Early Thermal Cracking Control of Concrete Structures in Qatar

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Abstract

Thermal cracks can occur in concrete elements at early stages during the hardening process. Also, the impact of thermal contraction and drying and autogenous shrinkage, may lead to excessive tensile strains and as a result cracks will occur. Consequently, an increase in reinforcements may be required to satisfy Early Thermal Cracking (ETC). ETC remains a major concern for concrete structures, especially for structures with high demand of water tightness. Considering the significance of water leaking in underground structures and the rising of the groundwater table in Qatar in the recent years, the Public Works Authority (ASHGHAL) has set the criteria to control early thermal cracks for Highway and Drainage Structures. This paper aims to present a comparison between the Early Thermal Cracking (ETC) codes and guidelines aiming towards providing sustainable and efficient design. This study compares the design method and parameters considered in BD 28/87, CIRIA C660 and CIRIA C766 currently used in Qatar for ETC calculations such as crack width permissible limit, minimum area of reinforcements, temperature change at early age, long term ambient temperature, autogenous shrinkage, drying shrinkage and restraint conditions. In addition, ETC calculations are carried out for a tunnel reinforced concrete box section with wall and top slab thicknesses ranging from 300mm to 1000mm. The least required area of reinforcements ($A_{s,req}$) for wall subject to edge restraint was by CIRIA C766 and for top slab subject to end restraint was by BD 28/87.

Keywords: Early Thermal Cracking; Underground Concrete Structures; CIRIA C766; CIRIA C660; BD 28/87

1 Introduction

After casting, concrete is subjected to volumetric changes at early age and in the long-term leading to cracks when subjected to restraint. The volumetric changes are caused by imposed deformations from temperature caused by heat of hydration due to concrete cooling from its peak temperature and ambient temperature contraction due to concrete cooling to lowest ambient temperature. Further, volumetric changes result from shrinkage due to drying shrinkage where concrete shrinks while drying and autogenous shrinkage where the concrete shrinks due to chemical hydration (Gilbert & Ranzi, 2010).

In Qatar, Public Work Authority (PWA)'s design criteria for highway structures follows Ashghal Interim Advice Note No. 009, Revision No. A2 (Ashghal, 2016) which states that checking for early thermal cracking is to be carried out by either BD 28/87 (Highway Agency, 1989) or CIRIA Report C660 (Bamforth, 2007). Further, design criteria for drainage structures such as water retaining structures follows PWA Standard Drawing # SD 8-4-106_Rev.03 (Ashghal, 2019), which requires structures to be designed following BS EN 1992-1-1 (BSI, 2004) and BS EN 1992-3 (BSI, 2006). In NA to BS EN 1992-3 (BSI, 2009), reference to CIRIA C660 (Bamforth, 2007) is specified for complementary guidance on ETC. Moreover, CIRIA C660 was superseded by CIRIA C766 (Bamforth, 2018) where several parameters were modified.

This paper aims to present salient points of our study with a comparison between the Early Thermal Cracking (ETC) codes and guidelines aiming towards providing sustainable and efficient design. This study will compare the design method and parameters considered in BD 28/87, CIRIA C660 and CIRIA C766 currently used in Qatar for ETC calculations such as crack width permissible limit, minimum area of reinforcements, temperature change at early age, long term ambient temperature, autogenous shrinkage, drying shrinkage and restraint conditions. In addition, example of a tunnel under a constant water table is considered to quantify the required reinforcements for ETC of typical concrete elements subject to similar configurations and restrain conditions.

2 Early Thermal Cracking Guidelines

2.1 Key differences between ETC guidelines

The approach followed by the guidelines, as listed below, is generally similar but there are key differences impacting the calculated required reinforcements to meet the allowable crack width limit.

