Temperature analyses of Concrete Frame Bridges with Finite Elements

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Abstract

FE-modeling is a rapidly spreading method to analyze structures nowadays. With this the understanding of the outcome is of very high importance and potential inaccuracies are important to find so that faulty and over dimensioning of the structure does not occur which leads to unnecessary costs. One of these inaccuracies is the unrealistic sectional forces that occur due to thermal effects in the transversal direction for concrete frame bridges which leads to an excessive amount much reinforcement in the structure than actually needed. This has been studied with several cases by using two approaches on how to apply the temperature in the frame bridge, only in the superstructure and in the whole structure, but also by analyzing several boundary conditions. By examining the results for the sectional forces and stresses one of the temperature approaches could be disregarded because of the extreme values in the transition between superstructure and support. But the other approach was much more useful because of its better compliance with reality. With these results and by calculating the reinforcement needed for the worst case, one model has been found to be the most favorable and can be used when modeling concrete frame bridges with acceptable outcome. The study resulted in a model where one applies a varying temperature on the whole structure, with spring boundary conditions over a surface that represents the bottom slab.

Keywords: Finite Element, modeling, thermal effects, concrete, frame bridge, sectional forces, reinforcement.
Preface

This master thesis is a final result of my master studies in Civil and Architectural Engineering at the Royal Institute of Technology in Stockholm, Sweden. Alongside my final year I have been working at ÅF-Infrastructure AB in their bridge division, more known as Konfem, with FE-modeling and the dimensioning of reinforcement for mainly concrete frame bridges. The idea for this thesis has been proposed by my colleagues Bertil Beck and Mahmoud Haghanipour.

A special thanks to them for their valuable input and advice but also to Prof. Raid Karoumi for his guidance and Abbas Zangeneh Kamali for reviewing the master thesis.

Stockholm, May 2014

Siamak Rouhani
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List of abbreviations

2D = Two-dimensional
3D = Three-dimensional
EC = Eurocode
FE = Finite Element
FEM = Finite Element Methods
TRVFS Bro = The Swedish Transport administrations Statutes for Bridges
TRVK Bro = The Swedish Transport administrations Technical Requirements for Bridges
TRVR Bro = The Swedish Transport administrations Technical Advice for Bridges
SLS = Serviceability Limit State
ULS = Ultimate Limit State
# List of notations

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Area</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$A_{ct}$</td>
<td>Cross sectional area of concrete in the tensile zone</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$A_{s,min}$</td>
<td>Minimum area of steel reinforcement</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$B$</td>
<td>Width of the casting during one stage</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$b_t$</td>
<td>Mean width of the tension zone</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$C$</td>
<td>Concrete content</td>
<td>$[kg/m^3]$</td>
</tr>
<tr>
<td>$c$</td>
<td>Cover to the longitudinal reinforcement</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$d$</td>
<td>Effective depth of a cross-section</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$E_s$</td>
<td>Modulus of elasticity for reinforced steel</td>
<td>$[Pa]$</td>
</tr>
<tr>
<td>$f_{ct,eff}$</td>
<td>Mean value of the concrete tensile strength effective when the cracks may first be expected to occur</td>
<td>$[Pa]$</td>
</tr>
<tr>
<td>$f_{ctm}$</td>
<td>Mean value of axial tensile strength of concrete</td>
<td>$[Pa]$</td>
</tr>
<tr>
<td>$f_{yk}$</td>
<td>Characteristic yield strength of reinforcement</td>
<td>$[Pa]$</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of the bridge in BRIGADE/Plus</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$h_{+,max}$</td>
<td>Height lower edge of superstructure</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$h_{+,min}$</td>
<td>Height lower edge of bottom slab</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$k$</td>
<td>Constant depending on the material used</td>
<td>[-]</td>
</tr>
<tr>
<td>$k_1$</td>
<td>Constant</td>
<td>[-]</td>
</tr>
<tr>
<td>$k_2$</td>
<td>Constant</td>
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<tr>
<td>$k_3$</td>
<td>Constant</td>
<td>[-]</td>
</tr>
<tr>
<td>$k_4$</td>
<td>Constant</td>
<td>[-]</td>
</tr>
<tr>
<td>$k_\ell$</td>
<td>Factor dependent on the duration of the load</td>
<td>[-]</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of the casting during one stage</td>
<td>$[m]$</td>
</tr>
<tr>
<td>$M$</td>
<td>Moment</td>
<td>$[Nm]$</td>
</tr>
<tr>
<td>$N$</td>
<td>Normal force</td>
<td>$[N]$</td>
</tr>
<tr>
<td>$S_{r,max}$</td>
<td>Maximum crack spacing</td>
<td>$[m]$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Bridge initial temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{e,\text{max}}$</td>
<td>High temperature component</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{e,\text{min}}$</td>
<td>Low temperature component</td>
<td>°C</td>
</tr>
<tr>
<td>$t_{\text{bottom}}$</td>
<td>Thickness of bottom slab</td>
<td>m</td>
</tr>
<tr>
<td>$t_{\text{super}}$</td>
<td>Thickness of superstructure</td>
<td>m</td>
</tr>
<tr>
<td>$y$</td>
<td>Internal lever arm</td>
<td>m</td>
</tr>
<tr>
<td>$w_k$</td>
<td>Crack width</td>
<td>m</td>
</tr>
<tr>
<td>$\alpha_e$</td>
<td>Ratio of modulus of elasticity between steel and concrete</td>
<td>[-]</td>
</tr>
<tr>
<td>$\varepsilon_{cm}$</td>
<td>Mean strain in the concrete between cracks</td>
<td>[-]</td>
</tr>
<tr>
<td>$\varepsilon_{sm}$</td>
<td>Mean strain in the reinforcement under the relevant combination of loads</td>
<td>[-]</td>
</tr>
<tr>
<td>$\varnothing$</td>
<td>Diameter of reinforced steel</td>
<td>m</td>
</tr>
<tr>
<td>$\Delta T_{N,\text{exp}}$</td>
<td>Characteristic maximum value for temperature giving expansion</td>
<td>°C</td>
</tr>
<tr>
<td>$\Delta T_{N,\text{con}}$</td>
<td>Characteristic maximum value for temperature giving contraction</td>
<td>°C</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Ratio for reinforcement content over the cross-sectional area</td>
<td>[-]</td>
</tr>
<tr>
<td>$\rho_{p,\text{eff}}$</td>
<td>Effective reinforcement ratio</td>
<td>[-]</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stress</td>
<td>Pa</td>
</tr>
<tr>
<td>$\sigma_s$</td>
<td>Stress in reinforced steel</td>
<td>Pa</td>
</tr>
</tbody>
</table>
List of explanations

