A Case Study on the Temperature Differences in a Concrete Composting Bunker.

BACHELOR THESIS

NAME:	E. M. R. (ESMEE) KOOPMAN
STUDENT NUMBER:	S1558560
EMAIL:	E.M.R.KOOPMAN@STUDENT.UTWENTE.NL
INTERNSHIP COMPANY:	TAUW, DEVENTER (THE NETHERLANDS)
CLIENT:	WASTE TREATMENT TECHNOLOGIES (WTT), OLDENZAAL (THE NETHERLANDS)
EDUCATIONAL INSTITUTION:	UNIVERSITY OF TWENTE, ENSCHEDE (THE NETHERLANDS)
INTERNSHIP PERIOD:	10-04-2017 TO 23-06-2017
DEADLINE THESIS SUBMISSION:	06-07-2017

Synopsis

Waste Treatment Technologies (WTT) designs waste treatment systems and delivers them all over the world. The (often local) building companies, building the concrete housing of their composting systems, have little experience with the environment and the temperature loads arising in these composting bunkers. As a solution they over-design the construction to protect the concrete bunker from an uncontrollable appearance of cracks appearing or they under-design, because they don't know how to take the unique circumstances into account. WTT wants to find an optimized solution for this. WTT also wants to stop the over- and under-designing, and the large material costs or the failing of the construction that come with it, by improving the communication with their building partners about the specifics of the bunker constructions.

ABSTRACT

Concrete structures are exposed to all sorts of environments and need to serve all sorts of functions. Designing a structure which can handle the difficult circumstances is challenging. This bachelor thesis contributes to the research in this field, by using a case study to research the influence of large temperature differences on a concrete construction.

PROBLEM STATEMENT AND METHODOLOGY

Waste Treatment Technologies (WTT) designs waste treatment systems, which are located all over the world. Their *composting* systems are placed inside concrete bunkers. During the composting process the temperature becomes 50 °C and even 85 °C when an error occurs. The concrete thus has to deal with large temperature differences. Temperature differences create a temperature gradient, which is a thermal load to the construction. This creates stresses in the concrete, which can result an uncontrollable appearance of cracks.

WTT outsources the designing of the concrete bunkers to (often local) building companies. These building partners don't know how to deal with the composting environment and the large temperature differences coming with the composting process. As a result they over-design the concrete bunkers, which is expensive, or they under-design, because they don't how to deal with the unique circumstances, which can result in damage. There is no general bunker template they can base their design on, so WTT encounters differences in the appearance of cracks and in amount of materials used. WTT wants to help the building companies with their design of the concrete bunkers by communicating with them about the building specifications. In the future this may result in a manual or a template they can base their design on. In this bachelor thesis the design of the bunkers is reviewed and the most critical temperature scenarios are identified, after which different optimized solutions have been proposed in order to stop the over- and under-designing.

Nine composting bunkers build in the summer of 2017 located in Swisttal, Germany, are used as a case study. The dimensions of this case study are analysed and modelled in the 3D simulation FEM program SCIA Engineer. This program is used to analyse the stresses and forces arising in the nine case study bunkers. The results are used to analyse the influence of the thermal load on the construction, to analyse the calculations made by building company Grotemeier Ingenieure for the case study and to optimize the solutions.

RESULTS AND DISCUSSION

A general manual and a specific case study manual, given by WTT to the building company, have been analysed and compared, together with the calculation report of the case study in Swisttal made by Grotemeier Ingenieure Bielefeld, Germany). Concluded was that the few guidelines given by WTT are too broad and don't match with each other. Specific guidelines need to be given, together with an explanation why certain things are required by WTT. The general and specific manual need to be integrated.

It is unclear which temperatures need to be used in the calculations. The temperatures used in the calculation report of Swisttal are compared to the temperatures used by this bachelor thesis (taken from NEN-EN 1991-1-5). None

of the temperatures matched. Even the temperature inside the composting bunker, given by WTT was different (75 °C and 85 °C). Some temperatures used by Grotemeier Ingenieure were higher, some were lower.
Next, all twenty-seven possible temperature scenarios have been listed. Out of these scenarios the most extreme one is taken to use in further calculations. The influence of this extreme temperature scenario is calculated in SCIA Engineer and expressed in the tensile normal stress. This parameter has been chosen, because concrete can't handle large tensile forces and cracks can arise due to that. The maximum tensile normal stress found is 12 N/mm^2 and this stress is for a major part caused only by the thermal load. Inside the filled bunkers *compressive* and outside *tensile* stresses arise, as predicted by the theory.

There needs to be an agreement on which temperatures need to be used for these special constructions of WTT. The advice is to take measurements of the *real* temperatures. WTT could then provide the building companies with all the twenty-seven possible temperature scenarios containing the *real* temperatures. Out of all these possible scenarios the most important scenario(s), for example the most extreme or the most common, need(s) to be selected and linked to a certain requirement it needs to meet, for example the crack width. It also needs to be given if the(se) scenario(s) need(s) to be calculated in the ULS or SLS and which forces work on the construction.

The parameter tensile normal stress has also been used for to optimize the solutions. If the tensile normal stress is larger than the concrete can handle (3.21 N/mm^2), the construction is damaged. Using the most extreme temperature scenario, there is found that the maximum tensile normal stress the concrete can handle, is exceeded due to the thermal load. Insulation can be used as a solution for this problem and has been researched further, because it isn't a solution that needs cracks in the concrete to work (like reinforcement does). Cracks are a risk, because the chemical composting environment can attack the reinforcement, which causes the construction to fail.

The insulation thickness is optimized by checking when the remaining tensile normal stresses are lower than 3.21 N/mm^2. The optimal thicknesses of three types of insulation (mineral wool, expanded polystyrene, polyurethane foam) have been calculated for the four structural elements in the concrete bunkers (roof, outer wall, floor, inner wall). The calculated thickness of the insulation layers lies between 5 mm and 40 mm, while Grotemeier Ingenieure has used 80 mm of insulation. Grotemeier Ingenieure didn't give an explanation on why this thickness is used and this confirms the fact that the building companies don't know how much material they need to lift influence of the thermal load on the construction.

So, the two main things that need to be included in the instruction manuals WTT gives to their building partners are: the real temperatures the building companies need to use in their calculations and giving the building companies insight on the type and amount of insulation they need to use.
Important to mention is that this bachelor thesis used tensile normal stress to draw conclusions and make calculations, but the bending moments that the thermal load causes aren't included in the research. This can be further researched in a follow-up study.

Figure 1: The white doors are the doors of concrete composting bunkers (top) (Waste Treatment Technologies, 2016). The inside of the composting bunker with spigots (in the floor embedded facilities connected to ventilation channels) still visible (left). These spigots are later on concealed by the concrete floor (right) (Waste Treatment Technologies, 2015).

TABLE OF CONTENTS

1. INTRODUCTION

Concrete structures are used in many different locations and are therefore exposed to different environments which can cause degradation of concrete. It is challenging to design durable concrete structures that are exposed to very aggressive environments. New research in this big field with lots of parameters is always welcome. This bachelor thesis focuses on high temperatures and quick temperature changes in a concrete structure.

Waste Treatment Technologies (WTT) is a company located in Oldenzaal, The Netherlands, which designs waste treatment systems. All over the world they design two types of waste treatment systems: anaerobic digestion and composting. These systems are placed in concrete bunkers, which are built by different building companies. Often these building partners of WTT are located nearby the location where the waste treatment system will be built, because these local companies know the local building requirements and traditions. As a result all the concrete bunkers differ and there is no general template for the building of these bunkers. Most building companies are unfamiliar with building a concrete bunker which has to deal with a waste treatment environment and large temperature differences. The unique circumstances can create stress in the concrete, which can result in an uncontrollable appearance of cracks. For this reason the building companies over-design the bunker by using more material than may be necessary, in order to be sure of a safe construction. Or they under-design, simply because they don't know how to take the unique circumstances into account. WTT wants to research this problem deeper, in order to optimize the design of bunkers and reduce the occurrence of premature damaging.

In the summer of 2016 WTT has contacted Tauw, a consulting and engineering agency located in Deventer, The Netherlands, regarding the problems with the housing of their waste treatment bunkers. This bachelor thesis will answer that call, with an analysis focused on the problems occurring in the concrete *composting* bunkers. A literature study is used to look at the effects of temperature differences on the concrete bunkers. Using a case study in Swisttal, Germany, the over- or under-designing will be investigated. With the 3D modelling program SCIA Engineer, the influence of the temperature differences on the case study structure will be researched. Then possible solutions are going to the proposed. First insulation as a solution is going to be researched. In the end the bachelor thesis will be summarized and the drawn conclusions will help WTT fill the gap in the communication process with their building partners.

1.1. READING GUIDE

Chapter 2 states the problem and the context in which this research takes place. Chapter 3 contains a literature study on the effects of temperature differences on a concrete construction. Chapter 4 contains the research aim and the limitations of this bachelor thesis. Chapter 5 covers the methods that will be used. Chapter 6 and 7 contain the results of research goal 1 and 2 and the answers to the belonging research questions. The report ends with a conclusion and recommendations in Chapter 8 and 9. A reference list and appendices can be found at the end of the report.

2. PROBLEM ANALYSIS

WTT has given a context: the influence of temperature differences on the concrete housing of their composting system. Multiple problems are identified within this context. With a problem statement insight is given about the focus of this bachelor thesis.

