

## Thermal Crack Risk of Concrete Structures – Evaluation of Theoretical Models for Tunnels and Bridges



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### ABSTRACT

An approach for thermal crack risk estimations was introduced in the Swedish design guidelines BRO 94. The cracking occurs during the early hardening process because of the exothermic reactions between water and cement and often result in high repair costs and delayed construction. This paper studies and validates the inherent safety levels for one typical case of concrete structure. Three slab-frame structures were analysed and the original crack risk estimations were compared to the actual cracking and post-calculations were carried out, using actual parameters. This paper shows that walls with computed strain ratios over 70% were affected by thermal cracks.

**Key words:** Thermal cracking, Structural Design, Sustainability, Concrete Tunnels.

## 1. INTRODUCTION

Thermal cracking may occur during the early hardening process of concrete [1]. The exothermic reactions of the hydration process leads to increasing core temperatures in the structure and thereby inducing thermal expansion of the concrete. However, prohibited deformation due to different types of restraints leads to compressive strains in parts of the structure. As the hydration rate reduces, the core starts cooling, inducing shrinkage and tensile strains within the restrained structure. The tensile strains may also 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 and shrinkage 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 is surface cracks. These cracks are restricted to the concrete surface and thereby remain thin, with widths below 0.1 mm [2]. Surface cracks may also emerge due to rapid surface cooling associated with form removal or rapid shifts in the weather.

Factors influencing the heat of hydration and thereby the thermal crack risk of concrete, may, according to [2] be divided into internal and external factors as stated in Table 1. The internal factors are governed by the concrete recipe and may be decided by adiabatic or semi-adiabatic tests. The external factors are mainly governed by the casting procedure and other environmental factors and may not be adjusted by changing the concrete properties.

Traditional crack preventing actions generally aims at reducing the tensile strains within the structure, typically by reducing the temperature differences within a massive concrete structure or between old and new concrete members. Existing slabs can for example be pre-heated before a new wall is cast to account for the thermal effects of the concrete hydration. Cooling pipes can also be installed in the new wall to avoid high temperatures and strains.

*Table 1 – Factors influencing the heat of hydration [2].*

<b>Internal factors</b>	<b>External factors</b>
<b>Concrete recipe</b>	<b>Casting procedure and environment</b>
Cement content and -type	Concrete temperature at casting, $T_c$
Aggregate content and -type	Air temperature, $T_{air}$
Aggregate size, $d_{max}$	Temperature of supporting structures, $T_{slab}$
Water-cement ratio	Heating/cooling
Additives	Formwork, insulation and hardening process
	Wind velocity, solar radiation, etc.

Effects of restraint have been studied in e.g. [3-5]. The degree of restraint may vary between 0 and 100%, where the case of full restraint comprises casting on a completely rigid support, for example crack free bedrock or massive slabs, with full bond to adjoining structures, and no restraint represents casting on a bond-free surface. The main factors influencing the restraint of a concrete wall is the geometry of the wall, the adhesion between new and old members, the geometry and stiffness of the base slab, and the flexibility and stiffness of the ground.

This paper considers two types of casting procedures: (1) casting of a free wall on top of a slab and (2) casting of a wall on top of a slab with one edge adjoining an existing wall while the other edge remains free. Figure 1 illustrates the restraint distribution for these two cases.

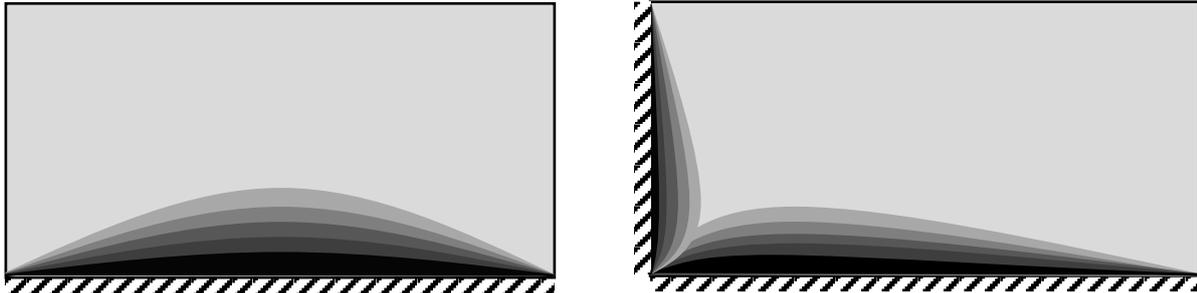


Figure 1 – Restraint distribution for the two types of castings studied in this paper.

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

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

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,  $\Gamma$ , is defined as the inverse of  $\eta$ :

$$\Gamma = \frac{1}{\eta} \quad (2)$$

If the crack risk  $\eta$  is too high according to AMA Anläggning [6], measures are needed to mitigate the risk of cracking. Typical methods for such thermal crack prevention aim at reducing the temperature differences within a concrete casting, between different castings or between a concrete member and its surroundings. This can be accomplished by installing heating cables in the slab or cooling pipes in the wall. The degree of restraint may also be regulated by, for example, expansion joints or optimizing the casting order to avoid adjoining walls for critical members, and the concrete properties may be customized to alter the heat of hydration and reduce the risk of thermal cracking.