High Temperature = Maximum “temperature component” as referred to in EC1-1-5.

Low Temperature = Minimum “temperature component” as referred to in EC1-1-5.

Temperature Gradient Plus = Maximum “temperature difference” as referred to in EC1-1-5. Top surface (exterior side) warmer than bottom surface (interior side).

Temperature Gradient Minus = Minimum “temperature difference” as referred to in EC1-1-5. Top surface (exterior side) colder than bottom surface (interior side).

Direction 1 = Transversal direction

Direction 2 = Longitudinal direction

Normal force in Direction 1 = Direct membrane force per unit width in Local 1-direction.

Normal force in Direction 2 = Direct membrane force per unit width in Local 2-direction.

Moment in Direction 1 = Bending moment force per unit width about Local 2-axis.

Moment in Direction 2 = Bending moment force per unit width about Local 1-axis.

Moment in Direction 3 = Twisting moment force per unit width in Local 1-2 plane.

Mesh0.3_SM1L = Mesh size 0.3m, Sectional Moment in Direction 1, Linear element type

Mesh0.3_SM1Q = Mesh size 0.3m, Sectional Moment in Direction 1, Quadratic element type

Support = The word support in this master thesis includes both bottom slab and side wall.

Surface – Superstructure = Springs on a surface with temperature applied on the superstructure (Analogously for the other applications of boundary conditions).

Surface – Whole structure = Springs on a surface with temperature in the whole structure (Analogously for the other applications of boundary conditions).
1 Introduction
FE-modeling is used more and more by designers in all areas of engineering. Today the Swedish Transport administration requires that all bridges in their projects are analyzed with their full mode of action which they advise is made with FE-modeling (Trafikverket, 2011). With this extensive usage of FE-modeling the understandings of the software is very important due to the interpretations of the results which are not always obvious. Not understanding the software can lead to faulty designs which can lead to catastrophic consequences, especially when dealing with large structures such as bridges. Today there is no guidance in EC2, which is the Eurocode for concrete bridges, of how to cope with the FE issues that are considered in this master thesis (EC2-1-1, 2005).

In bridge engineering there are several issues when modeling in FE-software but one very big issue is how to deal with the temperature in a concrete frame bridge. When modeling the temperature the normal forces in the superstructure and its connection to the support becomes unreasonable and extremely high which is not the actual reaction of a concrete frame bridge. In reality the normal forces are not as high as they seem in the software due to cracking in the concrete which releases most of the tension and thereby decreases the normal forces (Ansell, et al., 2012). So in this study the results that will be observed are moments, normal forces and stresses for important sections of the bridge. These are observed because these outputs from the FE-model are used when dimensioning bridges and is directly associated with the needed amount of reinforcement which the designers want to keep at a minimum. The approach for this will be to study three different cases where the first case is to model a 2D-model to compare the results from the 3D-model with. The second case is when the temperature load is applied only in the superstructure of the bridge and the third case is with the temperature load applied on the whole structure where the temperature distribution over the supports is calculated with a FE-software called ConTeSt Pro. The two latter cases will also be studied with four different kinds of boundary conditions and then an analysis of the needed reinforcement will also be made for comparison.

A FE-software that is used very often in bridge engineering is BRIGADE (Plus or Standard) which is based on the FE-software Abaqus which is why BRIGADE, the Plus version, will be used in this exploratory study. As mentioned this is an exploratory study but with the hope that the result will lead to a model that can be used generally for all types of frame bridges with this issue. This means that this study will try to lock down the issue and by trying several models with varying conditions hopefully the issue will be solved with one optimal model when the study is presented.

1.1 Background
The most realistic way to apply the temperature load on a model is to apply it on the whole structure because the temperature will affect the whole structure. With this being said the temperature will often not be the same at all locations of the model but it should still be loaded with some temperature. The temperature components that are applied when modeling are high temperature component, low temperature component and temperature gradients. Today engineers usually make a qualified decision on how the temperature should be applied by running the model several times with different application of the temperature and evaluating the results.
(Beck & Haghanipour, 2014). But even this approach is not always sufficient which definitely indicates that a study of this kind is very necessary. To understand what the issue is when modeling the temperature in a FE-software it is important to not only focus on the issue itself but also on the issues that may have an effect on the temperature load. So by also studying the boundary conditions of the structure the understanding of the reactions will be increased. For example when having a fixed boundary condition the structure will create very large normal forces in comparison to when having springs as a boundary condition instead. One of the important preparations for the study is therefore to understand the mechanics of the structure before modeling it so that the basic conditions are as good as they can be. These basic conditions have been discussed and developed with two bridge engineers with a long experience of bridge engineering, Bertil Beck and Mahmoud Haghanipour at ÅF-Konfem.

1.2 Objectives and Limitations
The aim of this master thesis is to primarily study how to apply the temperature load in a FE-software that will give the most realistic values. The secondary aim is to create a model and an approach that can be used for all kinds of concrete frame bridges so that the temperature load will not be an issue when dimensioning the amount of reinforcement needed for the bridge.