2.1. Background

WTT delivers their waste treatment systems and leaves the designing and building of the bunkers to a (local) building company. In most cases the building companies build a new bunker. In the few remaining cases the waste treatment systems are integrated in an already existing building. These bunkers can be integrated together in a hall or they can be build outside.

The composting materials in the bunker create an aggressive environment for the concrete. On the inside high temperatures can arise, while outside the seasons determine the temperature. This results in temperature differences, or so called temperature gradients, which create a constructive thermal load on the construction. These conditions are hard to deal with, for the building companies, because there is no general bunker template they can base their design on. Designing a concrete construction which has to resist large temperature differences and changes, is a new thing to most building companies and its engineers.

The temperature gradients create tensile stresses and bending moments in the concrete, which can result in an uncontrollable appearance of cracks. Cracks in concrete aren't immediately a problem, but the appearance of cracks needs to be controlled and building companies over- or under-design the bunkers to do this. They increase the amount of reinforcement to be extra safe or they don't take the hard conditions into account at all, because they don't know how to design with them. Because the building companies all have a different approach, WTT encounters extreme differences in the appearance of cracks and in amount of materials used, like reinforcement and concrete. An extensive use of materials is expensive, but an uncontrolled appearance of cracks in the bunkers can have a bad influence on the life cycle length of the composting bunkers. Both situations are undesired, so a solution needs to be found.

2.2. Problem statement

WTT has almost no standard guidelines to help the building companies in dealing with the unique conditions in the composting bunkers, whereby their building company partners over- or under-design the concrete bunkers to prevent an uncontrollable appearance of cracks from appearing. WTT wants to get a better grip on the design process of their concrete bunkers. Control of the cracks plays an important part in achieving this. First the design of the bunkers will be reviewed; then potential solutions will be analysed. Finally the conclusions drawn from this bachelor thesis will try to fill the gap in the communication process of WTT with their building partners.

2.3. Context

Concrete is used all over the world to build all sorts of constructions; from bridges to buildings to flood defences. These constructions find themselves in all sorts of circumstances: the climate can be hot, cold or windy and the use can be chemical, humid or radioactive. All these different constructions need to be approached differently in order to make them endure these hard conditions. Local building rules and traditions and the available technical measures influence the building process. While making the design of the construction, the aggressive environment needs to be taken into account.

This bachelor thesis focuses on concrete bunkers, whose purpose is to keep organic waste during their composting process. A composting environment is humid and has large temperature differences. By doing research about this type of environment, I will learn how to design concrete structures exposed to different loading and environmental effects. Thereby I will contribute to the research of building in difficult circumstances, appearing all over the world.

3. THEORETICAL FRAMEWORK

The current knowledge about the influence of temperature on concrete is summarised in this theoretical framework containing information about the composting bunkers, composting process and a literature review. The theoretical framework opens with a description of the composting bunkers and the composting process, to give the reader an understanding of the concrete housing and the environment it has to deal with. After that the influences of the temperature on the concrete and on the construction are summarized. The information and formulas necessary to perform the research are gathered here. Different causes for the creation of cracks due to large temperature differences are given, of which stress and bending seem to be the most important. The last section explains how the temperature differences can create a temperature gradient in the walls, floors and roofs of the concrete bunkers.

3.1. General data composting bunkers

The composting systems of WTT are placed in concrete bunkers (varying from 5 to 6 m high, 5.5 to 9 m wide, 25 to 35 m long). These concrete bunkers are placed inside existing halls or are built outside. Each bunker consists of a sealed concrete structure equipped with a special door provided with a rubber seal (Figure 1, top). Some general information about the composting bunkers can be found in Table 1. The bunkers are filled with the feedstock (source separated organic waste and municipal solid waste) through the front or top mounted door. The waste will stay there for two or three weeks till it is turned into compost. After the composting time of two or three weeks, the efficiency rate drops, because the composting process slows down. The compost is then taken out of the bunkers and optionally can be further composted outside the bunker (Waste Treatment Technologies, 2016).

The bunkers don't need to be filled all at the same time, so it can occur that one of them is filled and that the one next to it is empty. The bunkers may be emptied and filled in the same day. This means that the air in the bunker can go from the composting temperature to the ambient temperature in one day (Waste Treatment Technologies, 2016). However, the concrete needs more than one day to cool down.

TABLE 1: GENERAL INFORMATION ABOUT THE COMPOSTING BUNKERS (WASTE TREATMENT TECHNOLOGIES, 2016; KOMPOSTWERKE RHEIN-SIEG, 2016).

General information of composting bunkers	Value
General	
Feedstock	Source separated organic waste and municipal solid waste
Processed material	Compost
Life cycle	20 years
Temperatures	
Process temperature	50 °C
Maximum temperature during an error (occurring several times a year)	85 °C
Time schedule	
Composting time	2 – 3 weeks
Interim time (the time length when bunker is empty, before being filled again)	1 day
Weight and foundation	
Density feedstock With a maximum height	800 kg / m^3 4.5 m
Percolation liquid	1.1 kg / lt (100% full)
Foundation	Shallow foundation

3.2. COMPOSTING PROCESS

WTT's composting system speeds up the natural composting process of the feedstock. The feedstock is placed in the bunker by means of wheel loaders. These wheel loaders push the feedstock up against the back wall. This creates an extra force on the wall. For the composting system this feedstock consists of source separated organic waste and municipal solid waste (Waste Treatment Technologies, 2016). The composting process uses microbes, like fungi and bacteria, which are already present in the plant materials (Chen, Haro, Moore, & Falen, 2011). The microbes need oxygen, water and heat to break down the organic material. During this process carbon dioxide, water and heat is released (Pace, Miller, & Farrell-Poe, 1995). The organisms responsible for decomposing the materials require a certain water content for its activity. The amount of oxygen determines the speed of the digestion process and thus the heat release.

The composting process in the bunkers is optimized by WTT. After the door is closed, the percolation system controls the humidity. The aeration system controls the oxygen level and with that the temperature in the bunkers. For a brief explanation of the percolation system and the aeration system, see the caption beneath the Figure 2 and Figure 3. For an optimal composting process the temperature is set at 50 °C (Table 1). If a malfunction occurs, the temperature can become 85 °C (Waste Treatment Technologies, 2016). Such an error situation only happens several times a year, but this is most extreme situation that needs to be taken into account by the building companies.

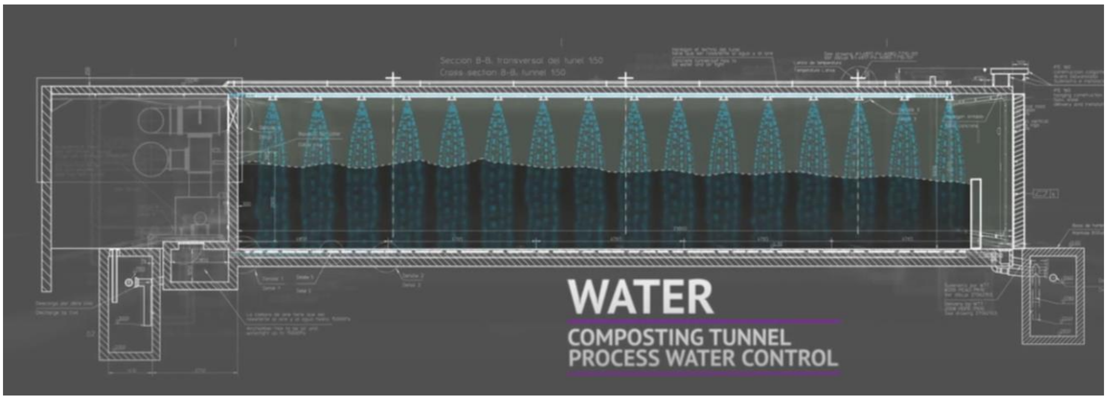


FIGURE 2: THE PERCOLATION SYSTEM.
SPRINKLERS ARE USED AS WATER SUPPLY. GUTTERS IN THE FLOOR GATHER THE WATER AND DISCHARGED IT (WASTE TREATMENT TECHNOLOGIES, 2016)

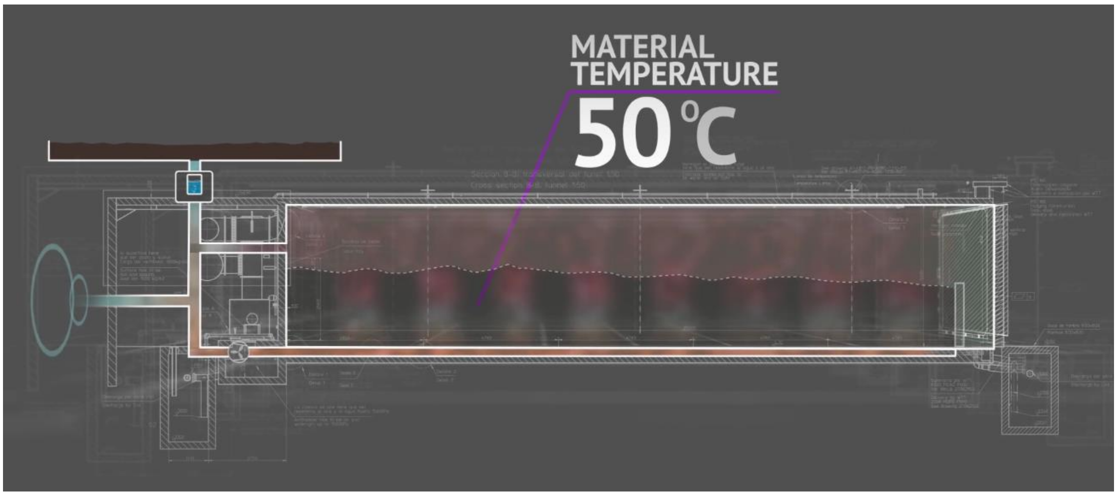


FIGURE 3: THE AERATION SYSTEM.
AIR FROM THE OUTSIDE OF THE BUNKER IS USED TO BLOW THROUGH THE MATERIAL. SO CALLED SPIGOTS (IN THE FLOOR EMBEDDED FACILITIES) ARE CONNECTED TO VENTILATION CHANNELS IN THE FLOOR. THESE SPIGOTS ARE USED TO BLOW THE AIR THROUGH THE CONCRETE FLOOR. AT THE TOP OF THE BUNKER THE AIR IS EXTRACTED AGAIN. A PART OF THE PROCESS AIR IS RE-USED; THE OTHER PART IS DISCHARGED (WASTE TREATMENT TECHNOLOGIES, 2016).