The prevailing concept for crack risk estimations was introduced in the Swedish construction standards BRO 94 [7], and can today be found in AMA Anläggning [6]. 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 2. 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,  $C$ .

The safety factor for thermal cracking of concrete infrastructure is given in the Swedish guidelines AMA Anläggning [6] and depends mainly on the structures exposure class, the cement content or whether the material parameters have been fully investigated. A summary of relevant safety factors is presented in Table 2.

*Table 2 – Safety factors (and corresponding strain ratios) for thermal cracking of concrete structures given in AMA Anläggning [6].*

Exposure class	Tested material parameters	Untested material parameters	
		$360 \leq C \leq 430 \text{ kg/m}^3$	$430 < C \leq 460 \text{ kg/m}^3$
XC2	1.05 (0.95)	1.18 (0.85)	1.33 (0.75)
XC4	1.11 (0.90)	1.25 (0.80)	1.42 (0.70)
XD1, XS2	1.18 (0.85)	1.33 (0.75)	1.54 (0.65)
XD3, XS3	1.25 (0.80)	1.42 (0.70)	1.67 (0.60)
<b>Structures exposed to one sided water pressure</b>			
All	1.42 (0.70)	1.67 (0.60)	2.0 (0.50)

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 [2] 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.

The objective of this paper is to study the Swedish procedures for crack risk estimation and validate the accuracy of current safety levels for some concrete structures. The study is limited to Method 3 and the use of one commercial and widely applied 2D FE software ConTeSt Pro 5.0 [8]. The study is applied on frame structures where the crack prevention consists of pre-heating the slab before casting the walls.

## 2. METHOD

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

1. Identifying relevant structures with adequate documentation.
2. Studying construction documentation.
3. Checking original thermal crack risk estimations and suggested crack preventing measures based on expected parameters.
4. Carrying out post-project thermal crack risk estimations based on actual parameters.
5. Field inventory of emerging thermal cracks.
6. Analysis of the procedure and accuracy of crack risk estimations.

The most critical parameter for this project was identifying relevant structures with adequate documentation of the construction process, with construction drawings, material properties, crack preventing measures, concrete pouring rates and temperature logs. 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 geometry of the 2D FE-models are shown in Figure 2 and structural parameters are found in Table 3. The structures were analyzed with ConTeSt Pro, a commercial FEM software developed for purpose of temperature, strength and crack risk calculations in young concrete [8].

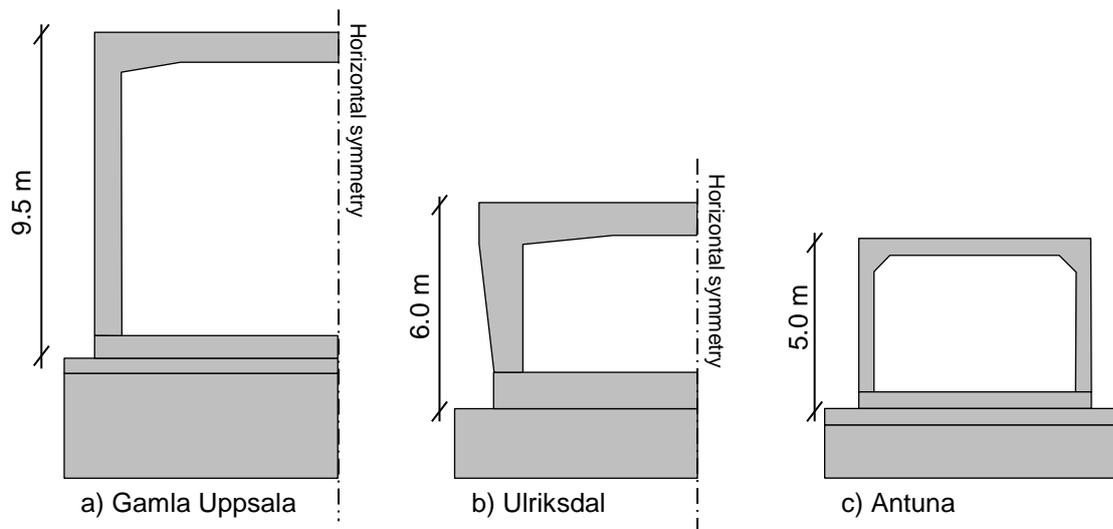


Figure 2 – Geometry of the three slab-frame structures. a) Railway tunnel b-c) road tunnels.

Table 3 – Structures analyzed in this paper.

Name of structure	Year of construction	Length	Casting length (walls)	Height	Wall thickness	References
Gamla Uppsala	2014-2016	610 m	10.0 m	9.5 m	0.7 m	[9-10]
Ulriksdal	1989-1990	41.6 m	10.4 m	6.0 m	0.8-1.2 m	[11]
Antuna	1993	35 m	35 m	5.0 m	0.45 m	[11]

Crack preventing measures were designed according to original crack risk estimations, carried out prior to casting. The crack preventing actions of the structures studied in this paper consisted of heating the slab with either internal heat cables or an external heat mat before and after the frame walls were cast. Construction fans were also used to increase the air temperature inside the tunnel for some castings. The original design was compared to the actual outcome of the project regarding temperatures and construction times. The recorded air and concrete temperatures were thereafter used in ConTeSt Pro for the post-project thermal crack risk estimations.

