Validation of the Swedish crack risk estimation models

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ABSTRACT
Thermal cracking may occur during the early hardening process of concrete as a result of the exothermic reactions between water and cement. An approach for thermal crack risk estimation and prevention was introduced in the Swedish design guidelines BRO 94. This paper studies and validates the current safety levels existing concrete structures. Three slab-frame structures were analysed and the preliminary crack risk estimations were compared to the actual cracking and post-estimations were carried out, using actual parameters. This paper shows that all the studied walls with a strain ratio over 70% were affected by thermal cracks.

Key words: Cracking, Structural Design, Sustainability, Testing.

1. INTRODUCTION

1.1 General

Thermal cracking may occur during the early hardening process of concrete [1]. The hydration process involves exothermic reactions between water and cement, increasing the core temperature of the structure and thereby inducing thermal expansion of the concrete. However, prohibited deformation due to different types of restraints may lead to compressive strains. As the hydration rate reduces, the core starts cooling, inducing shrinkage and tensile strains within the restrained structure. The tensile strains may be associated to uneven expansion and contraction of the concrete due to differential temperatures in the inner core and the outer layers.

In some cases the tensile strains exceed the ultimate strain of the concrete and thermal cracks appear. Thermal cracks are usually identified as through cracks, emerged in the cooling phase, and supported by restraints. These types of cracks are generally associated with massive concrete infrastructure such as dams, foundations and tunnels, where the core temperature may become high and vary considerably internally. More slender structures may also be subjected to thermal cracks if e.g. high temperature differences arise between a newly cast wall and a previously cast slab. Thermal cracks may also emerge during the heating phase if the internal temperatures vary considerably and the cracks can be located both in the slab and the wall. Another type of cracks that usually emerge during the heating phase, are the surface cracks. These cracks are restricted the concrete surface and thereby remain thin, with widths below 0,1 mm. Surface cracks may also emerge due to rapid surface cooling associated with form removal or rapid shifts in the weather.

The risk of thermal cracking, η, may be calculated as the structural stress ratio, or alternatively the strain ratio:

$$\eta = \left(\frac{\sigma_t(t)}{f_{ct}(t)}\right)^{max} \approx \left(\frac{\varepsilon_t(t)}{\varepsilon_{ct}(t)}\right)^{max} \tag{1}$$

Where $\sigma_t(t)$ is the tensile stress at the time t
$f_{ct}(t)$ is the tensile strength at the time t
$\varepsilon_t(t)$ is the tensile strain at the time t
$\varepsilon_{ct}(t)$ is the ultimate tensile strain at the time t

The safety level for cracking, Γ, is defined as the inverse of η:

$$\Gamma = \frac{1}{\eta} \tag{2}$$

The prevailing concept for crack risk estimations was introduced in the Swedish guidelines BRO 94 [2], and can today be found in AMA Anläggning [3]. The concept aims at reducing the risk of thermal cracking of concrete structures by introducing different safety levels for different exposure classes (previously denoted environmental classes). Originally there were three major safety levels and today the design approach has expanded into five levels, as shown in Table 1. Unknown material parameters require higher safety levels, while tested parameters result in lower requirements for the safety level. The untested concrete has been divided into two levels depending on the cement content, where a higher heat of hydration and thereby higher safety factor is expected for the higher cement content, C.

Table 1. Safety levels for thermal cracking of concrete structures.

Exposure class	**Material parameters**		
	Complete	$360 \leq C \leq 430$ kg/m^3	$430 < C \leq 460$ kg/m^3
XC2	1,05	1,18	1,33
XC4	1,11	1,25	1,42
XD1, XS2	1,18	1,33	1,54
XD3, XS3	1,25	1,42	1,67
Structures exposed to one sided water pressure			
All classes	1,42	1,67	2,0

The risk of thermal cracking should, according to AMA Anläggning, be reduced by applying one of the following three methods for crack prevention:

Method 1: Temperature requirements may be applied for the concrete and the surrounding air. Certain requirements for the geometry, cement content and structural restraints should also be fulfilled.

Method 2: Some typical design cases were studied in [4] and the most representative case, with associated design parameters and crack preventing actions, may be applied.