3.3. MATERIAL CHANGES

Concrete reacts in all sorts of ways on temperature. Zoomed in on micro level, the material undergoes physical and chemical changes when heated. It starts with slow water migration, cement paste dehydration and reduction of cohesion, as water evaporates and expands. These physical and chemical changes in the strength of the concrete depend on the water/cement ratio (w/c-ratio) and the concrete composition (Hager, 2013). The cement paste shrinks and aggregates expand, creating small cracks in the concrete. Because of these cracks, the concrete expansion, and thus the thermal strain, is non-linear. Besides that, the slope of the $\sigma(\varepsilon)$-graph becomes less steep, which indicates that the concrete becomes more elastic. This means that larger deformations can arise, when the same amount of force is applied (Hager, 2013). The slope of the $\sigma(\varepsilon)$ represents the modulus of elasticity (E) (Equation 1). When the σ decreases, the E decreases.

$$E\ [N/mm^2] = \frac{\sigma}{\varepsilon} \qquad (1)$$

When the temperature of the concrete exceeds 50°, the modulus of elasticity of the concrete (Ec), and thus the stiffness (EcI) of the concrete, decreases gradually. The amount of decrease depends on the types of aggregates used in the concrete (Breugel, Veen, & Walraven, 1996). The modulus of elasticity of the concrete can be calculated, using the characteristic strength (f'_{ck}, this is for example 35 when concrete type C35/45 is used) which depends on the type of concrete used (Equation 2). The moment of inertia (I) can be calculated for a rectangle by using the height (h) and width (w) (Equation 3).

$$Ec\ [N/mm^2] = 22{,}000 * \left(\frac{f'ck * 1.4}{10}\right)^{0.3} \tag{2}$$

$$I\ (rectangle)\ [m^4] = \frac{wh^3}{12} \tag{3}$$

Hager (2013) has tested three concrete samples with w/c-ratios of 0.3, 0.4 and 0.5. The output of the tests is, among others, the compressive strength of the three samples. The tests were performed at different temperatures and were performed while the samples were still hot. This is done to get a better insight in the concrete features, while concrete is still heated and not afterwards, when it is cooled down. Hager found that between the 20° and 120° the compressive strength of all three samples decreased between the 20% and 30%. At temperatures higher than 120° this percentage becomes lower, which means the compressive strength is decreasing ascending (Castillo, 1987). The decrease of compressive strength can cause a construction to fail, so construction companies need to include extra safety marges to overcome this decrease in compressive strength. The decrease of compressive strength can be explained by the water loss (hygral gradient), the reduction of cohesive forces and the appearance of supplementary stresses (Hager, 2013).

The tensile strenght of concrete is much smaller than the compressive strenght. The tensile strength can be calculated using Equation 4. The $fctm$ [N/mm^2] stands for the average tensile strength and the $f'ck$ [N/mm^2] stands for the characteristic cilinder compressive strength (the $f'ck$ for example is 35 N/mm^2 for the concrete type C35/45).

$$fctm = 0.30\ f'ck^{\frac{2}{3}} \tag{4}$$

Another cause of the appearance of cracks can be the different expansion coefficients of steel (αs = 12*10^{-6} [m/m°C]) and concrete (αc = 10*10^{-6} [m/m°C]) (Linden, Erdsieck, Gaalen, & Zeegers, 2013). The steel reinforcement expands quicker when heated than the concrete, which results in the appearance of cracks in the structure (Delincé & Parmentier, 2004).

3.4. Structural changes

When concrete is heated, it expands and if the expansion is blocked it creates compressive forces in the concrete. When it cools down again, it shrinks and creates tensile forces in the concrete. These forces have influence on the total concrete structure and in reverse the construction has influence on the individual structural elements. The effect of this expansion depends on the type of supports used. When a roller support is used, the volume expansion results in an extension of the structural element. In case the extension is obstructed by fixed supports, concrete expansion results in stress and deformations. This expansion of the concrete then creates axial forces (F), shear forces (R) and bending moments (M) in the construction. Temperature load results thus in extension or deformations, forces and bending moments (Breugel, Veen, & Walraven, 1996).

A roller support allows the concrete beam to expand, resulting in an extension. The extension can be calculated with Equation 6. The εt in the Equation 6. represents the strain caused by the temperature load (Equation 5). The αc represent the expansion coefficient of concrete and ΔT represents the temperature difference between the inside and the outside of the structural element (Breugel, Veen, & Walraven, 1996). This εt represents only the strain caused by the temperature; it doesn't include the strain cause by the physical load (εl), creep and relaxation ($\varepsilon cr,r$) and transitional thermal strain. These other factors are included in the εtot, which will be explained in the next Section *3.5. Creep, relaxation and transitional thermal strain*.

$$\varepsilon t\ [-] = \alpha c\ \Delta T \tag{5}$$

$$\Delta L\ [m] = L\ \varepsilon t = L\ \alpha c\ \Delta T \tag{6}$$

Stress (σt) and a resulting axial force arises in the concrete, when a fixed support blocks the expanding, caused by the temperature (Equation 7). The A in the formula represents the cross sectional area and the Ec represents the modulus of elasticity of the concrete (Breugel, Veen, & Walraven, 1996).

$$F\ [N] = A\ \sigma t = A\ Ec\ \varepsilon t\ = \ A\ Ec\ \alpha c\ \Delta T \tag{7}$$

When the temperature on one side of a concrete structure is higher than on the other side, the concrete expands and bends on the hot side. When the rotation is blocked by fixed supports, this can create a bending moment, forcing the structure to bend (Figure 4). The hot side then has to deal with compressive forces and the cold side with tensile forces. The exact size of the resulting forces and bending moments depends on the type of supports used. As can be seen in Table 2, the first mechanical system with one pinned and one roller support is the most favourable, because no forces or bending moments arise. The expansion of the concrete only results in an extension, as mentioned above (Equation 6). The system most practical to implement in concrete bunkers, and thus the most common mechanical system used, is the second mechanical system with two fixed supports. The third mechanical system is the least favourable, because it creates *and* a bending moment *and* shear forces (Sagel, Dees, Geest, & Braam, 2010).

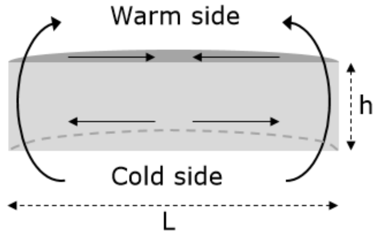
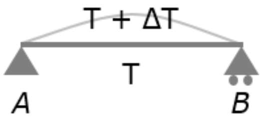
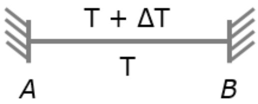
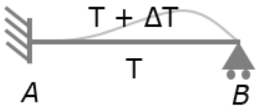


FIGURE 4: THE BENDING MOMENT CAUSED BY A TEMPERATURE DIFFERENCE. THE L REPRESENT THE LENGTH OF THE BEAM AND THE H REPRESENTS THE HEIGHT OF THE BEAM.

TABLE 2: POSSIBLE MECHNICAL SYSTEMS WITH CORRESPONDING BENDING MOMENTS (M) AND SHEAR FORCES (R). T [°] REPRESENTS THE TEMPERATURE; ΔT [°] REPRESENTS THE TEMPERATURE DIFFERENCE BETWEEN THE INSIDE AND OUTSIDE OF THE CONCRETE LAYER; L [M] REPRESENTS THE LENGTH OF THE BEAM; αc [M/M °C] THE THERMAL EXPANSION COEFFICIENT; EC I [NM²] REPRESENTS THE STIFFNESS OF THE BEAM; AND H [M] THE HEIGHT OR WIDTH OF THE BEAM (THE DISTANCE BETWEEN THE WARM AND THE COLD SIDE).