The material properties are given in Table 4. The heat development within the concrete is highly influenced by the heat transfer coefficient along the boundaries of the structure. All free surfaces (air), formwork and expanded polyethylene (EPE) foam were modeled with heat transfer coefficients of 500; 4.7 and 3.6 W/m<sup>2</sup>·K, respectively. A frame wall had for example heat transfer coefficient of 4.67 until the formwork was removed, whereon the heat transfer coefficient increased to 500 W/m<sup>2</sup>·K as the boundary surface was exposed to air.

The structures were visually inspected and the presence of cracks was recorded. The railway tunnel in Gamla Uppsala was thoroughly inspected for all types of cracks and all small cracks (< 0.1 mm) were divided into 8 zones for each casting sequence (wall) as seen in Figure 3. Only cracks in the mid-part of the wall with openings larger than 0.1 mm were considered as thermal cracks. The cracking was finally compared to the previous estimations.

*Table 4 – Material properties.*

Structure	Parameter	Soil	Gravel	Slab	Frame
Uppsala	Material/strength class	Fine soil	coarse soil	C30/37	C30/37
	Density, kg/m <sup>3</sup>	1700	2200	2350	2350
	Thermal capacity, J/Kg K	1950	1400	1000	1000
	Thermal conductivity, W/m K	1.4	2.1	0-120 h: 1.7 120- h: 2.1	0-120 h: 1.7 120- h: 2.1
	Cement type	-	-	Anläggning*	Anläggning*
	Cement content, kg/m <sup>3</sup>	-	-	365	365
	Water/cement	-	-	0.48	0.48
Ulriksdal	Material/strength class	Not used	coarse soil	C32/40	C32/40
	Density, kg/m <sup>3</sup>	-	2200	2350	2350
	Thermal capacity, J/Kg K	-	1400	1000	1000
	Thermal conductivity, W/m K	-	2.1	1.7	0-24 h: 1.7 24- h: 2.1
	Cement type	-	-	Anläggning*	Anläggning*
	Cement content, kg/m <sup>3</sup>	-	-	390	390
	Water/cement	-	-	0.45	0.45
Antuna	Material/strength class	Fine soil	coarse soil	C32/40	C32/40
	Density, kg/m <sup>3</sup>	1700	2200	2350	2350
	Thermal capacity, J/Kg K	1950	1400	1000	1000
	Thermal conductivity, W/m K	1.4	2.1	1,7	0-24 h: 1.7 24- h: 2.1
	Cement type	-	-	Anläggning*	Anläggning*
	Cement content, kg/m <sup>3</sup>	-	-	390	390
	Water/cement	-	-	0.45	0.45

\*CEM I 42.5N – Anläggning Degerhamn, Cements AB, Sweden

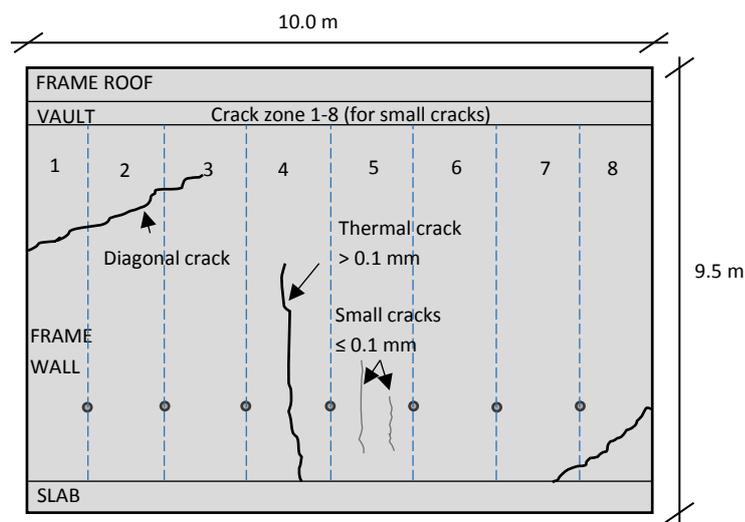


Figure 3 – Example crack types and crack zones (1-8) for the visual inspection of Gamla Uppsala.

### 3. RESULTS

#### 3.1 Original design of thermal crack prevention

The original crack risk design was aimed at avoiding thermal cracks in the concrete members of Gamla Uppsala, Ulriksdal and Antuna. For Gamla Uppsala. Some typical cases were identified and the construction of each casting sequence was adjusted according to the prevailing conditions, depending on the type of casting, the concrete temperature at delivery,  $T_c$ , and the air temperature,  $T_{air}$ . The type of casting was either: a) casting of a free wall, without previously cast adjacent walls, or b) casting of a wall in direct contact to one adjacent wall. The crack preventing actions based on the original design were pre- and post-heating of the previously cast slab to avoid large strain differences between the slab and the wall. The original design cases of the Gamla Uppsala tunnel are presented in Table 5.

Table 5 – Original design of the Gamla Uppsala tunnel.