This master thesis is written with the presumption that the reader is somewhat familiar with FEM and FE-modeling which is why the theory behind FEM will not be explained thoroughly in this master thesis. With this being a study within the area of FE-modeling and bridges it is assumed that the reader has a basic knowledge of these two subjects. However a theoretical background of calculating the reinforcement will be presented to give a deeper understanding of why this study is of high importance for the bridge engineers and bridge designers of today. The FE-software that is used in this study is BRIGADE/Plus and the result is therefore applicable on this software. This can be seen as a limitation but it can be assumed that the method is applicable on similar FE-software due to that similar software uses the same theory but the outcome is nothing that can be guaranteed for other software. It is for the reader to investigate which software this concern. BRIGADE/Plus is a very open and somewhat limitless software where one can model in several different ways which allows the user to model the frame bridge in different ways but here only one approach on the modeling will be made with all parts geometrically connected.

The cases that are going to be evaluated may not be the optimal cases to evaluate and it would be more satisfactory to evaluate some other cases as well. But these have been chosen after some discussion and consideration. But several more cases could be studied as well with larger spans, higher supports or if there are other ideas of how to apply the loads. One other limitation is that the results from a 3D-model are being compared to a 2D-model. The results from the 2D-model may not be sufficient for some results.
1.3 Disposition of the report
To understand why the results that has been extracted are important a short theoretical background will be presented in Chapter 2 with a description of how the amount of reinforcement is calculated in EC2.

The method that is used for this master thesis is presented in Chapter 3 and in Chapter 4 an explanation is given of the cases that are evaluated and why these particular cases. The results are presented in Chapter 5 where the figures visualize which case that has given the best values for the different sectional forces and stresses, but also for the needed amount of reinforcement.

Then these results are discussed in Chapter 6.2 with some analyses and finally the conclusions from the evaluations are made in Chapter 6.3 with suggestions for future work in Chapter 6.4.

1.4 Review of previous studies
To understand the importance of this study an extensive literature study has been made to show how large effects the temperature has on bridges and foremost frame bridges where the parts of the bridge are rigidly connected.

The temperature effects in bridges can be extremely large in reality due to restraint forces when the structure is not free to move. If a structure has no restraint the normal values for its movements are between 0.025-0.040 percent outdoors (Ansell, et al., 2012) and if these forces that are held back one can imagine the extreme stress that occurs in the concrete. Lots of research has been made on thermal effects on several different kinds of bridges. The research has been made during a long period with one example from 1984 where specific analyses were made of the thermal effects on bridges from solar radiation (Hirst, 1984) and even as we speak more analyses of thermal effects in various areas of expertise are made with this master thesis as an example. It is not difficult to see the tendency of the research where one example by Wu, et al. (2011) show that thermal effects obviously cannot be ignored and are very important in deciding the lifetime and designing of a bridge.

Studies have been made for several purposes and not only companies are eager to find out how to deal with this issue but also transport administrations want to be able to give requirements and guidance in this issue. One report that has been produced is a report of the thermal strains in transversal direction for concrete frame bridges (Zangeneh Kamali, et al., 2013) where the conclusion is to use hand-calculations according to EC2-3 which was found to be in good agreement with a non-linear analysis that was made of the crack width. One of their main suggestions is to release or neglect the temperature effects in the transversal direction. This approach however does not give guidance in how to use a linear analysis that may be sufficient.

Other similar studies have also been made in the same area as this study but with different approaches. One of these visualizes the issue that is being studied here (Andersson & Andersson, 2010). They approached the issue with a non-linear model, due to the non-linearity of concrete as a material, on an oblique frame bridge with comparison of the reinforcement amount to a method called Uppenberg’s method which is used for dimensioning in the transversal direction (Uppenberg, 1963).
2 Theoretical background

2.1 Thermal properties based on EC2

There are two important conditions given in EC2-1-1 Section 2.3.1.2 (2005) where the thermal effects in concrete structures are mentioned and these are:

1. “Thermal effects should be taken into account when checking serviceability limit states.”
2. “Thermal effects should be considered for ultimate limit states only where they are significant (e.g. fatigue conditions, in the verification of stability where second order effects are of importance, etc.). In other cases they need not be considered, provided that the ductility and rotation capacity of the elements are sufficient.”

Meaning that when calculating the reinforcement the partial coefficients used should be for the SLS which is the cracked stage and the ULS can be neglected for the thermal effects in frame bridges.

According to EC1-1-5 Section 6.1.2 there are two thermal effects that should be considered and these are the high and low temperature components and the temperature gradients. These should be applied according to Section 6.1.3.3 and Section 6.1.4.1. (EC1-1-5, 2005)

For high and low temperature components the values are calculated according to Equations 2.1 and 2.2. For the gradients there are specific values in Table 6.1 depending on the type of bridge.

\[ \Delta T_{N,\text{exp}} = T_{e,\text{max}} - T_0 \quad (2.1) \]
\[ \Delta T_{N,\text{con}} = T_0 - T_{e,\text{min}} \quad (2.2) \]

2.2 Reinforcement based on maximum allowed crack width

According to EC2-2 Section 7.3.1 (2005) there are certain maximum allowed crack widths which are used when calculating the reinforcement. So to fulfill this requirement Equation 2.3 is used after making an experienced assumption for the area of the reinforcement and the result should give a crack width near the maximum allowed crack width to have optimized the amount of reinforcement needed. The maximum value from Equation 2.5 is used, where \( f_{ct,\text{eff}} = f_{ctm} \) and the forces from the analysis are introduced in the stress calculation that is made with Navier’s formula, Equation 2.6.