Mechanical system:			
Bending moment:	(8) $M\,[Nm] = 0$	(9) $Ma\,[Nm] = Mb = \frac{\varepsilon t\ Ec\ I}{h} = \frac{\Delta T\ \alpha c\ Ec\ I}{h}$	(10) $Ma\,[Nm] = \frac{3\ \varepsilon t\ Ec\ I}{2h} = \frac{3\ \Delta T\ \alpha c\ Ec\ I}{2h}$
Shear force:	(11) $R\,[N] = 0$	(121) $R\,[N] = 0$	(13) $R\,[N] = \frac{3\ \varepsilon t\ Ec\ I}{2h\ L} = \frac{3\ \Delta T\ \alpha c\ Ec\ I}{2h\ L}$

3.5. CREEP, RELAXATION AND TRANSITIONAL THERMAL STRAIN

The physical load on a concrete structure causes the construction to deform when pinned supports are used: strain (εl). When fixed supports are used, tension arises (σl). The strain can increase over time, due to the ageing of the concrete structure: creep. Creep is the gradual and permanent deformation of a material over time, caused by a permanent load. Temperature can speed up the creep process (Breugel, Veen, & Walraven, 1996).

The original strain, caused only by the load, can be multiplied with the creep coefficient (Φ). This results in the total strain caused by the load and creep (Equation 15). The creep coefficient depends on the concrete type, the humidity and the age of the concrete. There are two ways to determine the creep coefficient (linear and non-linear), depending on the compressive tension (σc) (European Committee for Standardisation, 2010).

If σc ≤ 0.45 f'_{ck}, the creep coefficient is assumed linear (Φlin) and Figure 5 applies. The thickness of the structural component and the concrete type intersect in the right graph. From there a horizontal line can be drawn to the left graph. Depending on the cement type, the Φlin can be determined.

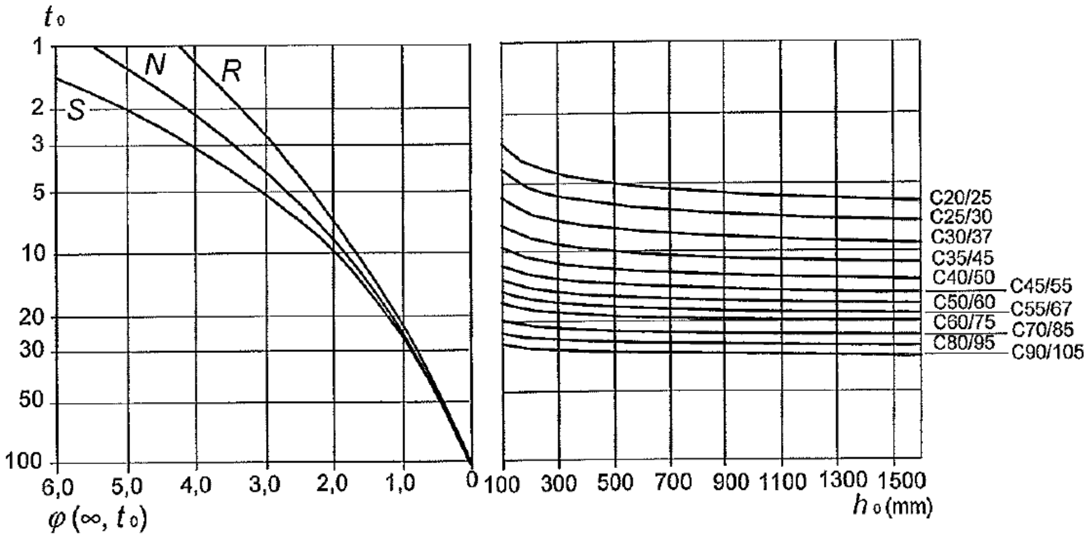


FIGURE 5: METHOD FOR DETERMINING THE CREEP COEFFICIENT (Φ) FOR CONCRETE IN NORMAL ENVIRONMENTAL CONDITIONS. REPRINTED FROM "NEN-EN 1992-1-1" BY EUROPEAN COMMITTEE FOR STANDARDISATION (P31).

If σc > 0.45 f'_{ck}, the creep coefficient is assumed non-linear (Φnonlin) and Equation 14 applies to calculate the non-linear creep coefficient (Φnonlin), using the linear creep coefficient (Φlin):

$$\Phi nonlin\ [-] = \Phi lin\ e^{1.5\ (k-0.45)}\ with\ k = \frac{\sigma c}{f'ck} \qquad (14)$$

$$\varepsilon l, cr\ [-] = \ \varepsilon l\ \Phi\ (lin\ or\ nonlin) \qquad (15)$$

Relaxation is the loss of tension after a material has been under tension for a while. This decrease in tension can be calculated using the relaxation coefficient (Ψ). The relaxation coefficient is calculated by using the linear or non-linear creep coefficient (Equation 16) (Breugel, Veen, & Walraven, 1996). The relaxation coefficient thus contains the creep *and* the corresponding relaxation. When multiplied with the original tension caused by the load, the total tension caused by the load, creep and relaxation is calculated (Equation 16 and 17).

$$\Psi(\Phi)\ [-] \ = \frac{1}{1 + \Phi\ (lin\ or\ nonlin)} \qquad (16)$$

$$\sigma l, cr, r\ [N/m^2] = \ \sigma l\ \Psi(\Phi) \qquad (17)$$

When the temperature of the concrete exceeds the 50˚, the creep deformation speed goes up. At the same time when a structural element with fixed supports is heated, transitional thermal strain will reduce the tension. The β is an experimentally derived factor representing the combined factor: transitional thermal strain (Equation 18) (Breugel, Veen, & Walraven, 1996).

$$\beta\ [^\circ] = \ 1 - \frac{\Delta T}{160} \qquad (18)$$

The strain the temperature causes (εt, from Section *3.4. Structural changes*), multiplied by the relaxation coefficient ($\Psi(\Phi)$) and the transitional thermal strain coefficient (β), results in the total strain (εtot) in Equation 19 (Breugel, Veen, & Walraven, 1996).

The εo represents the strain caused by the original load (thermal and other types of loading). The εtot takes the original load, creep, relaxation and transitional thermal strain into account by multiplying the original strain with all the coefficients (Equation 19).

$$\varepsilon tot\ [-] = \varepsilon o\ \frac{1}{1+\beta\Phi} \tag{19}$$

When fixed supports block the total strain, tension arises. The tension (σtot) (caused by the load, creep and relation and the transitional thermal strain) can be calculated by Equation 20 (Breugel, Veen, & Walraven, 1996).

$$\sigma tot\ [N/m^2] = Ec\ \varepsilon tot\ = Ec\ \varepsilon o\ \frac{1}{1+\ \beta\Phi} = Ec\ \alpha c\ \Delta T\ \frac{1}{1+\ \beta\Phi} \tag{20}$$

3.6. Temperature gradient

When the temperature changes equally on both sides of a structural element the average temperature changes accordingly. If only on one side of the structural element the temperature changes, the temperature difference creates a temperature gradient inside the structural component (Orosz, 1980). The temperature gradient inside a certain material layer depends on the heat transmission of that material layer. The heat transmission is the resistance of a material to let heat through. The total heat transmission and the heat transmission of a separate layer can be calculated using Equation 21 and Figure 6 (Orosz, 1980).

$$\mathrm{Rtotal}\ [m^2\mathrm{K/W}] = (\frac{1}{\mathrm{U}}) = \mathrm{Ri} + \mathrm{Rc} + \mathrm{Ro} = \frac{1}{\alpha\mathrm{i}} + \frac{\mathrm{h}}{\lambda} + \frac{1}{\alpha\mathrm{o}} \tag{21}$$

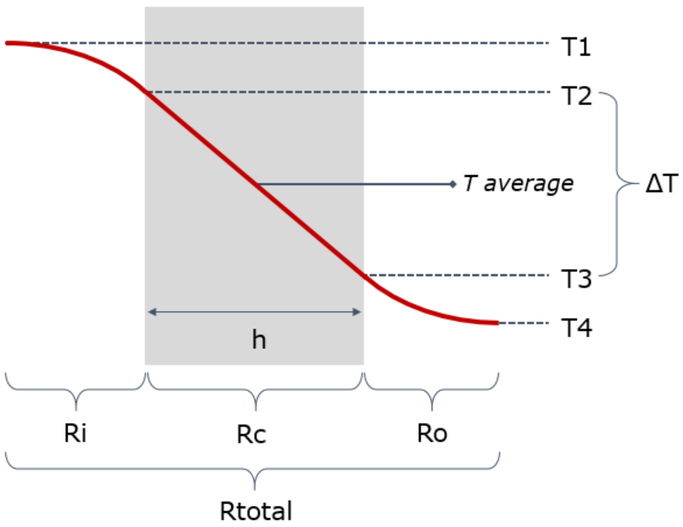


Figure 6: The temperature gradient in a structural element.

Rtotal [m^2K/W] represents the heat transmission of the whole structural component. The Ri and Ro are the inner and outer resistance arising on the inner and outer side of the material layer. The heat flow encounters here a resistance, depending on the surrounding environment. The $\alpha\mathrm{i}$ and $\alpha\mathrm{o}$ [W/m^2K] represent the inner and outer heat transmission coefficient.
Rc is the heat transmission of the material layer(s). A structural element can contain multiple material layers (for example concrete or insulation materials). In that case the Rc becomes $\mathrm{Rc1}$, $\mathrm{Rc2}$ and so forth. The h [m] represents the

thickness of the wall and λ [W/m°C] represents the resistance coefficient of the materials that form the structural component.

