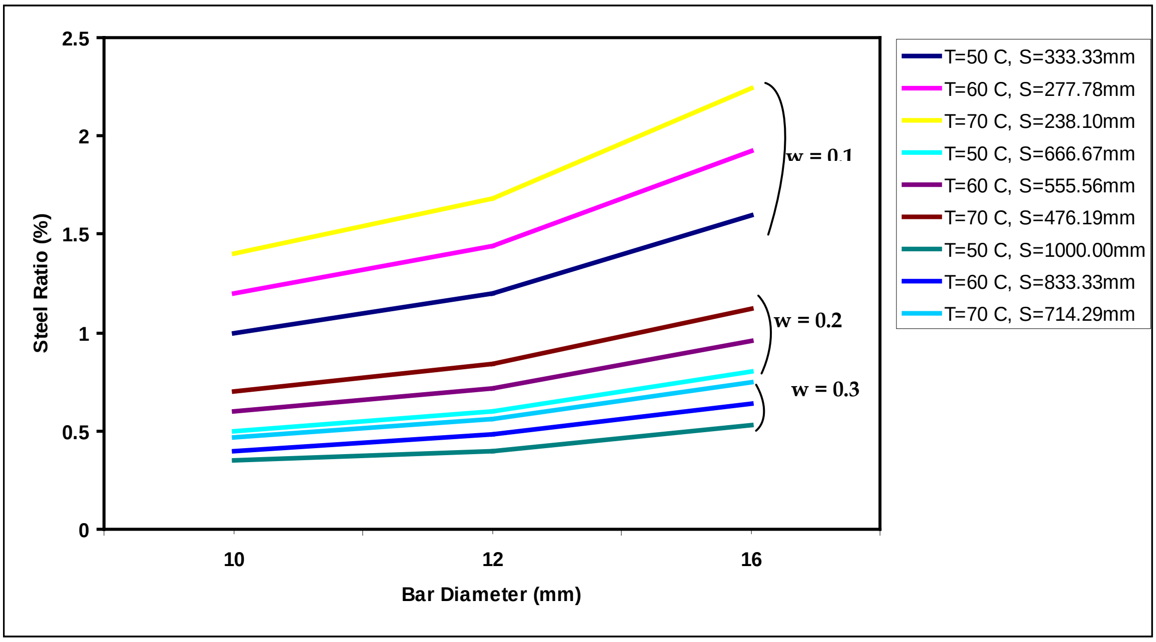


Figure 9: Steel ratio function of bar diameter and spacing, temperature and crack width**.**

Conclusions

1. The comparison between the Code equations and finite element analysis of crack width and spacing for watertight continuous construction shows good agreement.
2. As the bar diameter increases, the required steel ratio increases proportionality to match the assumed crack width. For minimum steel ratio, it must use smallest bar diameter in order to not validate the required crack width, but unfortunate this is limited by minimum practical bar spacing.
3. Continuous construction option for crack control compared with the other two options; semi-continuous and jointed construction proves the high steel area required especially for class A exposure.

References

[1] **ACI 209.2R-08, 2008**, “Guide for modeling and calculating shrinkage and creep in hardened concrete”, American Concrete Institute.

[2] **ACI 350M-06, 2006**, “Code requirements for environmental engineering concrete structure”, American Concrete Institute.

[3] **Anchor R. D. 1992**, “Design of Liquid Retaining Concrete Structures”, Book of Great Britain second edition.

[4] **BS 8007. 2003**, “Design of concrete structures for retaining aqueous liquids”, British Standard Institution, Sheffield University.

[5] **Deacon R. C. 1978,** “Watertight concrete construction”, Cement and Concrete Association. London.

[6] **Huges B. P. and Mahmood, A. T.** 1988, “An investigation of early thermal cracking in concrete and the recommendations in BS8007”, Structural Engineering, 66 (4), 61-69

[7] **Harrison T. A. 1991, “**Earl-age thermal crack control in concrete”, 2nd edition, CIRIA Report 91, London.

[8] **Lee M. S. and Seo T. S. 2013,** “Prediction method of drying shrinkage crack in reinforced concrete walls”. International Journal of Civil Engineering.

[9] **Madenci E. and Guven I. 2006, “**The finite element method and applications in engineering using ANSYS”, Book by Springer Science+Business Media, LLC.

[10] **Westbrook R. 1988,** “ Structural engineering design in practice”, 2nd edition, Longman, Harlow,

[11]

السيطرة على التشققات الناتجة من الانفعالات المبكرة للمنشاءت المائية المستمرة المصنوعة من الخرسانة المسلحة

حسام كاظم رسن
جامعة النهرين، كلية الهندسة، قسم الهندسة المدنية، بغداد، العراق.

الخــلاصــة:

تشقق المنشاءات الخرسانية المسلحة يكون اما نتيجة الاحمال الخارجية المسلطة او الحرارة المبكرة الناتجة من تفاعل اماهة الاسمنت والزحف والانكماش او نتيجة التاثيرات الفصلية المتعلقة بالظروف البيئية. اغلب المدونات العالمية تخمن كمية الحديد اللازمة للسيطرة على التشققات الناتجة من الانفعالات المبكرة بتحديد اقل كمية لا يمكن تجاوزها عن التصميم، لكن هذه الكمية غالبا ما تكون اقل من المطلوب خاصة بالمنشاءات المائية. في هذا البحث، تم اجراء تحليل عددي لعضو انشائي مستمر مصنوع من الخرسانة المسلحة باستخدام طريقة العناصر المحددة ثلاثية الابعاد. تم دراسة تغير قطر حديد التسليح ودرجة الحرارة المسلطة نتيجة مجموع تاثير حرارة تفاعل الاسمنت المبكره والحرارة المتوقعة من الظروف البيئية على عرض التشققات والمسافات بينهم. استخدمت معادلات المدونة البريطانية للمقارنة مع نتائج طريقة العناصر المحددة. اظهرت النتائج تطابق مقبول بين طريقة العناصر المحددة والمعادلات المستخدمة في المدونة المذكورة. استخدم هذا التطابق لدراسة خصائص التشققات من حيث السمك والتباعد بينهم، حيث شملت الدراسة ثلاثة انواع من التعرض (أ، ب، جـ) لثلاث قيم من الحرارة المسلطة بتغير قطر حديد التسليح لثلاثة قيم (10, 12, 16mm). اكدت النتائج من هذه الدراسة، كلما زاد قطر حديد التسليح يؤدي الى زيادة نسبة حديد التسليح للحصول على نفس عرض التشقق المطلوب. لذلك يفضل استخدام اقطار حديد صغيرة لتقليل كمية الحديد اللازمة للسيطرة على التشققات ولكن يجب عدام تجاوز البعد الادنى بين قضبان حديد التسليح. كما اشار هذا البحث بشكل عام بحاجة المنشاءات المائية المستمرة والمتعرضة لصنف التعرية (أ) الى نسبة حديد عالية اكثر من المذكور في اغلب المدونات.