\[ w_k = S_{r,\text{max}} (\varepsilon_{sm} - \varepsilon_{cm}) \quad (2.3) \]
\[ S_{r,\text{max}} = k_3 c + \frac{k_1 k_2 k_4 \varnothing}{\rho_{p,\text{eff}}} \quad (2.4) \]
\[ \varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s}{E_s} - \frac{k_t f_{ct,\text{eff}} (1 + \alpha_e \rho_{p,\text{eff}})}{E_s} \geq 0.6 \frac{\sigma_s}{E_s} \quad (2.5) \]
\[ \sigma = \frac{N}{A} + \frac{M}{I} * y \quad (2.6) \]
2.3 Minimum requirement of reinforcement

Sometimes the forces occurring in the concrete does not generate to any reinforcement but this is not applicable and as a precaution and to control cracks in areas where these small tensile forces occur a minimum requirement of reinforcement is demanded in the EC and from The Swedish Transport administration. In Section 7.3.2 in EC2-1-1 (2005) an equation for crack control is given for checking how much reinforcement is generally needed where the amount depends on constants and the area of concrete in that part of the section which is calculated to be in tension just before cracking (see Equation 2.7).

\[ A_{s,\text{min}} = \frac{k_ek_{ct,\text{ef}}fa_{ct}}{\sigma_s} \]  

(2.7)

In Section 9.3.1.1 for solid slabs there is a reference to Section 9.2.1.1 where an equation is given specifically for the minimum longitudinal reinforcement in beams where the amount depends on the tensile zone and effective depth of a cross-section which means that the geometry of the cross-sectional area is taken into account (see Equation 2.8).

\[ A_{s,\text{min}} = 0.26 \frac{f_{ct,\text{m}}}{f_{yk}} b_{t} d \]  

(2.8)

Then there are formulas for calculating the requirement of minimum reinforcement in all directions and all sides of the structure in TRVK Bro and TRVR Bro which states that the requirements in Equations 2.9 and 2.10 should be checked as well (Trafikverket, 2011).

\[ A_{s,\text{min}} \leq 4.0 \frac{f_{ct,\text{m}}}{3} \]  

(2.9)

\[ 0.05\% \quad \text{or} \quad 0.08\% \quad \text{if} \quad L > 5t \]  

(2.10)

When it comes to the transversal reinforcement Section 9.3.1.1 in EC2-1-1 states that this minimum reinforcement should be 20% of the principal reinforcement for one way slabs when FE-modeling is not used (2005). Although TRVR Bro states that for the superstructure Equation 2.11 and for the support Equation 2.12 can be applied (Trafikverket, 2011). Both of these have traditionally been used for dimensioning the transversal reinforcement for bridges in Sweden before the implementation of EC with reference to the standard that was used before EC, BRO 2004 (Vägverket, 2004). Although these are used for the shrinkage when casting the concrete it is a good approximation for the minimum reinforcement for the temperature induced loads. So all of these requirements should be checked and then the maximum value from the equations is dimensioning. In this case Equation 2.9 gave the highest value of 4.3cm².

\[ B \leq 45k - \frac{C}{10} + 40\rho \]  

(2.11)

\[ L \leq 30k - \frac{C}{15} + 25\rho \]  

(2.12)
3 Method
The method used in this study will be explained here so the reader can understand more of why and how the issue has been approached.

Investigations for the area of this master thesis were done by extensive research to increase the knowledge in this subject and also to gather information in general. But this was also done to see which problems other have had during their research or studies in this area and with that taken into account the method and the approach have been developed.

3.1 Background
When bridge designers have been modeling frame bridges with 2D-models during the last couple of years the temperature has only been applied in the superstructure and this has not led to any issues with the temperature because of the 2D-approach where transversal directions have not been taken into account, because of the fact that they are known to not cause any issues in reality (Beck & Haghani Pour, 2014). But with FE-modeling there is no specific guidance of how to apply the temperature which is why it has been up to the engineer to decide. So to emphasize the issue here, it lays mainly in the transversal direction which has only been taken into consideration with general formulas before FE-modeling.

When modelling frame bridges the temperature is either applied in the superstructure or in the whole structure and this approach is much exaggerated because of the existing varying temperature in the structure. Often when designing a frame bridge there is soil on the outside of the supports. This means that it would be wrong to model the same temperature in the supports as in the superstructure of the bridge. When the temperature is high in the air it is cooler in the soil and when it is low temperature in the air it is warmer in the soil. This is a result of the different heat transfer coefficients of different materials (Sundberg, 1991).

So the issue with restraint forces comes mostly because the model is in 3D and that the transversal forces are included but also because of the theory behind FEM with degrees of freedom in nodes (Cook, et al., 2002) where large restraining forces occur in the connection between two parts where one is restrained and the other is free to move. The modeling is often a linear model because of the complexity and time-consuming nature of non-linear analysis. One direct consequence of this is that the software does not account for the non-linear behavior of concrete which means that when the stresses that occurs reaches the maximum stress in the concrete, in reality the tension seizes to exist (Ansell, et al., 2012) but in a linear model the stresses increase.

3.2 Approach
The results that are observed are first of all the moment because of the relationship between the moment and normal force, therefor the associating normal forces will be observed as well. The stresses will also be observed to visualize the stress distribution and to see what the moment and normal force generates. This is because the stress is the best way to show how much reinforcement is needed more visually in the diagrams but the reinforcement will also be calculated and shown in a table because that is what a bridge designer will be reviewing to see how much the models differ. This calculation will be presented for those load cases that generates the largest forces and stresses.
Values from some software that can be known as sufficient when designing bridges and that has been used by bridge engineers is a useful tool to validate the models. Therefore the first case is a model that has been made in a calculation software called Strip Step 2 where the software takes one meter strip of a frame and gives the results per meter which makes this a 2D-model (ELU Konsult AB, 1992). So the associating forces that can be given in BRIGADE/Plus (Scanscot Technology AB, 2013) cannot be given in Strip Step 2 but most importantly it only gives results in the longitudinal direction and the transversal direction is disregarded. Although, with this being a software that has been used for a very long time in bridge engineering it is sufficient as a verification of the models. Then there are two main cases for the 3D-models where the temperature is defined differently. In each of these two cases there are four different kinds of boundary conditions. The temperature will first be applied on the superstructure and then in the whole structure. When using the latter application the temperature variation in the bridge will be calculated with a FE-software named ConTeSt Pro.