The temperature difference is distributed over the structural component by using the heat transmission of the material layers in the structural component and the inner and outer heat transmission ($\mathrm{Ri}, \mathrm{Rc}, \mathrm{Ro}$). Then temperature gradient per material layer can be calculated using so called weighted average in Equation 22 (Orosz, 1980). The temperature gradient over a material layer is represented by taking the inner and outer temperature of that material layer (in the case of one material layer is this T2 and T3 from Figure 6).

$$\Delta \mathrm{Tseperate\ layer}\ [^{\circ}] = \frac{\mathrm{Ri}\ or\ \mathrm{Ro}\ or\ \mathrm{Rc(1\ or\ 2)}}{\mathrm{Rtotal}} * (\mathrm{T1} - \mathrm{T4}) \qquad (22)$$

When these formulas are applied, the following assumptions are made (Orosz, 1980):

- Stresses and strains appearing in the material of a structural component, don’t *cause* temperature changes.
- Deformations present in the structural component are small enough to allow an analysis of the original form.
- Superposition is valid: the effects of several causes can be summed, when those effects appear at the same time. The causes and effects don’t influence each other.
- Thermal stresses are unaffected by shrinkage or creep.

As can be seen in Equation 22: the higher the R of a material layer, the higher the temperature gradient in that material layer. Insulation material has a high R, which results in a high temperature gradient in the insulation and a low temperature gradient in the other materials. Insulating a concrete wall results thus in a low temperature difference in the concrete.

4. RESEARCH PLAN

The problem context in this bachelor thesis is very broad, so this chapter tries to clarify the focus. The delimited part of the problem on which the focus will be, is: the influence of temperature gradients on a concrete composting bunker and the proposition of optimized solutions which will stop de over- and under-designing of the building companies. The given limitations are used to create a research aim which can be handled during the internship period.

4.1. Research aim

Out of the problem statement, two research goals are established. These two goals follow each other and each goal deals with a part of the problem statement. The first goal is to identify the problem, by looking at the over- and under-designing of the building companies and the most critical temperature scenarios. The second goal is to analyse the potential solutions in order to create optimized dimensions.

The large temperature differences is stated as main cause by Tauw and WTT. The theoretical framework confirms this. Using the dimensions and the corresponding calculations of the case study, the over- and under-designing will be reviewed. The different temperature gradients appearing in the structural elements of the case study bunkers will be listed and analysed. The most extreme temperature gradient scenario working on the case study bunkers will be modelled in the 3D program SCIA Engineer and the influence of the thermal load will be calculated. The results in SCIA Engineer are going to be used to get better insight in the calculations of the case study bunkers made by the building company Grotemeier Ingenieure (located in Bielefeld, Germany). This way the over- and under-designing will be researched.

The second goal is to analyse potential optimized solutions to prevent an uncontrollable appearance of cracks from appearing in the concrete housing of the composting systems. The objective is to analyse different temperature scenarios and to propose design solutions. Insulation will be first explored as a possible solution. The insulation will be optimized, using the tensile normal stress arising in the concrete bunkers as a criterion. Important to mention is that a case study will be used to draw general conclusions about the research. The effect of insulation as a solution will be studied by modelling the solution in the case study situation. From there, a general conclusion will be drawn about the effects and implementation of the insulation.

When no large delays occur in the planning, the bachelor thesis will be wrapped up to give WTT a way to fill the gap in the (communication) process with the building partners about their concrete composting bunkers. This will be done with a summary of my research, a conclusion and recommendations. WTT can use this to instruct their building companies about the concrete bunkers. With more knowledge about the processes in the bunker, the uncontrollable appearance of cracks and the possible solutions, the building companies can reduce the amount of materials they use now. These recommendations can be the first step to a template or detailed instruction manual in the future. The result will be a reduction of the material and cost.

4.2. Research questions

The two research goals are transformed into questions that are going to be answered. The results can be found in Chapter *6. Designing with critical temperature differences* and Chapter *7. Optimized solutions*.

Goal 1: *Look at the most critical situations related to the large temperature differences.*

- Research question 1:
  Which dimensions are over- or under-designed by the building companies and why?
  Answered in: Section *6.1. The over- and under-designed dimensions*.

- Research question 2:
  What are the possible temperature gradients appearing in the walls, roof and floor of the concrete bunkers?
  Answered in: Section *6.2. The temperature gradient scenarios.*

- Research question 3:
  How do the temperature differences influence the concrete bunkers?
  Answered in: Section *6.3. The influence of the thermal loading on the concrete bunkers.*

Goal 2: *Analyse potential optimized solutions to prevent an uncontrollable appearance of cracks from appearing in the concrete housing of the composting systems.*

- Research question 4:
  What solutions (insulation and constructive) can be investigated to decrease the stress in the concrete caused by the temperature differences?
  Answered in: Section *7.1. Possible solutions.*

- Research question 5: *How do these solutions stop the concrete from cracking uncontrollably?*
  Answered in: Section *7.2. First researched solution: insulation*.

The research will be summarized, so that WTT has a start in communicating with the building partners. The given recommendations can be the first step to a template or detailed instruction manual in the future.

4.3. Limitations

This problem topic stated by WTT contains many sub-problems. The internship will be completed in eleven weeks, so a clear focus is necessary. Several limitations are established to give a clear view on where the focus lies and which things won't be taken into account.

WTT has two types of systems placed in bunkers to deal with waste. This thesis will focus on the housing of the *composting* systems and thus not on the *anaerobic digestion*. This means the feedstock that will be turned into compost in the bunker, is natural and dry; it won't contain *highly* chemical material or be flammable.

The creation of possible solutions requires an analysis of the problem and an identification of the cause. WTT and Tauw, based on their experience, designate the large temperature differences as the main cause. This bachelor thesis will acknowledge their designation and will thus accept the large temperature differences as the main cause. The literature study is used to confirm this and determine the effects appearing in the concrete housing. The composting environment and the hydration of the concrete will thus be neglected as a cause for this bachelor thesis.

Because a case study in Swisttal, Germany is used in this bachelor thesis, the research will only apply to this case study. It needs to be kept in mind that this research can only examine a small part of the problem. In order to create recommendations, a general conclusion will be drawn from the research about this case study. Further investigation will have to confirm the general statements made.

5. METHODOLOGY

The research aim will be achieved using different methods. These methods are tools to answer the research questions which are defined in the research plan.

5.1. LITERATURE

A list with papers and reports used to prepare for the research can be found in Chapter *10. Reference list*. This list is used in creating Chapter *3. Theoretical framework*. This chapter summarizes the composting process, the influence of temperature differences on concrete and temperature gradients in concrete housing. Besides this, the literature list also contains documents from WTT with data and specifications in general about the concrete composting bunkers and about the specific case study in Swisttal.

5.2. CASE STUDY

In the summer of 2017 a concrete composting bunker in Swisttal, Germany, is being built. This bunker in Swisttal will be used as case study (Figure 7). The case study will serve as an example to get the information necessary to perform the research, like the measures and materials used in the bunker.

FIGURE 7: THE CASE STUDY SITE CALLED KOMPOSTWERKE RHEIN-SIEG (KRS) IS LOCATED IN SWISTTAL, GERMANY. THE EXISTING SITE WILL BE EXPANDED WITH A DELIVERY AND LOGISTICS BUILDING AND NINE NEW COMPOSTING BUNKERS. THESE NINE COMPOSTING BUNKERS WILL BE USED AS A CASE STUDY. REPRINTED FROM WASTE TREATMENT TECHNOLOGIES WEBSITE (PAGE: PROJECT ANNOUNCEMENT: SWISTTAL-MIEL – GERMANY – NEW TUNNEL COMPOSTING FACILITY, N.D.).

The research questions will be answered using the case study in Swisttal, Germany. This means the case study will be implemented in the modelling program SCIA Engineer. For this the dimensions, materials and other data about the case study will be used to model the concrete composting bunkers that are now being built in Swisttal. The solutions will also be implemented in this case study. Based upon the analysis and results from the case study, a general statement will be made about the concrete composting bunkers. Especially the potential optimized solutions must be suitable to be implemented in other composting bunkers, other than the case study. This means a general statement about the implementation of the possible solutions is going to be made.

5.3. Modelling program: SCIA Engineer

The information from the case study will be used to simulate the processes in the bunker. The program which is going to be used for this is called SCIA Engineer (version 16.1). SCIA Engineer is a 3D simulation FEM program used by Tauw in order to model structures for analysing bending moments, forces and deformations. The bunker located in Swisttal, Germany will be modelled in SCIA Engineer and the most critical temperature gradients will be implemented as loads. The forces, deformations and stresses arising are calculated with SCIA Engineer. The implementation of the solutions will also be modelled in SCIA Engineer. SCIA Engineer is thus used to get insight in the effects of temperature differences on and implemented solutions in the case study bunkers.

6. DESIGNING WITH CRITICAL TEMPERATURE DIFFERENCES

The building companies of WTT have to design concrete bunkers for a composting environment. The building companies each deal in a different way with the arising temperature differences, because there isn't a template available on how to take the thermal load into account. First, two manuals and one report are going to be compared to each other in order to find the problems occurring in the communication and the way of designing. After that the influence of the temperature is further researched. All the possible temperature scenarios are going to be listed and the belonging temperature gradients are going to be calculated. Then the influence of the most extreme temperature gradients on the concrete are modelled and calculated.

6.1. THE OVER- AND UNDER-DESIGNED DIMENSIONS

The over- or under-designing is analysed, using the two manuals and the one report given by WTT. WTT has a general manual they give to their building partners. This manual contains the information, which the building companies need to know about the composting system and the other type of waste treatment system WTT produces: anaerobic digestion. It also gives some broad guidelines about the building specifications. WTT also has a specific manual for the case study bunkers in Swisttal, Germany. In here the minimum requirements the building companies have to meet, are given.
The calculation report of the composting bunkers in Swisttal is analysed by looking at over- or under-designing by the building company Grotemeier Ingenieure.