- BD 28/87 (Highway Agency, 1989) generally follows the method of BS 8007 (BSI, 1987) and CIRIA C660 (Bamforth, 2007) & C766 (Bamforth, 2018) follow BS EN 1992-3 (BSI, 2006).
- Concrete effective area is calculated differently impacting the required minimum area of reinforcement and calculated steel ratio considered in crack width calculations.
- Concrete cover is included in crack width calculations with CIRIA C660 (Bamforth, 2007) & C766 (Bamforth, 2018). In contrast, BD 28/87 Highway Agency (1989) only states to place the reinforcement as close to the surface in compliance with cover requirements without including the influence of cover on crack width.
- In CIRIA C660 (Bamforth, 2007) & C766 (Bamforth, 2018), expressions for crack width calculations (i.e. crack-inducing strain) varies depending on the nature of the restraint (i.e. continuous edge restraint, end restraint or internal restraint) unlike BD 28/87 (Highway Agency, 1989).
- Autogenous shrinkage is included in CIRIA C660 (Bamforth, 2007) & C766 (Bamforth, 2018).

2.2 Key Differences between CIRIA C660 and CIRIA C766

The approach followed by the guidelines, as described below, is generally similar but there are key differences impacting the calculated required reinforcements to meet the allowable crack width limit:

- Minimum area of reinforcements ($A_{s,min}$):

  $A_{s,min}$ required in CIRIA C766 compared to C660 is significantly reduced by considering $f_{ct,r}$ = 0.7 f_{ctm} instead of f_{ctm} and introducing the k_{Redge} coefficient, where f_{ctm} is the concrete's mean value of tensile strength, $f_{ct,r}$ is the concrete's low characteristic tensile strength and k_{Redge} is a coefficient accounting for transferring part of the load to the restraining element (edge) when crack happens.

- The crack-inducing strain (ε_{cr}):

  In crack-inducing strain calculations, CIRIA C766 recommends using $f_{ct,r}$ = 0.7 f_{ctm} instead of f_{ctm} used in CIRIA C660 as the value of concrete tensile strength.

- Coefficient for bond properties of reinforcements (k_1):

  CIRIA C660 recommended to increase k_1 value proposed in BS EN 1992-1-1 from 0.8 to 1.14 by implementing a reduction factor of 0.7 to cover cases with poor bond, unless the lower value is verified by experience. CIRIA C766 stated that poor bond applies to elements with thickness larger than 300 mm and also have concrete cover ≤ 50 mm.

- Concrete cover (C):

  CIRIA C660 considers using nominal cover (C_{nom}) in compliance with BS EN 1992-1-1 by adding an allowance for deviation (ΔC_{dev}) of 10 mm to the minimum cover (C_{min}). However, in CIRIA C766, C_{min} is recommended to be used.

- External Edge Restraint (R):

  Restraint factor is adjusted in CIRIA C766 to consider the restraint at the location of the maximum crack width and not at the joint and accordingly reducing the restraint value.

2.3 Minimum Area of Reinforcements ($A_{s,min}$)

$A_{s,min}$ is required to control crack width by limiting the steel stress to its yield strength due to the stress transfer to steel after cracking. For $A_{s,min}$ calculation, refer to equations 2, 3.12 and 3.20 provided in BD 28/87, CIRIA C660 and CIRIA C766, respectively.

2.4 Crack Width (CW)

Area of reinforcements required to meet allowable crack width limit ($A_{s,cw}$) is determined in accordance with equations 3, 3.15 and 3.23 provided in BD 28/87, CIRIA C660 and CIRIA C766, respectively.

2.5 Other Factors Affecting ETC

2.5.1 Temperature drop from hydration peak to mean ambient (T1).

The main variables affecting T1 are summarized under Table 1. In BD 28/87, tabulated T1 values are provided depending on the defined cement content, formwork type and casting season. In addition, for sections with thickness larger than 500 mm, T1 is increased by 10 °C. On the other hand, in CIRIA C660 and C766, T1 values maybe determined from excel spreadsheets developed by CIRIA taking into consideration many influencing variables such as binder content, binder type, concrete placing temperature, temperature ambient conditions, section thickness, formwork and insulation, etc.