---

**Temperature components**

- **High temperature**
- **Low temperature**
- **Temperature Gradient Plus**
- **Temperature Gradient Minus**

**BRIGADE/Plus (3D)**
- Temperature in superstructure
- Boundary condition 1-4
- Temperature in whole structure
- Boundary condition 1-4

**Strip Step 2 (2D)**
- Temperature in superstructure
- Boundary condition 1

**ConTeSt Pro**
- Calculations for whole structure only

---

**Figure 3.2.1 Overview for the approach of the method.**

As mentioned earlier the usual application of the temperature in 3D-models is wrong which is why the distribution of the temperature has been studied in a software called ConTeSt Pro, a FE-software for temperature- and stress-calculation in concrete (JEJMS Concrete AB, 1999), which gives a better understanding of the temperature distribution in the frame bridge.

The final results of the earlier mentioned forces are visualized with plots for the separate forces but with all the cases and their boundary conditions in each plot to see the differences from each case and subcase. First by verifying the behavior of the models with the 2D-results and then comparing all the models to each other final conclusions can be drawn.

To summarize, the model that has been created is a frame bridge that is geometrically connected between the superstructure and the supports and it is important to understand that when doing so the whole support is completely fixed to the superstructure, as it is in reality. The model will be a linear model because as explained the issue occurs in the linear model which is what is preferably used when modeling today.
3.2.1 Convergence study
To decide which element size and type is best for the model a convergence study in the load case for the dead weight was made and all the sectional forces were consistent except one which is presented in Figure 3.2.1.1. As can be seen the difference between the linear element type for the largest and smallest mesh size is the biggest. For the quadratic element type the two smallest mesh sizes show exactly the same result. Therefore, the following has been chosen.

- Element type: Quadratic shell
- Element mesh size: 0.3m

![Moment in Direction 1](image)

Figure 3.2.1.1 Comparison of mesh sizes and element types.
4 Studied cases

In this chapter the prerequisites of the model will be presented and the cases with their differences will also be shown in figures and explained as well. The input used in the case when applying the temperature in the whole structure will also be presented in Subchapter 4.2.1.

The foremost important criteria for this study have been to model a bridge that reflects the reality as much as possible. Therefore a bridge that has been constructed in real life by the engineers at ÅF-Konfem has been used as a base which has rather general conditions. Some simplifications and rounding have been made for the dimensions of the bridge to create full symmetry.

So the basic conditions for the bridge are a straight frame bridge with no curves so that the possible restraining effect of different lengths on the supports is eliminated. Even though this bridge does not have various lengths for the supports this condition is one that occurs often in reality, but it is better for the outcome of the study that these kinds of possible effects are eliminated (Beck & Haghanipour, 2014). Also the effect of long slabs is eliminated by having a rather short length of the bridge even though this effect should not be so extensive due to that the supports will absorb most of the forces. But to again eliminate the possible effects from the plates in the longitudinal direction the bridge will not be too long (Jonasson, et al., 2012). Therefore the length of the bridge will be 10 meters with a span of 8 meters which can be seen in Figure 4.1 and Figure 4.2 and by also including the wing walls with certain dimensions given in Figure 4.4. The height of the bridge was calculated approximately from drawings of the original bridge. According to TRVK Bro, Section D.2.2.1.4 (2011) when the bottom slab is cast directly on soil the lower 50mm from the bottom slab should be considered idle.

\[
h = h_{+,max} - h_{+,min} - t_{bottom}\left(1 - \frac{1}{2}\right) + \frac{t_{super}}{2} - \frac{0.050}{2} \\
= 17.12 - 10.5 - \frac{0.6}{2} + \frac{0.44}{2} - \frac{0.050}{2} = 6.515
\]  (4.1)

As mentioned some dimensions may vary for achieving symmetry and for some simplifications. The inclinations that can be seen in the mentioned figures will neither be taken into account.
Figure 4.1  Dimensions for the bottom slab and the support and thus the length of the bridge.

Figure 4.2  Dimensions for the span of the bridge and thicknesses for the cross-section of the frame.
Figure 4.3  Dimensions for the wingwall for the real bridge that has been used as a base.

Figure 4.4  Dimensions used in BRIGADE/Plus for the wing wall.
4.1 Strip Step 2
For the first case the temperature is only in the superstructure.

1. Spring in one point because of the properties of the software.

4.2 BRIGADE/Plus
For cases 2 and 3 the same boundary conditions are used so that the results can be compared without any discrepancies but with the difference of how the temperature has been applied as mentioned in Subchapter 3.2.

So the boundary conditions used for cases 2 and 3 are as follows:

1. Spring in only one point under the bottom of the support. The spring will be defined by its rotational spring. But the rotation in longitudinal direction has to be locked so that the whole structure will not be rotating around one point. See Figure 4.2.1.
2. Springs to ground at the bottom of the support as a line that will represent the foundation. Here the springs will be defined by their rotational springs. See Figure 4.2.2.
3. Springs to ground over a surface that represents the foundation. Here the springs will be defined by their translational springs and not the rotational springs as the rotational aspect will be absorbed by the surrounding springs. See Figure 4.2.3.
4. Springs to ground over a surface as well but with the difference from condition 3 that the horizontal movements will be free to remove the horizontal restraints but with a fixed node in the middle of the support (for future purposes when horizontal loads occur). See Figure 4.2.4.

Figure 4.2.1 Boundary condition 1, springs in one node.
Figure 4.2.2  Boundary condition 2, springs on a line.