The dimensions of the case study bunkers are taken over from the calculation report. The loads working on the construction, including the thermal load, are determined using the Eurocode. The results can be found in Subsection *6.1.4. Layout and dimensions case study bunkers* and Section *6.2. The temperature gradient scenarios*. In the conclusion the differences between the loads calculated by Grotemeier Ingenieure and calculated in this bachelor thesis are going to be compared, to spot over- and under-designing.

6.1.1. GENERAL MANUAL

WTT has a general manual, containing general information for the building companies about the project and machines that will be implemented by WTT in the composting *and* anaerobic digestion (AD) bunkers. There are also some broad guidelines about the building specifications given in the general manual for the building companies. In Table 3 the building specifications for the *composting* bunkers are given.

TABLE 3: THE GUIDELINES GIVEN BY WTT IN THEIR GENERAL MANUAL FOR THE COMPOSTING BUNKERS.

General requirements	Value
Minimum type concrete: Floor	C35/45; F3; XS3, XD3, XA3
Minimum type concrete: Wall	C35/45; F3; XC4, XS3, XD3, XA3, XF2, XF3
Wall thickness	≥ 0.30 m
Crack width (Wmax)	< 0.10 mm
U-value of the insulation on the floor, roof, outer walls	≤ 0.25 W/m^{2}K

This general manual is an attempt by WTT to give their building partners some guidance in building these composting and anaerobic digestion (AD) concrete bunkers. The information about the machines and the project is extensive, but not specifically directed at the information civil engineers need to design the concrete bunkers. This results in over- and under-designing of the bunkers and the broad guidelines given by WTT aren't sufficient enough to prevent this.

The consistency class of concrete represents the processability of the concrete slab (*F3* in Table 3). This is prescribed by WTT, but it is wiser to leave this decision to the building company (B. Van Ens, personal communication, April 25, 2017). The consistency class depends on the circumstances of the project and the construction site, so the building companies are in the most suitable position to choose the best consistency class.

WTT advises many different types of exposure classes. A lot of different exposure classes are advised, because WTT operates all over the world and thus needs to take all sorts of climate conditions into account. If WTT would explain when and why they advise certain exposure classes, it gives the building companies the opportunity to apply the right exposure class in the right climate and in the right project.
In this explanation the difference between the classes XD, XS, XC and XF, XA should be mentioned. XD, XS, XC are used to protect the reinforcement, while XF, XA are used when even the concrete need to be protected (B. Van Ens, personal communication, April 25, 2017).

The given crack width of 0.10 mm is the strictest requirement possible for the crack width (NEN-EN 1992-1-1). By explaining *why* the strictest norm needs to be met, the building companies know how to design their construction. They can understand why cracking is such a problem and how it is caused.

6.1.2. CASE STUDY MANUAL

WTT also creates a specific manual per project and thus also one has been created for the case study in Swisttal. The specific manual of the case study contains information about the composting system and machines (Table 4). They also give some guidelines about the building specifications.

TABLE 4: THE GUIDELINES GIVEN BY WTT IN THEIR SPECIFIC MANUAL FOR THE CASE STUDY IN SWISTTAL, GERMANY.

Case study requirements	Value
Composting tunnel (Roof, Inner wall, Outer wall)	
Minimum type concrete	C35/45; XC4, XA3 (uncoated), XF1, XD1
Crack width	≤ 0.15 mm
Thickness structural element	≥ 300 mm
ΔT	80 (70 inside compost, -10 outside)
Spigot floor	
Minimum type concrete	C35/45; XC4, XA3 (uncoated), XM2
Crack width	≤ 0.15 mm
Thickness structural element	≥ 250 mm
ΔT	80 (70 inside compost, -10 outside)
Back wall	
Minimum type concrete	C30/37; XC4, XA2, XF1
Crack width	≤ 0.20 mm
Thickness structural element	≥ 300 mm

These guidelines are a bit more specific than the guidelines in the general manual, but they still leave a lot of room for the building company to design in. A more important problem is that the general guidelines and the case study guidelines don't match. The concrete type of the back wall is in the case study manual weaker than in the general manual. Also, the allowed exposure class and the allowed crack width don't match. The crack width of 0.15 mm isn't even a possible requirement mentioned in the NEN-EN norms.

6.1.3. CASE STUDY CALCULATION REPORT

With the calculation report about the case study in Swisttal, there is looked at the calculation of the dimensions by the building company Grotemeier Ingenieure. The parameters they have used in their calculation can be found in Table 5.

TABLE 5: THE PARAMETERS USED IN THE CALCULATION MADE BY GROTEMEIER INGENIEURE FOR THE NINE CASE STUDY BUNKERS IN SWISTTAL, GERMANY.

Case study	Value
Forces	
Own weight	*Calculated by hand.*
Density feedstock With a maximum height	850 kg/m^3 4.0 m
Percolation liquid	*None*
Machines	*Taken from a drawing.*
Snow	650 N/m^3
Wind	580 N/m^2
Life load on the roof	4,000 N/m^2
Temperature	
Bunker (filled)	70 $^\circ$C
Bunker next door (empty)	30 $^\circ$C
Outside	-12 $^\circ$C
Hall	-5 $^\circ$C
Ground	-10 $^\circ$C
Insulation (only placed on outer walls)	
Heat resistance coefficient	0.04 W/m$^\circ$C
Thickness	0.08 m
Other parameter	
Crack width	0.20 mm

There is a difference between the general manual and the calculation manual in the crack width. The crack width of 0.20 N/mm in the calculation report is larger than the one allowed in the general manual *and* in the case study manual (which thus also both don't correspond completely with each other). The temperatures used by Grotemeier Ingenieure are going to be compared to the temperatures used in this bachelor thesis, taken from the Eurocode (the next Subsection *6.1.4. Layout an dimensions case study bunkers*).

6.1.4. LAYOUT AND DIMENSIONS CASE STUDY BUNKERS

The case study composting bunkers are built on the site called Kompostwerke Rhein-Sieg (KRS) located in Swisttal, Germany. The existing site will be expanded with a delivery and logistics building and nine new composting bunkers. This will enlarge the capacity of Kompostwerke Rhein-Sieg with 26 * 10^6 kg per year.

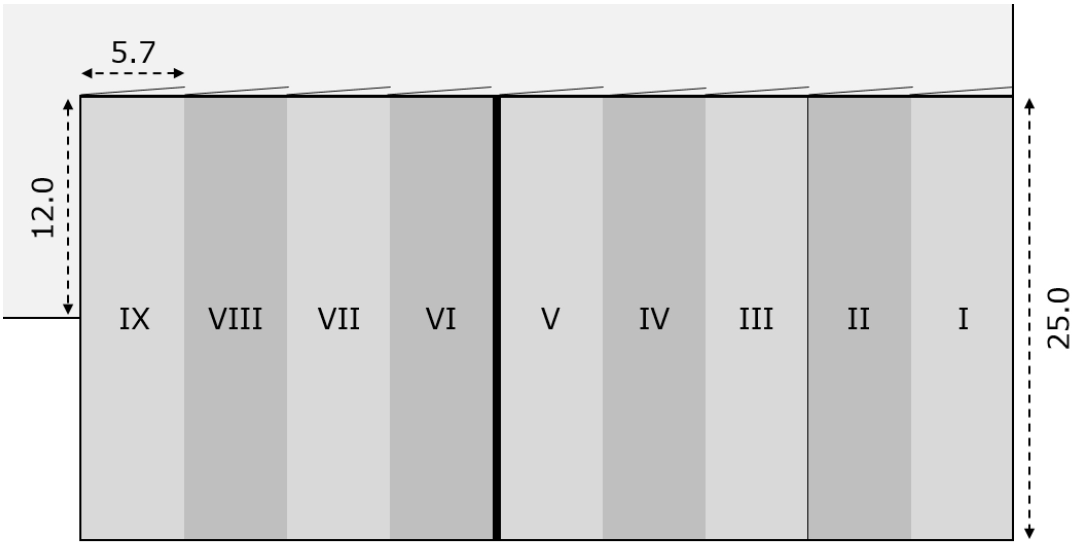


FIGURE 8: THE NINE COMPOSTING BUNKERS ARE PARTIALLY BUILD INSIDE A LARGE HALL. THE INNER WALL BETWEEN BUNKER V AND VI IS TWICE AS LARGE AS THE NORMAL INNER WALL. IN THE DRAWING, THE DOORS ARE LOCATED AT THE TOP OF THE BUNKERS AND THE BACK WALLS ARE THUS LOCATED AT THE BOTTOM OF THE DRAWING. THE BACK WALLS ARE SOMETIMES MENTIONED AS A SEPARATE STRUCTURAL ELEMENT, BUT THEY ARE PART OF THE OUTER WALLS.

A top view on the nine composting bunkers is given in Figure 8. The case study in Swisttal contains nine composting bunkers, which will all be built in the summer of 2017. The bunkers are partially placed inside a large hall and partially outside. The dimensions calculated by Grotemeier Ingenieure for the case study can be found in Table 6. The outer walls are a little bit thicker than the inner walls. The inner wall between bunker V and VI is twice as thick as the other inner walls. The floor consists of two parts: the basic constructive concrete floor (0.30 m) and the concrete spigot floor (0.29 m). The total thickness of the floor (0.59 m) will be used in calculating the temperature gradients and only the basic constructive floor (0.30 m) will be used in calculating the stresses and forces with SCIA Engineer arising in the concrete bunkers.