Type of casting	$T_c$ °C	$T_{air}$ °C	Pre-/Post-heating h/h	Form removal h	$T_{max}$ °C	$\eta$ Limit Design limit	$\eta$ Original Calculated ratio	strain
Free seq.	15	-5	48/48	120	42.9	0,80	0.57	
Free seq.	15	5	0/0	72	43.1	0,80	0.77	
Adj. wall	15	-5	144/48	120	43.1	0,80	0.77	
Adj. wall	15	5	96/24	120	43.1	0,80	0.77	
Adj. wall	15	10	72/24	72	42.2	0,80	0.79	
Adj. wall	25	20	72/24	72	58.0	0,80	0.80	

\*Free sequence corresponds to a wall without adjacent walls at casting

Figure 4 illustrates the typical crack preventive measures for wall casting in the Gamla Uppsala tunnel in cold weather, between  $-5^{\circ}\text{C}$  and  $+5^{\circ}\text{C}$ . The slab was pre-heated with heat cables of type 1 and 2 according to Figure 4. Both types of cables had an output of  $40\text{ W/m}$ , but as the wall was cast, the type 1 cables under the wall were switched off and only the type 2 cables were used for post-heating. The slab was insulated with a  $10\text{ mm}$  layer of EPE foam which was removed as the post-heating was terminated. For temperatures over  $5^{\circ}\text{C}$ , the type 2 cables furthest from the wall were removed and no heat cables on the bottom reinforcement were used for temperatures over  $10^{\circ}\text{C}$ .

Figure 5 illustrates an example of temperature evolution for the case of casting a wall in direct contact to an existing adjacent wall, with  $T_{\text{air}} = -5^{\circ}\text{C}$  and  $T_c = 15^{\circ}\text{C}$ . The horizontal axis represents the time after casting the slab, while the vertical axis represents the temperature to the left and the strain ratio to the right. Casting of the wall started at the relative time  $t = 0\text{ h}$  with a concrete temperature of  $15^{\circ}\text{C}$ . The concrete temperature increased to a maximum of  $36^{\circ}\text{C}$  due to the exothermic reactions, and after the peak, the concrete started to cool off. The concrete exhibited a negative strain ratio (compression) of about  $\eta = 0.40$  relatively fast where after it was subjected to a strain ratio of maximally  $\eta = 0.77$ . The crack preventing actions can also be seen by the temperature development within the slab. The temperature of the slab was governed by the air temperature until the heating was started at  $t = -158\text{ h}$  (the slab was covered/insulated  $16\text{ h}$  later). The heating ended at  $t = 0$  and  $24\text{ h}$  for the type 1 and 2 cables, respectively. The slab was also uncovered  $24\text{ h}$  after the wall was cast. Note that the temperature gauge in the slab was located directly below the wall and the slab temperature was strongly influenced by the temperature development in the wall.

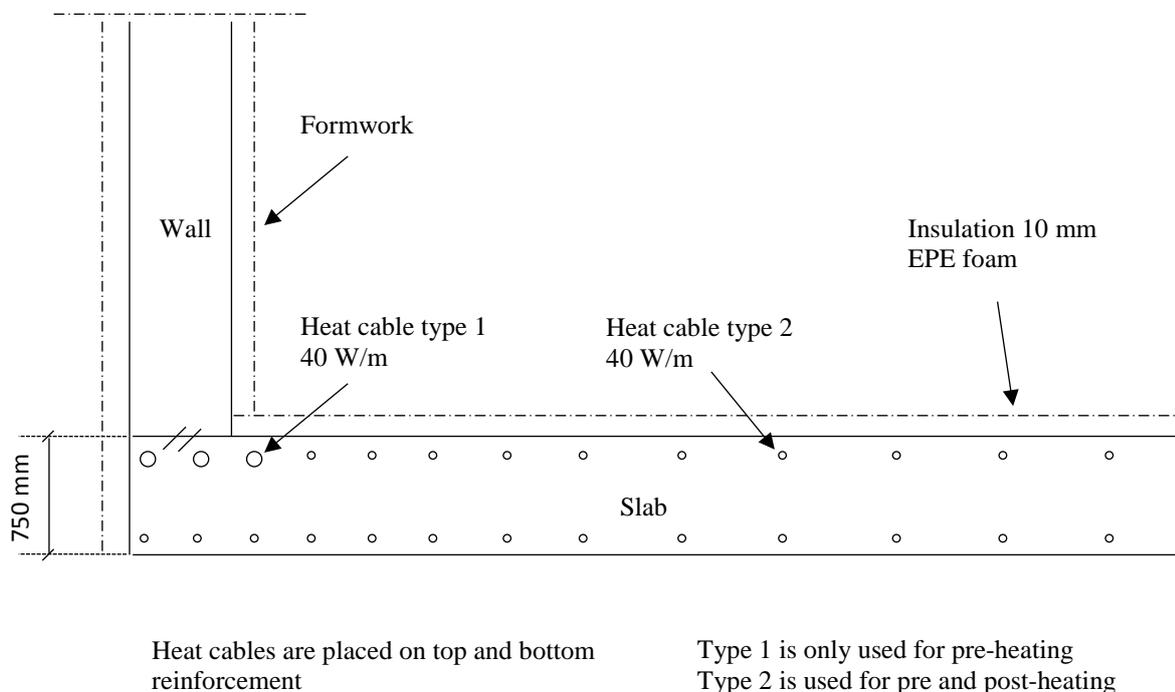


Figure 4 – Typical approach for crack prevention with heating cables for Gamla Uppsala.