Figure 4.2.3  Boundary condition 3, springs to surface.

Figure 4.2.4  Boundary condition 4, springs to surface with no restraints in horizontal directions.
The locale directions in the model are shown in Figure 4.2.5 which should be kept in mind when reviewing the results.

![Diagram showing locale directions](image)

**Figure 4.2.5** Local directions for the shells.

### 4.2.1 ConTeSt Pro

The parameters used in ConTeSt Pro can be seen in Table 4.2.1.1.

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<thead>
<tr>
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<th>Concrete</th>
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<tr>
<td>Density [kg/m³]</td>
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<td>2200</td>
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<tr>
<td>Heat capacity [J/(kg*K)]</td>
<td>1000</td>
<td>1400</td>
</tr>
<tr>
<td>Heat conductivity [W/(m*K)]</td>
<td>1.7</td>
<td>2.1</td>
</tr>
</tbody>
</table>

![Diagram showing defined blocks and chosen mesh](image)

**Figure 4.2.1.1** The defined blocks and the chosen mesh in ConTeSt Pro.
The varying distribution of the temperature that has been applied with a function in BRIGADE is given by the results extracted from ConTeSt Pro and recreated with diagrams so that the function could be given. The first objective was to see how the temperature varies over a year in a certain location, here Stockholm is chosen simply because this thesis is written in Stockholm. These values were given from a report of cracks due to temperature in concrete (Jonasson, et al., 2002) and then inserted in a diagram to digitalize the variation, see Appendix A. It could be seen that the variation followed a sinus-curve which then was used to create a curve adjusted to the maximum and minimum temperatures for this bridge which were taken from TRVFS Bro, Appendix 2 (Trafikverket, 2011). This gave the values that were inserted in ConTeSt Pro with a timespan over one year with one value for each week. The distribution in the soil and the bridge are shown in Figure 4.2.1.2. The function for the temperature distribution along the supports for the high and low temperature and the gradients are shown in Figure 4.2.1.3 and Figure 4.2.1.4.

![Figure 4.2.1.2 Temperature distribution when the temperature is at maximum (left) and minimum (right).](image)

![Table 4.2.1.2 Calculated formulas for the temperature variation over the supports.](table)

<table>
<thead>
<tr>
<th>Load case</th>
<th>Formula</th>
</tr>
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<tbody>
<tr>
<td>High Temperature</td>
<td>$y = -0.1891y^3 + 2.2279y^2 - 9.434y - 11.137$</td>
</tr>
<tr>
<td>Low Temperature</td>
<td>$y = 0.1326y^3 - 1.1441y^2 + 3.2106y + 10.859$</td>
</tr>
<tr>
<td>Temperature Gradient Plus</td>
<td>$y = -0.0148x^4 + 0.1545x^3 - 0.2835x^2 - 0.4037x - 0.3935$</td>
</tr>
<tr>
<td>Temperature Gradient Minus</td>
<td>$y = -0.0198x^4 + 0.3784x^3 - 2.6071x^2 + 6.287x + 1.7621$</td>
</tr>
</tbody>
</table>
Figure 4.2.1.3  Temperature variation along the supports for high and low temperature.

Figure 4.2.1.4  The variation for the temperature gradient along the supports.
4.2.2 Observed sections
The observed sections in BRIGADE are the midsection at L/2, one quarter section at L/4 and one end section where the distance from the edge is approximately 600mm. The latter is calculated with advice from TRVR Bro where it says that the maximum values in the ultimate limit state can be distributed over a width of three times the thickness of the superstructure (Trafikverket, 2011). Therefore the values that should be used as mean values for this width are taken from the chosen path that was created at the end section.

Figure 4.2.2.1  The observed sections with end section, quarter section and midsection in that order.
5 Results

The results that give a better understanding of the phenomena that is being studied in this master thesis are shown in this chapter. First the sectional forces with normal force and moment are shown for one of the worst load cases to show the issue at hand. The stress distribution is also visualized just to give an understanding of how the distribution differs in the models. Then the needed reinforcement amount is presented for the worst load case.

As mentioned before, and it can be seen, that the longitudinal direction does not give remarkably unrealistic values even though its results can differ some for the several approaches. It is the transversal direction that will show more abnormal results and therefor the focus will lay there. The calculated reinforcement is thus for the transversal direction with a minimum reinforcement calculated according to BRO, 2004 (Vägverket, 2004) and not with Strip Step 2 because of its 2D nature. Also to be mentioned is that even though the midsection has been observed, results from the different sections follow the same relation but with slightly lower values when coming closer to the midsection. Therefor the midsection will not be presented; neither in this chapter nor in Appendix B, but comparing the end section with the quarter section will show that the results actually do follow the same relation.

5.1 Sectional forces

When examining the results for the high and low temperature components an observation was made that when applying the temperature only on the superstructure the results tend to be very unrealistic and therefore obvious that these can be disregarded as a good model. So modeling the temperature in the whole structure and with a varying temperature along the supports is clearly a better model which is very logical. So to create a better overview of the diagrams only some results will be presented in this chapter while all the results can be seen in Appendix B.

Following legend is used for all figures in this chapter except for Subchapter 5.3 and the interpretation of the figures is shown in Figure 5.1.1.
Figure 5.1.1  The figure shows how to interpret all of the diagrams for the results where they all follow the same convention.
As can be seen large restraining normal forces occur in the transversal direction in the transition between support and superstructure when the temperature is only in the superstructure. But with the temperature in the whole structure the problem is moved to the bottom slab and very large restraining forces occur there instead but observe which boundary conditions have been used.

For the moment the boundary condition does not have great influence in the transversal direction but more for the longitudinal direction. Observe the results for the 2D-model in the longitudinal direction and its conformity with the 3D-results.
Figure 5.1.3  High temperature – End section, moments in transversal and longitudinal direction respectively.