Estimated T1 values considering the variables as defined under Table 1 were plotted in Figure 1 and Figure 2. Figure 1 shows a comparison between the guidelines under consideration for binder type CEM 1 considering different temperature values for Qatar (QA) and United Kingdom (UK). Unlike BD 28/87, the spreadsheet calculator provided by CIRIA considers the placing and ambient temperatures as variables and therefore can be adjusted to accommodate Qatar's hot climate. This can be observed in Figure 1 where higher T1 values resulted from CIRIA when placing temperature and ambient temperature were adjusted to suit Qatar's hot climate.

Figure 2 shows estimated T1 calculated in accordance with CIRIA guidelines for different binder types and taking into consideration Qatar's higher temperatures. It can be observed that T1 values obtained for binder Type CEM1 and Fly Ash are exactly similar. However, the key difference is the overestimated T1 values obtained from C660 for concrete with ground granulated blast-furnace slag (GGBS) binder type which were recalibrated in C766 based on feedback from users.

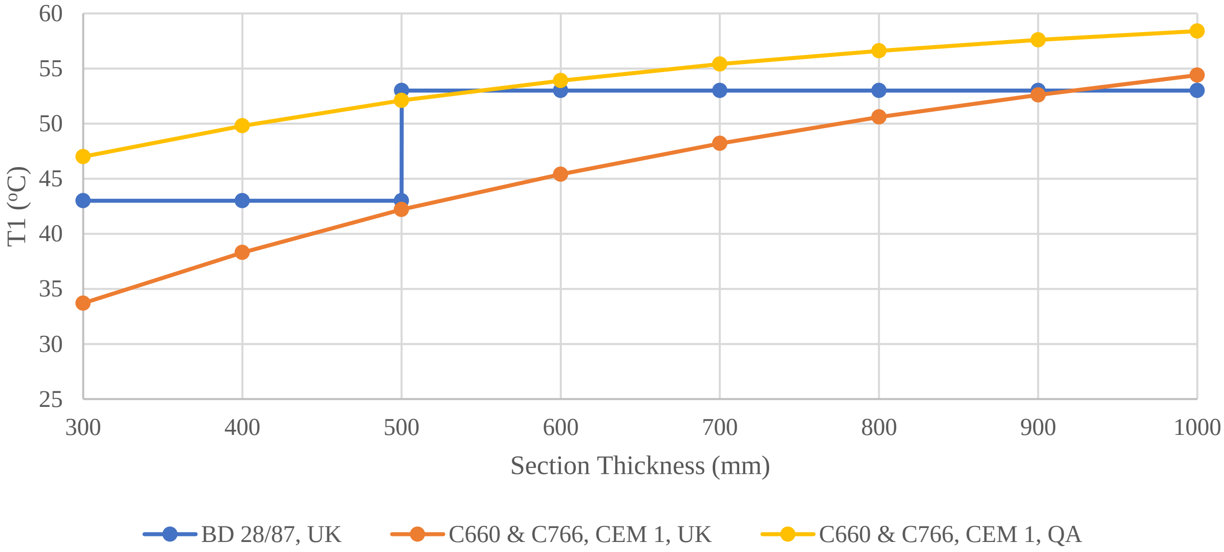

Fig. 1: T1 Values for CEM 1 Binder Type in Qatar (QA) and United Kingdom (UK)