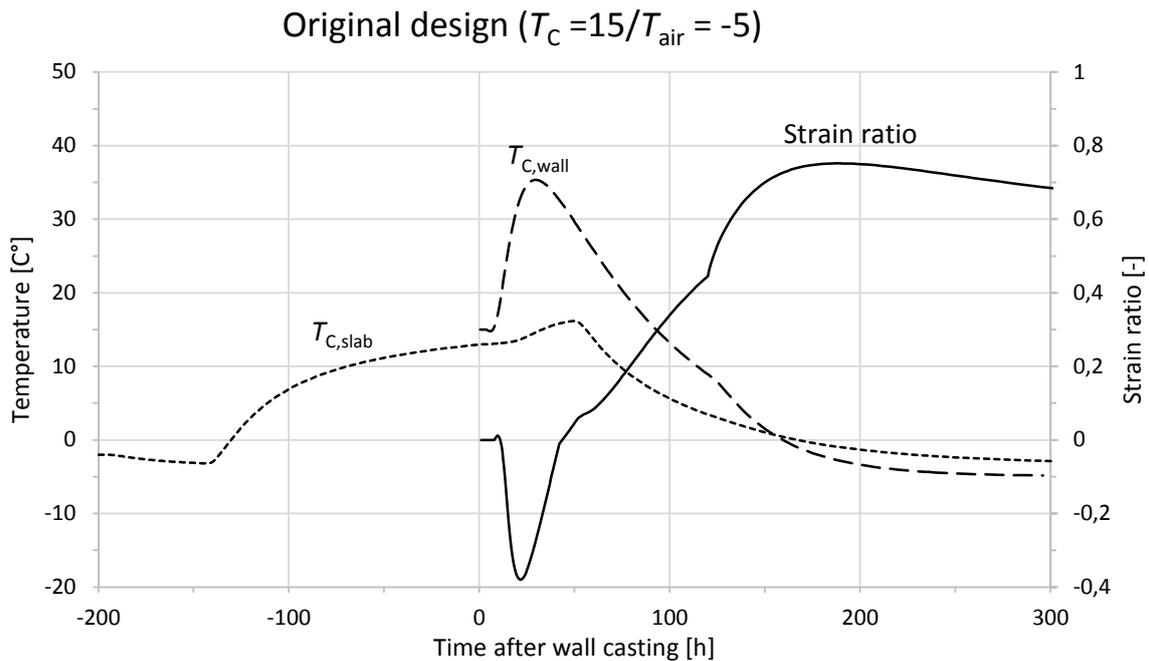


Figure 5 – Example of temperature evolution in the Gamla Uppsala Tunnel for the original design case with  $T_{air} = 15^{\circ}\text{C}$  and  $T_c = -5^{\circ}\text{C}$ .

### 3.2 Post design of thermal crack prevention

Figure 6 presents the air ( $T_{air}$ ), wall ( $T_{wall}$ ) and slab ( $T_{slab}$ ) temperatures. Each temperature is given for the original and post-design, as well as the actual measured values. The figure shows that the measured air temperature was much higher than assumed in the original design and the post-design was carried out according to a simplified temperature curve with straight lines between temperature peaks. Due to the assumed lower temperatures in the original design, the maximum temperature in the wall, as well as in the slab, was substantially underestimated. However, the post-design shows a relatively good adaption to the measured temperatures in the wall as well as the slab. The figure shows a common problem where the air temperature changes considerably after the crack preventing actions have already started. For this casting sequence, the typical case with an air temperature of  $+5^{\circ}\text{C}$  would have been more suitable.

Figure 7 illustrates the strain distribution for casting sequence 5.1.2 of Gamla Uppsala at the time of maximum strain. Thermal cracks are assumed to develop as the average strain in a cross section exceed the ultimate strain of the concrete [12]. The strain ratio was calculated as an average value over a region of  $0.7 \cdot 0.2 \text{ m}^2$ , centered over the point of maximum strain, see the magnified part in Figure 7. The maximum strain developed in the center of the wall, approximately 0.7 m over the slab. Previous research has shown that thermal cracks in wall-slab structures typically initiate at a height corresponding to the wall thickness above the joint [13-14]. The maximum strain ratio for sequence 5.1.2 was  $\eta = 1.02$  and the average strain for the shadowed region of Figure 7 was  $\eta = 0.90$ . This value can be compared to the strain ratio  $\eta = 0.77$  from the original design and the strain limit of  $\eta = 0.90$  for exposure class XC4 and tested material parameters.