TABLE 6: DATA ABOUT THE CASE STUDY BUNKERS IN SWISTTAL, GERMANY. THE DIMENSIONS ARE GIVEN BY THE CIVIL BUILDING COMPANY OF THE SWISTTAL COMPOSTING BUNKERS (BEKON GMBH, 2017A, 2017B, 2017C).

Dimensions of case study Swisttal	Value
General dimensions	
Amount bunkers	9
Height bunker (internal)	5.0 m
Width bunker (internal)	5.7 m
Length bunker (internal)	25.0 m
Thickness	
Inner wall	0.30 m (2 * 0.30 m between V and VI)
Outer wall	0.40 m
Door	0.20 m
Floor	0.59 m (0.30 m concrete + 0.29 m spigot floor)
Roof	0.28 m

Bunkers II, III, IV, VII and VIII have the same characteristics and dimensions, so the results from one of these bunkers are equal to the results calculated in the other bunkers. The same applies to bunker V and VI. However, bunker IX and I are both different. To simplify the amount of calculations only these four bunker types are going to be used (II, III, IV, VII or VIII; and V or VI; and IX; and I).

Besides the dimensions, also the loads need to be implemented in order to get a clear view on the case study situation. The forces caused by the loads are calculated. Later on these forces are used to see the total influence of the loads (thermal and the rest) on the composting bunkers. The following loads are working on the case study bunkers and need to be taken into account:

1. Own weight of the concrete construction.
2. The weight of the content: the feedstock and the percolation liquid. This works vertically on the floor.
3. The machines of the composting system. The machines are placed on the roof of the bunkers.
4. The thermal loads on the walls, floor and roof. The temperature gradients causing the thermal load are going to be determined in Section *6.2. The temperature gradient scenarios*.
5. The snow load.
6. The wind load.
7. The live load, such as people walking on the roof.

Numbers 1 and 3 are always present and are called permanent loads. The remaining numbers are variable loads. Numbers 2 and 4 are always appearing at the same time, while 5, 6 and 7 can appear at different times *and* at the same time. The calculation of size of the forces and the given locations can be found in Chapter *12. Appendix B: Calculation of the forces working on the case study bunkers*.

Besides the temperature inside the bunkers, WTT doesn't give any indication about the other temperatures that need to be used in the calculation of the thermal load. This bachelor thesis will use the temperatures from Table 7 that are taken from NEN-EN 1991-1-5 and the belonging National Appendix.

TABLE 7: THE TEMPERATURES USED IN THE CALCULATIONS FOR THE CASE STUDY USED IN THIS BACHELOR THESIS (TAKEN FROM NEN-EN 1991-1-5)

Temperatures	
Bunker (filled; during an error)	85 °C
Bunker next door (empty)	17 °C
Outside	-25 °C
Hall	17 °C
Ground	10 °C

There a major differences between the temperatures used by Grotemeier Ingenieure and the temperatures used in this bachelor thesis (based on the Eurocode). Even the temperature inside the bunkers, given by WTT, is different. Grotemeier Ingenieure has taken the temperature inside the bunker during the hygienisation phase (75 °C), while this bachelor thesis has used the temperature inside the bunker when an error occurs (85 °C) as maximum temperature. The temperature during an error is higher and has thus a larger influence on the construction, but also occurs less often.
The assumed temperature for the bunker next door (empty) and the assumed outside temperature by Grotemeier Ingenieure are also lower than the temperatures used by this bachelor thesis. However, the temperature inside the hall and in the ground are higher. There are thus a lot of differences between the temperatures used by Grotemeier Ingenieure and the temperatures given by the Eurocode. It is remarkable that some temperatures are higher and some lower. There is no pattern in the differences between temperatures used by Grotemeier Ingenieure and the temperatures given by the Eurocode.

6.1.5. CONCLUSION RESEARCH QUESTION 1

There are many differences between the three analysed reports and manuals. In the first place, the guidelines given in the manuals are broad. There's no explanation on why certain requirements are given by WTT. Specific guidelines need to be given and they need to be explained. These specific guidelines can contain different options the building companies can choose from. With help of the explanation given by WTT, they can choose the right options for their specific circumstances. Also the manuals need to match with each other. For example, the general and the specific manual can be integrated and adapted per project. This way there is no repetitions in the two document that can cause confusion.

The loads calculated in this bachelor thesis (given in Chapter *12. Appendix B: Calculation of the forces working on the case study bunkers*) follow the Eurocode. A few differences have been noticed between the forces calculated by Grotemeier Ingenieure and the forces calculated in this bachelor thesis. The snow load is negligibly different and the force caused by the percolation liquid isn't taken into account by Grotemeier Ingenieure. This is however also a negligible force.
As life load Grotemeier Ingenieure has a value twice as high as calculated in the appendix. There is also a difference in the way Grotemeier Ingenieure calculated the wind force. This bachelor thesis has placed the wind force on one long and one short side of the construction (the whole nine composting bunkers). Grotemeier Ingenieure has done the same, but besides that they also added a pulling wind force on the walls perpendicular to the wind direction and a pulling

wind force on the wall opposite of the wall on which the pushing wind force works.

The major ambiguities arise when it comes to the temperatures. WTT gives the temperatures arising in the bunker to the building companies, but other temperatures have to be estimated by the building companies self. The differences between the calculation report of Grotemeier Ingenieure and the temperatures used in this bachelor thesis (taken from the Eurocode) can be found in Table 8. The temperatures inside the empty bunker next door and the outside temperature are estimated higher by Grotemeier Ingenieure while the temperature inside the hall and the ground temperature are lower.
There are even different temperatures used as temperature inside the filled bunkers (75 °C and 85 °C), while this information is provided by WTT. This may be related to the fact an error (85 °C) occurs only several times a year, so Grotemeier Ingenieure may have neglected this temperature because of that. Further research needs to point out of this simplification can be accepted. Measurements need to be taken to indicate the real temperatures that the building companies need to take into account.

TABLE 8: THE DIFFERENT TEMPERATURES USED BY GROTEMEIER INGENIEURE AND IN THIS BACHELOR THESIS.

Temperature	Grotemeier Ingenieure	Bachelor thesis
Bunker (filled; during an error)	70 °C	85 °C
Bunker next door (empty)	30 °C	17 °C
Outside	-12 °C	-25 °C
Hall	-5 °C	17 °C
Ground	-10 °C	10 °C

6.2. The temperature gradient scenarios

The concrete composting bunkers of WTT have to deal with temperature gradients appearing in the roof, outer wall, floor and inner wall. The temperature, and with that the temperature gradient, varies and creates different scenario's, depending on the season, the thickness of the construction part and the schedule of the feedstock (is the bunker filled with compost or not).

First, all the possible temperature gradient scenarios are listed. These scenarios are applicable in general, so these scenarios apply to all the composting bunkers of WTT over the world, apart from their location. Next, the temperature gradients are calculated using equations from Section *3.5. Creep, relaxation and transitional thermal strain*. The values for the parameters are taken from NEN-EN 1991-1-5 (including national appendix). The *general* scenarios are used to calculate all the temperature gradients appearing in the *case study* bunkers in Swisttal. Because the thickness differs per structural element (roof, outer wall, floor, inner wall), the temperature gradient differs per structural elements. So all the temperature gradients appearing the different structural elements from the case study composting bunker are calculated. Eventually one normative temperature scenario is chosen. Using this one temperature normative scenario, the influence of the most extreme temperature gradients on the concrete is researched.
This so called normative temperature *Scenario 1 Extreme* occurs only several times a year. Because this scenario is rare, the most extreme *common* temperature scenario (Scenario 2) is given too, so that Scenario 1 Extreme can be placed in perspective by the reader.

6.2.1. All possible scenarios

In Table 9, Table 10 and Table 11 all the possible temperature scenarios occurring in a concrete composting bunker can be found. Table 9 portrays that the bunker where the focus lies on is empty. Table 10 portrays all the scenarios where the bunker is filled with feedstock and processing it to compost. Table 11 portrays all the scenarios were an error has occurred and the temperature inside the bunker reaches a maximum.

The columns of the tables represent the outside climate situation: summer, winter or the composting bunkers are placed inside a large hall, whereby the influence of the outer climate is restricted. The rows (a to i) of the tables represent the situation in the composting bunker next door (the numbering of the rows continues in all three tables). This bunker next door can find itself in the same three possible situations as the bunker the focus lies on in the scenario: empty, during composting process and during an error.
Every scenario is indicated, using two letters: an uppercase letter (from the column) and a lowercase letter (from the row). For example: I want to indicate the scenario where it is winter; the bunker with the focus on it is empty, while its neighbour is full and in the middle of the composting process. This is scenario B-b (from Table 9).

In Table 9, Table 10 and Table 11 some repetition can be seen in the scenarios. This repetition arises, because all the different temperature gradients arising in one structural element can be combined with all the different temperature gradients arising the other structural elements. This results in the twenty-seven different combinations and thus twenty-seven different scenarios.

Table 9: The possible temperature scenarios that can appear when the right bunker is empty.