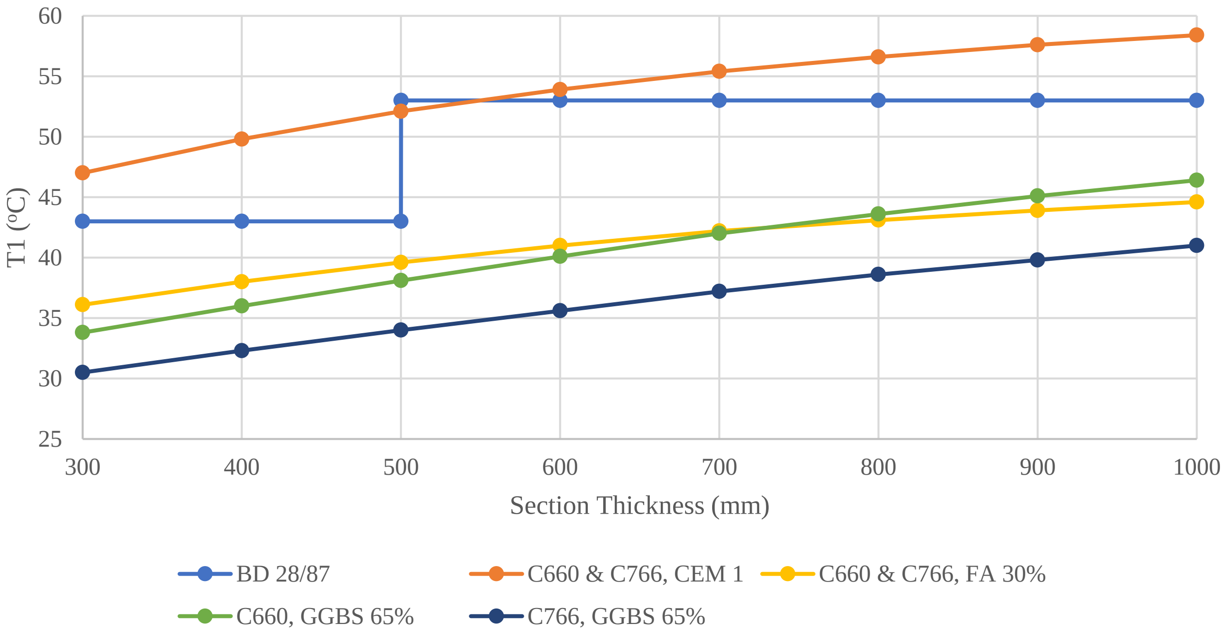

Fig. 2: T1 Values for Different Binder Types in Qatar (QA)

Table 1: Variables Impacting T1

Variable			BD 28/87	CIRIA C660	CIRIA C766	Assumed Values	Reference to Local Conditions Applicable to Qatar
			Standards				
Concrete Mix Details	Binder Content		✓	✓	✓	400 kg/m^3	Maximum cementitious content without special consideration as per QCS 2014, Section 05, Part 06, Cl. 6.3.1(2) (Technical Regulation, 2014)
	Binder Type	CEM 1	✓	✓	✓	CEM 1, 100%	-
		Fly Ash	×	✓	✓	Fly Ash, 30%	% of cementitious material is based on ranges specified under QCS 2014, Section 05, Part 06, Table 6.6 (Technical Regulation, 2014)
		GGBS	×	✓	✓	GGBS, 65%	
	Wet Density		×	✓	✓	2400 kg/m^3	-
	Specific Heat		×	✓	✓	1 kJ/kg^{o}C	-
	Thermal Conductivity		×	✓	✓	2 W/m^{o}C	Applicable to Aggregate from Gabbro type with siliceous sand as per CIRIA C766, Cl. 4.5 (Bamforth, 2018).
Temperature Input	Casting Season		✓	×	×	Summer	-
	Placing Temperature		×	✓	✓	32 ^{o}C (QR) 20 ^{o}C (UK)	Maximum fresh concrete temperature as per QCS 2014, Section 05, Part 06, Cl. 6.3.1(4) (Technical Regulation, 2014)
	Ambient Temp.	Min.	×	✓	✓	5 ^{o}C (QR) 10 ^{o}C (UK)	Qatar (QA) values are as per QCS 2014, Section 01, Part 01, Cl. 1.5.2(4) (Technical Regulation, 2014). UK values are as per CIRIA 766, Cl. 4.2.2 (Bamforth, 2018).
		Mean	×	✓	✓	27.5 ^{o}C (QR) 15 ^{o}C (UK)	
		Max.	×	✓	✓	50 ^{o}C (QR) 20 ^{o}C (UK)	
		Constant or variable	×	×	✓	Variable	-
	Placing Time		×	✓	✓	10 hours	Assumed placing time for maximum impact
Section and formwork details	Section Thickness		✓	✓	✓	300 mm to 1000 mm	-
	Formwork/ Insulation Type		✓	✓	✓	18mm plywood	-
	Wind Speed		×	✓	✓	0 m/s	Wind speed assumed for underground structure
	Formwork Removal time		×	✓	✓	48 hours	Minimum period prior to stripping of formwork is 24 hours for walls as per QCS 2014, Section 05, Part 09, Table 9.1 (Technical Regulation, 2014)