The results for the torsional moment are not interesting due to their relatively low values in comparison with the two principal directions. For the temperature gradients the results generally have a very high compliance regardless of temperature application and boundary condition so those results are not shown due to relatively small restraint forces in comparison to the high and low temperature components. See all results in Appendix B.
Figure 5.2.1  Contour plots of stress in transversal direction for high temperature. Boundary condition 1 (upper) and 4 (lower). Observe the numerical values, especially the maximum and minimum.

The stresses follow a similar behavior as the sectional forces, which can be seen in Figure 5.2.2, and to visualize the difference in how the stresses are distributed between the most and least restrained models see Figure 5.2.1.
Figure 5.2.2  High temperature – End section, stresses in both principal directions.

For the longitudinal direction the stresses are somewhat realistic for all the models but as can be seen in the transversal direction the restraints are very large in some of the models, just a for the sectional forces.
5.3 Reinforcement
As mentioned in Chapter 3, it was observed that the high and low temperature were the load cases with much larger forces and stresses. Therefore the reinforcement is only presented for these although calculations were made for all load cases. It was observed that the High Temperature did not result in much reinforcement because of the large compressive forces and therefore only the Low Temperature is presented in Figure 5.3.1 and Figure 5.3.2 following the convention for drawings of needed reinforcement amount. Following legend is used for the figures in this subchapter which is the same as earlier with the Minimum reinforcement replacing Strip Step 2.

![Diagram of reinforcement needed in lower edge of superstructure in the transversal direction.](image)

**Figure 5.3.1** Reinforcement needed in lower edge of superstructure in the transversal direction.
Figure 5.3.2  Reinforcement needed in exterior and interior side of the support in the transversal direction.
6 Discussion and Conclusions

6.1 General
When modeling temperature loads in concrete frame bridges with FE, issues occur in the transversal direction which leads to very large amounts of reinforcement that is not needed in real life which makes this a large and unnecessary cost. The main focus has therefore been on how to approach the issue with large restraining forces when modeling concrete frame bridges. In general there are always four different temperature load cases to consider and all of these have been studied. These four load cases have been applied in two different ways to see which one is the optimal one. The first one was with the temperature loads applied only in the superstructure, which is how it is done by convention, and the second one where it was applied on the whole structure with a varying temperature along the supports, which is a developed approach. The results presented show the difference between the models and it can be seen that one model stands out from the others.

6.2 Discussion
With the limitation of comparing the results with a 2D-model it may seem as though these results are excessive but they give an indication that the 3D-results are logical and follow the same relation. They also show how the traditional approach differs from the modern approach with FE-modeling and the values they generate. It could be of value to calculate the reinforcement needed from the 2D-model and compare it with the 3D-models but because the 2D-model only gives results in the longitudinal direction this is not evaluated because the issue and focus lays in the transversal direction.

One could argue that this study does not have sufficient number of cases or models to be able to draw good conclusions but even if several more cases were to be studied where the size or the model would differ, the result would most definitely have the same relation between the several approaches as they do in the studied bridge in this master thesis. With that being said maybe a larger bridge should have been used to really show how large the effects are on the needed amount of reinforcement.

For the observed sections it is highly relevant to observe the section forces in the end section and quarter section but not in the midsection which is why these values where only taken just to show and verify that the relation between the models follow the same behavior as in the end section. This makes the conclusions made for the end section valid for the whole model.

As mentioned in the beginning of Chapter 5 all the results are shown in Appendix B instead of in the chapter itself because the goal is to present results that give a better understanding of the issue and the solution. As explained the results when applying the temperature only in the superstructure were disregarded. The explanation to why this type of modeling is wrong in practice is because this causes the superstructure to move while the supports are held still which results in the developing of very large restraining forces in the transition from superstructure to support. When applying the temperature in the whole structure and having fixed conditions in horizontal directions in the bottom slab causes the restraining forces to occur in this section instead. This shows that the problem is not completely solved, but only moved elsewhere which can be seen in e.g. Figure 5.1.2. In practice this leads to unnecessarily large amounts of
reinforcement in which ever section that has been subjected to these restraints. This makes it obvious that it is not only how the temperature is applied but also the boundary conditions of the model that gives extreme results.

The real comparison if these results are valuable is in the calculation of the reinforcement. In hindsight the load case for the Low Temperature was the only one resulting in any high reinforcement amount in the transversal direction. But it has to be mentioned that the High Temperature did not give much reinforcement because of the very large normal forces that causes large compression which results in no reinforcement. But this does not reflect reality which is why any valuable results are difficult to present in this load case. Also, if the ratio between the moment and normal force would be bigger the forces could result in large reinforcement amounts, which is what happens when modeling a real bridge because of the several other load cases that are considered in e.g. the SLS and the combination of these load cases.

6.3 Conclusions
The conception of the issue before doing this study was that there are two properties that are mostly significant for the outcome of the sectional forces when dealing with temperature effects. Throughout this study it has been even clearer that this conception is correct and the following conclusions have been made to the modeling of concrete frame bridges.

- It is not only how the load is applied that matters, but also the boundary conditions.
- Only applying the temperature in the superstructure as conventionally done in 2D-models is highly inaccurate for 3D-models.
- Apply the temperature in the whole structure and let it vary in the structure in a realistic way. It could be time-consuming to examine the exact variation for every bridge that will be modeled so if not with the exact variation, a competent approximation would suffice e.g. with a linear variation along the supports from the maximum/minimum temperature to a reasonable temperature at the bottom of the bridge which depends on the soil and depth among other things.
- Use as realistic boundary conditions as possible. Try not to give them unnecessary and unrealistic fixations. In this case with a bottom slab, model the bottom slab as a surface and try to keep the horizontal directions free to some extent.
- The mentioned conclusions give a model and results without large unnecessary restraining forces and excessive reinforcement can be avoided.