Method 3: Using sophisticated computer software to calculate the risk of thermal cracking and customize the crack preventing actions. The applied software should be thoroughly validated and the material parameters should be known.

2 METHOD

The method for this project can roughly be divided into 6 steps:

1. Identifying relevant structures with adequate documentation.
2. Studying construction documentation.
3. Checking preliminary thermal crack risk estimations and actual crack preventing measures based on expected parameters.
4. Carrying out post-project thermal crack risk estimations based on actual parameters, i.e. Method 3 according to AMA Anläggning.
5. Field inventory of emerging thermal cracks.
6. Analysis of the procedure and accuracy of crack risk estimations.

Three concrete structures were chosen for this project: a railway tunnel in Gamla Uppsala (2016) and two existing portal frame bridges in Ulriksdal (1990) and Antuna (1993). The structural parameters are found in Table 2. The structures were analyzed in 2D with ConTeSt Pro 5.0, a commercial FEM software developed for purpose of temperature, strength and crack risk calculations in young concrete.

Table 2. Structures analyzed in this paper.

Name of structure	Year of construction	Length	Cast length (walls)	Height	Wall thickness
Gamla Uppsala	2014-2016	610 m	10,0 m	9,5 m	0,7 m
Ulriksdal	1989-1990	41,6 m	10,4 m	6,0 m	0,8-1,2 m
Antuna	1993	35 m	35 m	5,0 m	0,45 m

3 RESULTS

Table 3 shows a presence of thermal cracks for all walls with $\eta > 0,70$ in the post-design and a few thermal cracks could also be seen on walls with even lower strain ratios. No temperature cracks were supposed to be formed according to the preliminary design for Gamla Uppsala, Ulriksdal or Antuna. Three casting sequences of the Gamla Uppsala tunnel exceeded their limiting strain ratio $\eta = 0,90$ in their post-design. However, temperature cracks were found on 10 out of 14 analyzed sections. Small surface cracks, < 0,1 mm openings, were also studied and counted in the crack inspection and the amount of small cracks ranged from 6 – 38 cracks for each casting.

For Ulriksdal, one out of four casting sequences exceeded the limiting strain ratio $\eta = 0,70$ (based on exposure class XD3/XS3 and a cement content of 390 kg/m3) in the post-design and temperature cracks were found on two sections during the visual inspection. The single casting of Antuna was not supposed to crack according to neither the preliminary design, nor the post-design, and no temperature cracks were indeed detected.

Crack risk estimations according to the Swedish standards have probably reduced the amount of thermal cracks in the Swedish infrastructure, but there are still a large number of uncertainties involved in the design. Based on the results of this study, it seems relevant to question whether higher strain ratios than 0,70 should be allowed.

Table 3. Summary of the preliminary- and post-designs for thermal crack risks.

Seq.	Exposure class	η Limit	η Preliminary	η Post	Temp. cracks >0,1 mm	Average crack width, mm	Small cracks ≤0,1 mm
Gamla Uppsala							
3.1.1	XC4/XF4 Tested material parameters	0,90	0,57	0,58	**1**	0,20	25
3.1.2			0,77	0,55	0	-	6
3.2.1			0,77	**0,97**	**1**	0,20	30
5.1.1			0,77	0,67	0	-	23
5.1.2			0,77	0,90	**1**	0,30	38
5.2.1			0,77	**1,01**	**1**	0,20	27
5.2.2			0,77	0,75	**1**	0,30	11
6.1.1			0,77	0,65	**1**	0,20	28
6.1.2			0,77	**1,04**	**2**	0,40	15
6.2.1			0,77	0,69	0	-	31
8.1.1			0,57	0,49	0	-	13
9.1.2			0,77	0,81	**4**	0,40	8
9.2.2			0,77	0,74	**2**	0,20	32
10.2.2			0,77	0,84	**3**	0,37	17
Ulriksdal							
1	XD3/XS3 360 < C < 430	0,70	0,70	0,693	**1**	0,4	-
2			0,70	0,461	0	-	-
3			0,70	0,438	0	-	-
4			0,70	**0,809**	**3**	0,27	-
Antuna							
1	XD3/XS3	0,70	0,70	0,55	0	-	-

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