3 Practical Example in Qatar

Area of reinforcements (A_s) required to satisfy early thermal cracking requirements is calculated in accordance with BD 28/87, CIRIA C660 and CIRIA C766. The calculation is carried out for a below ground tunnel structure subject to high water table and stringent requirements for watertightness. The tunnel consists of reinforced concrete box section with an in-situ concrete top slab, integral with side walls on reinforced concrete base slab. ETC required area of reinforcements is determined for top slab and walls of varying thicknesses ranging from 300 mm to 1000 mm.

3.1 Qatar's Parameters

Parameters impacting ETC which are applicable to Qatar are summarised in Table 2.

Table 2: Qatar's Design Parameters

Parameter		Value	Unit	Reference
Concrete Grade		**C40**	Cubic Strength	IAN009_Rev.A2, Design Criteria # 13 (Ashghal, 2016)
Binder Type		Fly Ash 30	%	QCS 2014, Section 05, Part 06, Table 6.6 (Technical Regulation, 2014)
Actual Cover (C_{actual})	Base slab Bottom Face	**100**	mm	IAN009_Rev.A2, Design Criteria # 17 (Ashghal, 2016)
	Earth Face	**75**	mm	
	Internal Face	**50**	mm	
Minimum Cover (C_{min})		**35**	mm	BS EN 1992-1-1, Section 4.4.1.2, $C_{min,dur}$ for Structural Class S6 and Exposure Class XC3 (BSI, 2004)
Nominal Cover (C_{nom})		**45**	mm	BS EN 1992-1-1, Section 4.4.1.3 Δc_{dev} = 10mm (BSI, 2004)
Reinforcement Grade		**500**	MPa	IAN009_Rev.A2, Design Criteria # 14 (Ashghal, 2016)
Temperature Drop - T1		**See Section 2.5.1**		
Temperature Drop After Early Age- T2		**0**	ºC	BD 28/87, Cl. 5.9 (Highways Agency, 1989) CIRIA C660 and CIRIA C766, Cl. 4.3
Coefficient of Thermal Expansion		**12×10^{-6}**	/ ºC	IAN009_Rev.A2, Design Criteria # 6 (Ashghal, 2016)
Ambient Relative Humidity		**70**	%	IAN009_Rev.A2, Design Criteria # 6 (Ashghal, 2016)
End of Curing		**7**	Days	QCS 2014, Section 05, Part 10, Cl. 10.2 (Technical Regulation, 2016)
Design Life		**120**	Years	IAN009_Rev.A2, Design Criteria # 3 (Ashghal, 2016)
Allowable Crack width		**0.2**	mm	IAN009_Rev.A2, Design Criteria # 11 (Ashghal, 2016)

3.2 ETC for Walls

The nature of the restraint considered for walls cast onto base is external edge restraint. Restraint factors considered are provided in Table 3.

Table 3: External Edge Restraint Factors

Standard	Restraint Factor			Reference
	Restraint (R)	**Early Age Restraint (R1)**	**Long Term Restraint (R2 & R3)**	
BD 28/87	0.6	-	-	BD 28/87, Table 2
CIRIA C660	-	0.59	0.5	CIRIA Annex A, Restraint Calculator (R1, An/Ao = 1 & En /Eo = 0.7) (R2 and R3, An/Ao = 1 & En /Eo = 1.0)
CIRIA C766	-	0.45	0.38	

3.3 ETC for Top Slab

The nature of the restraint considered for top slab cast between rigid walls is external end restraint. CIRIA C660 and C766, recognize that cracks resulting from end restraint would be larger than those resulting from edge restraint. In end restraint, the restrained strain only impacts crack occurrence and the number of cracks and not the crack width. Crack width is dependent on the concrete strength and reinforcement ratio. On the other hand, following BD 28/87, ETC calculations for top slab are considered similar to walls subject to external edge restraint but with a restraint factor of 0.5.