6.4 Suggestions for future work
Some assumptions and simplifications have been made and to be able to model more according to reality a suggestion is to determine the used constants more accurately, e.g. the spring constants for the boundary conditions where the constants in all directions would reflect reality better. This could possibly be made with measurements for a real bridge of how much the bridge is restrained in different directions.

As mentioned the cases that have been studied have been narrowed down to a few after discussing the matter with two very competent and experienced bridge engineers, so the cases and their suggested conditions can be assumed to be of very high importance and validity to have
solved this problem that occurs in FE-modeling. But it could be satisfactory to study more cases, e.g. with different lengths and spans, to be able to make conclusions based on more extensive research.

Some companies may not have access to software that can calculate the temperature variation in a structure. So to be able to apply the suggested conclusion with a temperature variation along the support one could examine different types of frame bridges with different height, thickness etc. to be able to create figures or tables which then could be used when dimensioning a bridge to know how the temperature varies in the support for that bridge.

The theory behind FEM is the same for all FE-software which is why an assumption that this approach would be applicable for other FE-software as well is a highly competent assumption. But this is nothing that can be guaranteed because of the different ways of modeling in different FE-software so a suggestion is to investigate if this approach can be used for other software as well so companies that do not have BRIGADE can use the same approach.
7 References


Appendix A - Calculations

A.1 Spring stiffness

Calculation of spring stiffnesses:

\[ k_{q,k,L} = E_k \times B^2 \times L / 5 \quad [\text{kNm/rad}] \quad \text{According to Appendix 107.1, TRVK Bro 11} \]
\[ k_{q,k,T} = E_k \times L^2 \times B / 5 \quad [\text{kNm/rad}] \]
\[ k_{q,k,V} = 2 \times E / (\alpha \times B) \quad [\text{kN/m}^2] \quad \text{According to BVH 541.2 Appendix 303-11} \]

\[ f_k = 38 \text{ grader} \quad \text{Packed filling} \]
\[ E_k = 40 \text{ MPa} \quad \text{The characteristic value for the modulus of elasticity is used} \]

\[ L = 9.5 \text{ m} \quad \text{Dimensions of bottom slab} \]
\[ B = 2.4 \text{ m} \]

According to BVH 541.2 Appendix 303-11, Table 332.144a

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<tr>
<th>B/L</th>
<th>1</th>
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<th>0.6</th>
<th>0.4</th>
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<tbody>
<tr>
<td>(\alpha)</td>
<td>0.65</td>
<td>0.69</td>
<td>0.75</td>
<td>0.83</td>
<td>0.94</td>
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\[ B/L = 0.25 \]
\[ \alpha = 0.91 \]

For Strip Step 2

\[ k_{q,k,L} = 438 \quad [(\text{MNm/rad})/\text{m}] \]
\[ 1 / k_{q,k} = 2.2E-05 \quad [\text{rad m/kNm}] \quad \text{Rotational weakness because of Strip Step 2 definitions} \]

For BRIGADE/Plus

\[ k_{q,k,L} = 438 \quad [(\text{MNm/rad})/\text{m}] \quad \text{Rotational stiffness in the slabs weak direction} \]
\[ k_{q,k,T} = 1733 \quad [(\text{MNm/rad})/\text{m}] \quad \text{Rotational stiffness in the slabs stiff direction} \]
\[ k_{q,k,V} = 37 \quad [(\text{MN/m})/\text{m}] \quad \text{Translational stiffness in vertical direction} \]
\[ k_{q,k,L} = 4161 \quad [(\text{MNm/rad})/\text{m}] \quad \text{Rotational stiffness in the slabs weak direction only for Boundary condition 1} \]
A.2 ConTeSt Pro
The temperature variation that is mentioned in Subchapter 4.2.1 is shown in the figures below.
Appendix B - Forces and Stresses
All results shown in this appendix follow the same legend posts in the following legend.

- Node - Superstructure
- Node - Whole structure
- Line - Superstructure
- Line - Whole structure
- Surface - Superstructure
- Surface - Whole structure
- Surface Vertical - Superstructure
- Surface Vertical - Whole structure
- Strip Step 2
B.1 High temperature

B.1.1 Endsection

Normal Force in Direction 1

Normal Force in Direction 2
B.1.2 Quarter section (L/4)

Normal Force in Direction 1

Distance along frame [m]

Normal Force in Direction 2

Distance along frame [m]
B.2 Low temperature

B.2.1 Endsection

Normal Force in Direction 1

Normal Force in Direction 2
B.2.2 Quarter section (L/4)

Normal Force in Direction 1

Normal Force in Direction 2
Normal stress in Direction 2

Shear stress in Direction 3
B.3 Temperature Gradient Plus

B.3.1 Endsection

Normal Force in Direction 1

Normal Force in Direction 2
Normal stress in Direction 2

Shear stress in Direction 3
B.3.2 Quarter section (L/4)

Normal Force in Direction 1

Force [N/m] vs Distance along frame [m]

Normal Force in Direction 2

Force [N/m] vs Distance along frame [m]
Moment in Direction 1

Moment in Direction 2
B.4 Temperature Gradient Minus

B.4.1 Endsection

**Normal Force in Direction 1**

- Force [N/m] vs. Distance along frame [m]

**Normal Force in Direction 2**

- Force [N/m] vs. Distance along frame [m]
Moment in Direction 3

Normal stress in Direction 1
B.4.2 Quarter section (L/4)

Normal Force in Direction 1

Normal Force in Direction 2
Normal stress in Direction 2

Shear stress in Direction 3
## Appendix C - Reinforcement

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<tr>
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<td>Lower Edge</td>
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<td>Life length</td>
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<td>$\gamma_c$</td>
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<tr>
<td>Maximum allowed crack width</td>
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### Material properties and constants

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<td>$f_{yd}$ [MPa]</td>
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## Support - Transversal direction - Exterior side

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