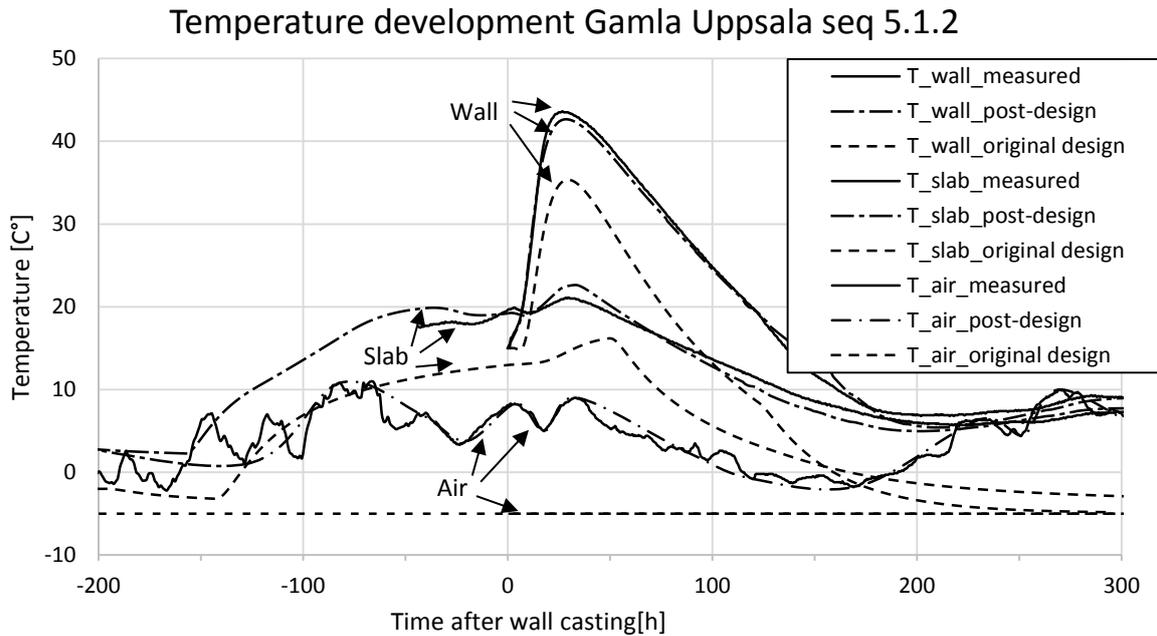


Figure 6 – Measured, pre-calculated and post-calculated temperatures for the walls, slab and air for casting sequence 5.1.2 of the Gamla Uppsala tunnel.

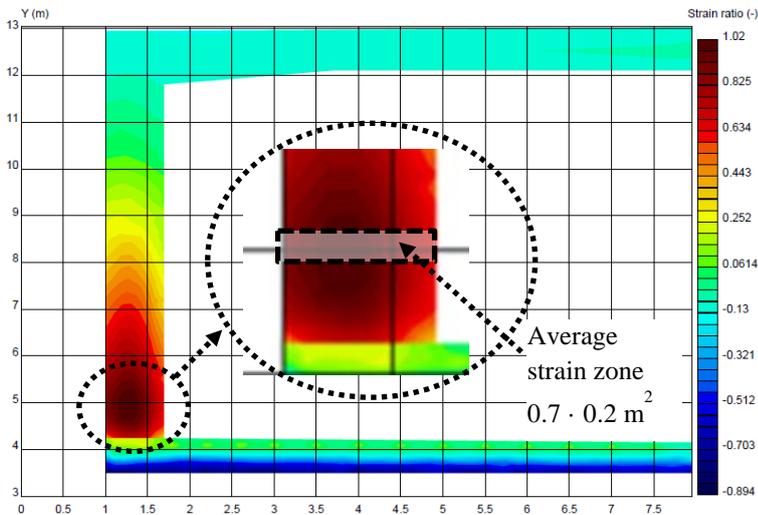


Figure 7 – Strain distribution and average strain zone ( $0.7 \cdot 0.2 \text{ m}^2$ ) for the Gamla Uppsala tunnel, casting sequence 5.1.2.

### 3.3 Crack inventory

A summary of the original design, the post-design and the crack inventory is given in Table 6. Initially it is noted that no temperature cracks were supposed to be formed according to the original 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. Note that the post-design was based on tested material parameters and that the limiting strain ratio therefore was increased from 0.80 in Table 5 (untested material properties) to 0.90 in Table 6 (tested material properties). However, temperature cracks were found on 10 out of 14 analyzed sections. Small surface cracks,  $< 0.1 \text{ mm}$  openings, were also studied and counted in the crack

inspection. The compilation in Table 6 shows a large number of small cracks for all casting sequences of the Gamla Uppsala tunnel. 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  $390 \text{ kg/m}^3$ ) 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 original design, nor the post-design, and no temperature cracks were actually detected.

*Table 6 – Summary of the original and post-designs for thermal crack risks.*

Seq.	Exposure class	$\eta$ Limit	$\eta$ Original	$\eta$ Post	Temp. cracks > 0.1 mm	Average crack width, mm	Small cracks $\leq 0.1 \text{ mm}$
<b>Gamla Uppsala</b>							
3.1.1			0.57	0.58	1	0.20	25
3.1.2			0.77	0.55	0	-	6
3.2.1			0.77	<b>0.97</b>	1	0.20	30
5.1.1			0.77	0.67	0	-	23
5.1.2	XC4/XF4		0.77	0.90	1	0.30	38
5.2.1			0.77	<b>1.01</b>	1	0.20	27
5.2.2	Tested	0.90	0.77	0.75	1	0.30	11
6.1.1	material		0.77	0.65	1	0.20	28
6.1.2	parameters		0.77	<b>1.04</b>	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
<b>Ulriksdal</b>							
1	XD3/XS3		0.70	0.69	1	0.4	-
2			0.70	0.46	0	-	-
3		0.70	0.70	0.44	0	-	-
4	$360 < C < 430$		0.70	<b>0.81</b>	3	0.27	-
<b>Antuna</b>							
1	XD3/XS3	0.70	0.70	0.55	0	-	-

#### 4. ANALYSIS AND DISCUSSION

Traditional crack preventing actions generally aims at reducing the tensile strains within the structure, typically by reducing the temperature differences within a massive concrete structure or between old and new concrete members. Existing slabs can for example be pre-heated before a new wall is cast to account for the thermal effects of the concrete hydration. Cooling pipes can also be installed in the new wall to avoid high temperatures and strains. All three structures within this study had their slabs pre-heated prior to casting the walls. The crack prevention was not always completely successful due to a number of factors and thermal cracks could be found in 12 of the 19 studied wall castings (63%).