3.4 Results and Discussion

Required area of reinforcements ($A_{s,req} = \max[A_{s,min}, A_{s,cw}]$) for ETC calculated as per Sections 2.3 and 2.4 are presented in Figure 3 for walls and Figure 4 for top slab with thicknesses varying from 300 mm to 1000 mm.

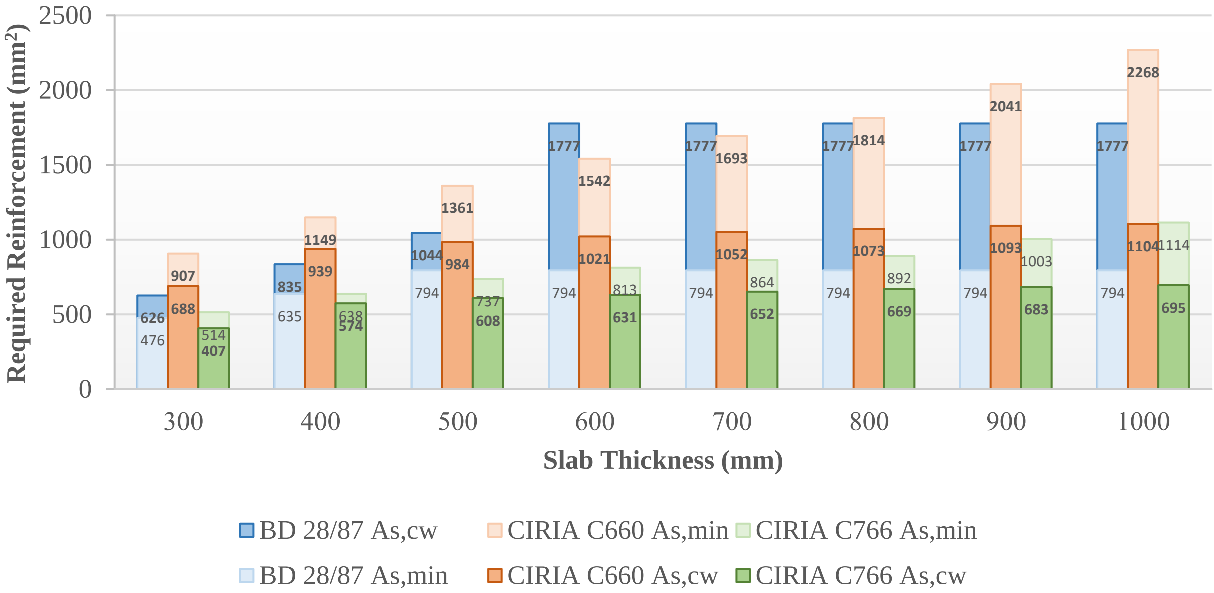

Fig. 3: Edge Restraint Required Area of Reinforcement (As,req)

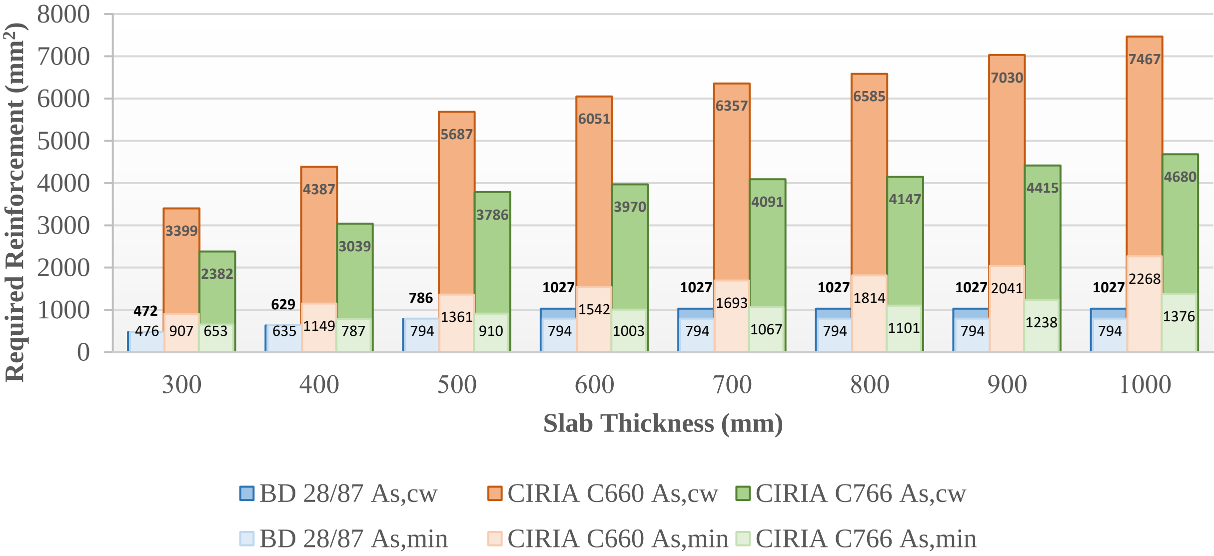

Fig. 4: End Restraint Required Area of Reinforcement (As,req)

The below can be observed from Figure 3 and Figure 4.

- There is a significant decrease in the required area of reinforcements in the latest CIRIA C766 in comparison with CIRIA C660 due the changes listed under Section 2.2. This decrease ranges from 43 to 51% for edge restraint and 30 to 37% for end restraint.
- $A_{s,min}$ requirements in CIRIA guidelines are generally more stringent than BD 28/87 especially for members with thickness larger than 500 mm as the effective area of concrete is considered as half the thickness but limited to 250 mm maximum in BD 28/87. $A_{s,min}$ required by CIRIA C766 is higher than BD 28/87 by a factor of 1.40 and 1.73 for 1000 mm thickness subject to edge restraint and end restraint, respectively.
- External Edge restraint (walls): $A_{s,min}$ is higher than $A_{s,cw}$ following CIRIA C660 and C766 and the opposite applies to BD 28/87 where $A_{s,cw}$ is controlling. Also, following CIRIA C766 requires the least reinforcements with reduction in required area of reinforcement of 18% to 54% compared with BD 28/87 and 43% to 51% compared with CIRIA C660.
- External End restraint (top slab): Higher crack width is anticipated in cracks developed due to end restraint which is not captured in BD 28/87. $A_{s,cw}$ is noted to be more than 3.4 times $A_{s,min}$ for CIRIA guidelines. Accordingly, the required area of reinforcement following BD 28/87 is significantly lower than CIRIA guidelines. However, it is recognized in the latest CIRIA C766, that in many situations where end restraint exists, the magnitude of the restraint might not be sufficient for cracking to develop. Thus, risk of cracking shall be calculated prior to unnecessarily increase in the reinforcements.

4 Conclusion

This paper provides a brief overview of Early Thermal Cracking (ETC) codes and guidelines used in Qatar, which are BD 28/87, CIRIA C660 and CIRIA C766. BD 28/87 has several limitations such as not accounting for the impact of concrete cover and Qatar's hot climate in crack width calculations. On the other hand, the updated CIRIA C766 guideline provides sustainable design in comparison with CIRIA C660 mainly due to adjustments in calculating minimum area of reinforcements and crack-inducing strain. ETC calculations were carried out for walls and top slabs of a tunnel reinforced concrete box section. For walls subject to edge restraint, CIRIA C766 requires the least reinforcements with reduction in required area of reinforcement of 18 to 54% compared with BD 28/87 and 43 to 51% compared with CIRIA C660. For top slab subject to end restraint, although $A_{s,req}$ by CIRIA C766 is 30 to 37% less than CIRIA C660, it is significantly higher than BD 28/87 as the higher crack width anticipated in members subject to end restraint is not captured by BD 28/87.

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