Based on the results of this study it is observed that a correct weather forecast is crucial for an accurate original design, and can ultimately be the factor determining whether the structure remains crack-free or not. Under- or overestimated air temperatures in the original design leads

to improper crack preventing actions, typically due to rapid temperature changes after the actions have started. Table 5 showed that six typical cases were used for the original design of the Gamla Uppsala tunnel. However, Fig. 5 showed that a constant air temperature of  $-5^{\circ}\text{C}$  was chosen for the original design of casting sequence 5.1.2, but the measured temperature was in fact up to 15 degrees higher. This resulted in a higher wall temperature than anticipated in the original design. The construction process followed the original design restrictions and even though the formwork was removed later than planned, it was still a bit too early.

The concrete temperature was higher than planned at the point of form removal, resulting in a rapid cooling of the wall and accelerating tensile strains, see Figure 8. Instead of the originally anticipated strain ratio of 0.77, the strain ratio for this wall reached the limit  $\eta = 0.90$ . Other factors that may affect the accuracy of the crack risk estimation are the quality and function of the cooling/heating equipment, the workmanship, effects of sun exposed (locally heated) surfaces, etc. By using accurate quality controls, most functional errors may be avoided. However, the original design could be updated with a more reliable weather forecast and accordingly adjusted actions just before the wall casting starts. Another approach that may be used to reduce the risk of thermal cracks is more comprehensive monitoring of the concrete temperatures and avoiding unnecessary high tensile strains due to premature form removal.

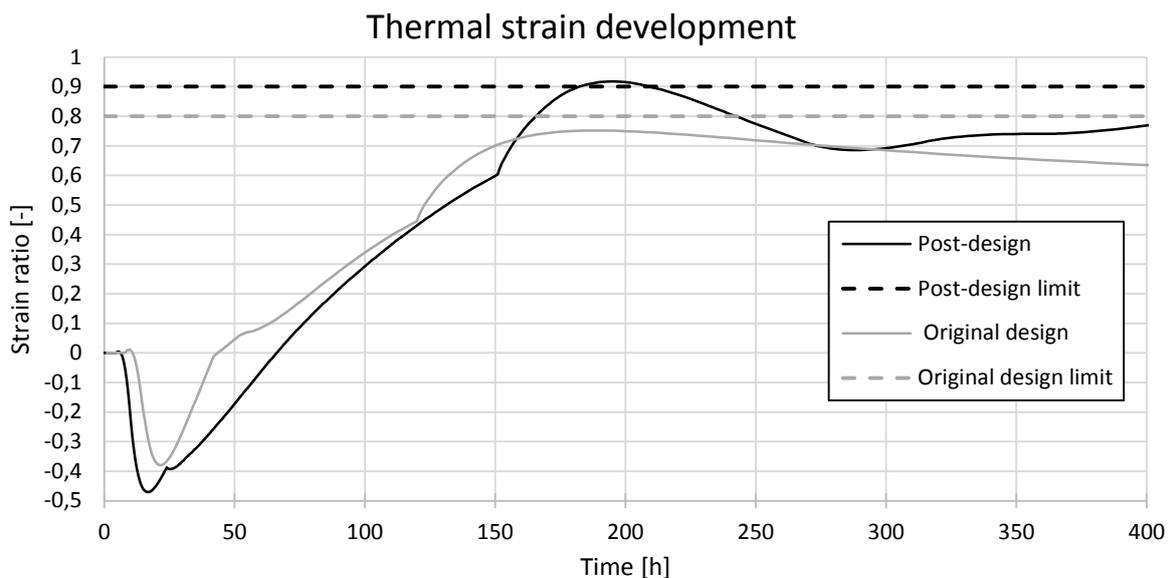


Figure 8 – Comparison of average strain ratios in the original- and post-designs for casting sequence 5.1.2 of the Gamla Uppsala tunnel.

Table 6 showed 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. A more thorough analysis of the planned and executed crack preventive actions is presented in Table 7. The Table shows that the prescribed pre- and post-heating was relatively well complied, but there was still a high frequency of thermal cracks. 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 discuss whether the maximum strain ratio for exposure class XC4 should be 0.90 as it is in the Swedish guidelines today or if it should rather be reduced to 0.70 to avoid certain cracking. However, the results of this study are based on a limited number of slab-frame

structures where the only crack preventing action was pre-heating of the slab. Further studies of relevant structures with different crack prevention are required to validate these results. Finally, the visual crack inspection of the Gamla Uppsala tunnel showed that there was a strong correlation between the wall's degree of restraint and the presence of surface cracks with crack widths  $< 0.1$  mm. Totally 144 frame-walls of the Gamla Uppsala tunnel were inspected and surface cracks were found on each one of them. According to theory [3], the restraint is supposed to be higher in the mid-part of the wall and decrease towards the wall-ends. Figure 9 shows a FE-analysis of the restraint situation for a wall cast in direct contact with an adjacent wall. The frequency of small cracks is plotted in front of the wall to illustrate the correlation between restraint and surface cracks.

Table 7 – Summary of planned and actual parameters for the Gamla Uppsala tunnel.

Seq.	$T_{\text{air}}$ Pre-design °C	$T_{\text{air}}$ Average °C	Planned heating Pre-/Post- h/h	Actual heating Pre-/Post- h/h	$\eta$ Original design	$\eta$ Post- design	$\eta$ Limit	Cracks > 0.1 mm
3.1.1	-5	+4	48/48	100/50	0.57	0.58		Yes
3.1.2	-5	+6	144/48	150/40	0.77	0.55		-
3.2.1	+5	+10	96/24	150/30	0.77	<b>0.97</b>		Yes
5.1.1	+5	+5	96/24	45/35	0.77	0.67		-
5.1.2	-5	+5	144/48	160/25	0.77	0.90		Yes
5.2.1	-5	0	144/48	160/30	0.77	<b>1.01</b>		Yes
5.2.2	-5	-2	144/48	350/50	0.77	0.75	0.90	Yes
6.1.1	-5	+3	144/48	120/30	0.77	0.65		Yes
6.1.2	+5	+1	0/0	0/0	0.77	<b>1.04</b>		Yes
6.2.1	+5	+5	96/24	140/30	0.77	0.69		-
8.1.1	-5	0	48/48	110/50	0.57	0.49		-
9.1.2	-5	+2	144/48	110/40	0.77	0.81		Yes
9.2.2	-5	+4	144/48	160/25	0.77	0.74		Yes
10.2.2	+10	+12	72/24	25/60	0.79	0.84		Yes

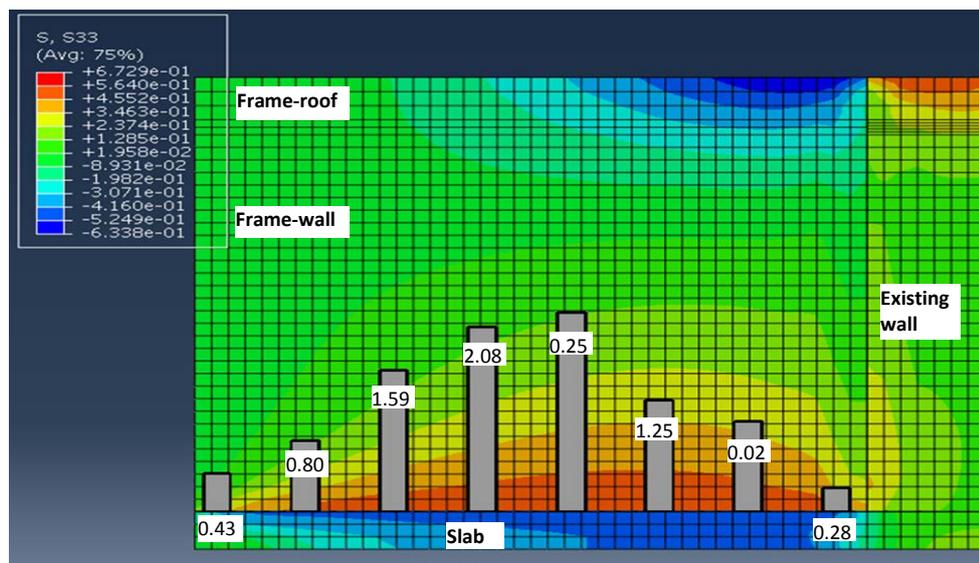


Figure 9 – Illustration of the correlation between wall-restraint and the frequency of small surface cracks ( $< 0.1$  mm). The numbers represent the observed average number of small cracks in each of the eight crack zones (cracks/wall) and the colours represent the calculated degree of restraint.

## 5. CONCLUSIONS

Thermal crack risk estimations were carried out for three concrete frame structures according to the directions in the Swedish design guidelines AMA Anläggning [6]. The original crack risk estimations are influenced by a large number of uncertainties which may affect the outcome substantially. Typical uncertainties in thermal crack risk estimations include:

- Material properties of concrete, formwork and insulation.
- Environmental conditions, e.g. wind, temperatures, sun exposure.
- Structural properties, e.g. degree of restraint.
- Function and efficiency of heating and cooling equipment.
- Accomplishment of planned activities.

This paper demonstrates how thermal cracks have emerged in structures that were not supposed to crack according to their original crack risk estimations. All structures that reached tensile strains higher than 70% of the concretes ultimate strain within the first weeks after casting were actually cracked. The Swedish guidelines presently allow strain ratios of 0.90 for exposure class XC4 if the material properties have been tested and 0.80 otherwise. However, the results of this paper indicate that the limit should be reduced to 0.70. Further studies are needed to analyse other types of structures and crack preventing measures, and also to validate the results of this paper.

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