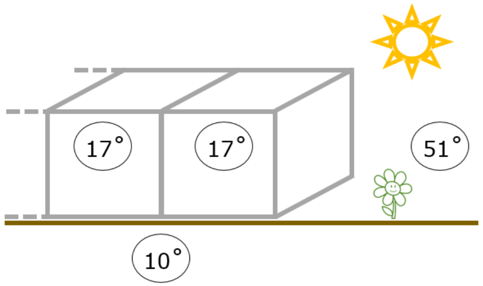
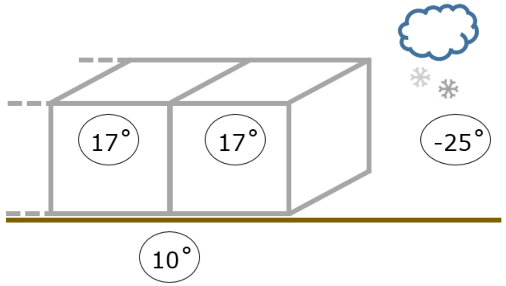
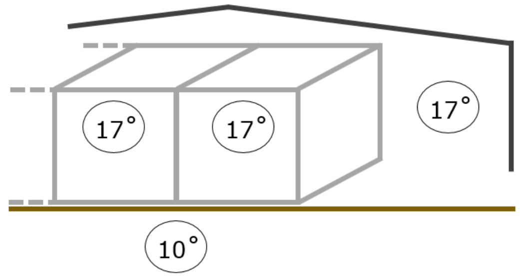
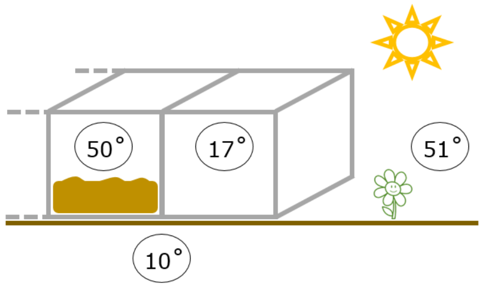
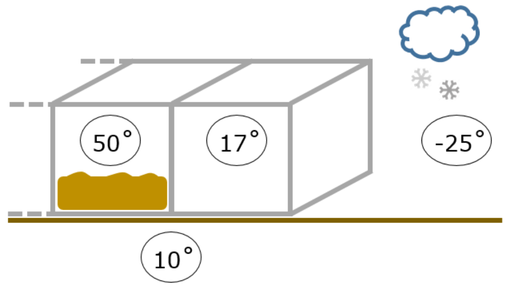
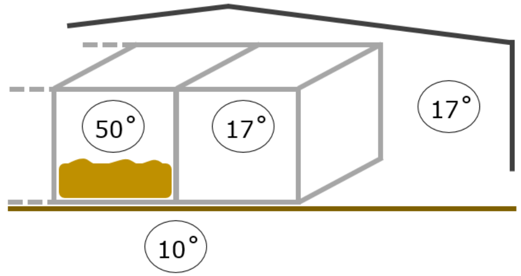
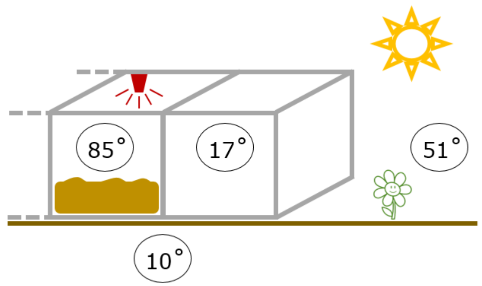
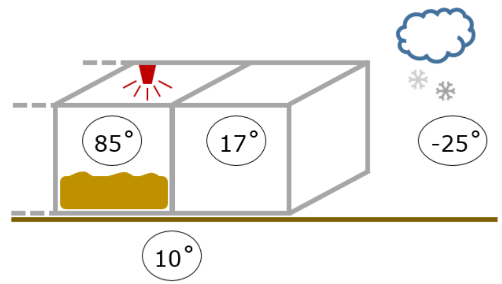
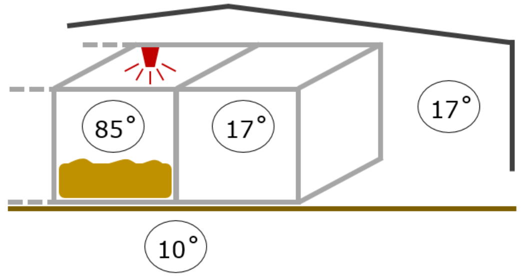
<table>
<tr><th colspan="4">Empty bunker</th></tr>
<tr><th></th><th>A – Summer</th><th>B – Winter</th><th>C – Inside large hall</th></tr>
<tr><td>a</td>
<td></td>
<td></td>
<td></td></tr>
<tr><td>b</td>
<td></td>
<td></td>
<td></td></tr>
<tr><td>c</td>
<td></td>
<td></td>
<td></td></tr>
</table>

TABLE 10: THE POSSIBLE TEMPERATURE SCENARIOS THAT CAN APPEAR IN THE RIGHT BUNKER DURING THE COMPOSTING PROCESS.

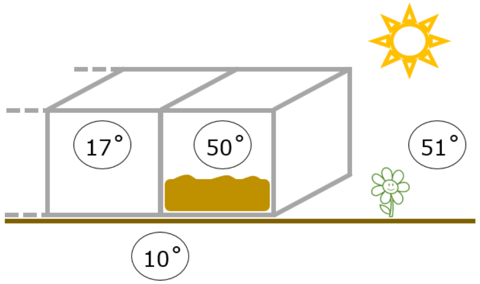
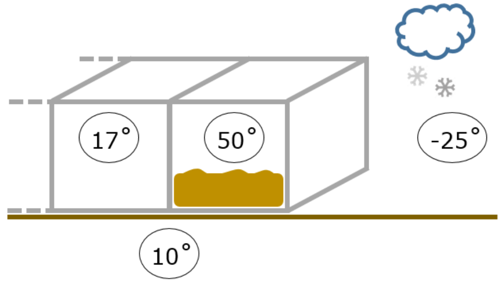
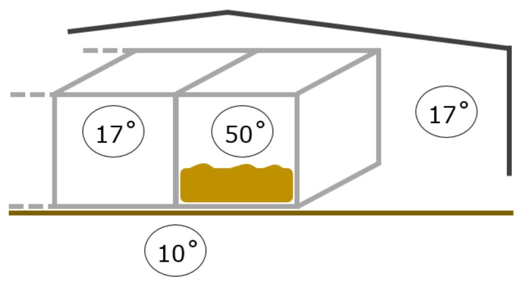
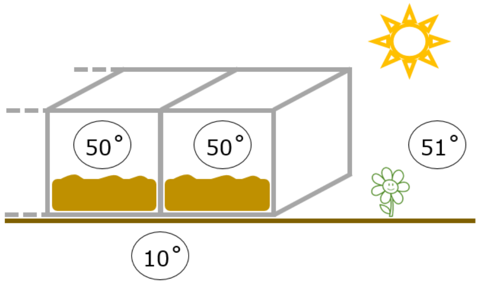
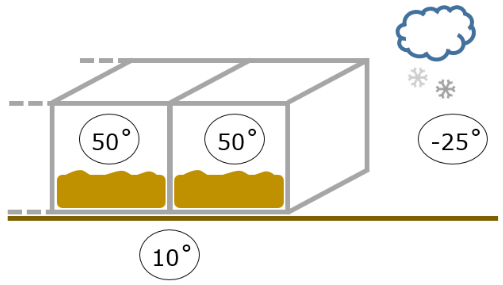
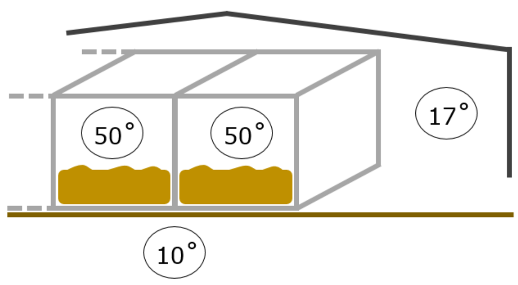
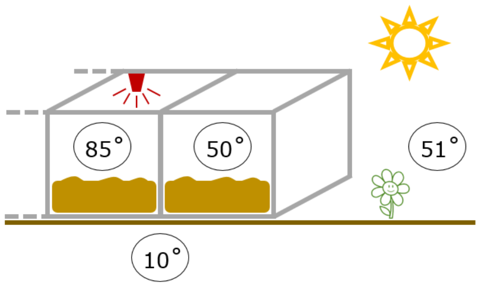
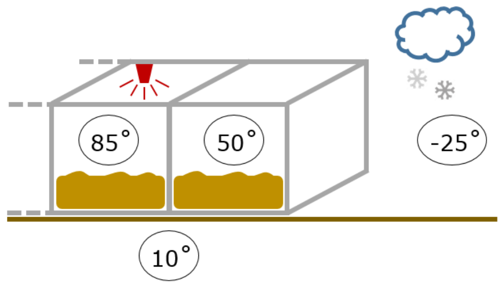
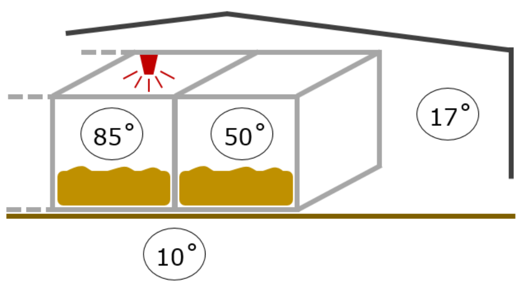
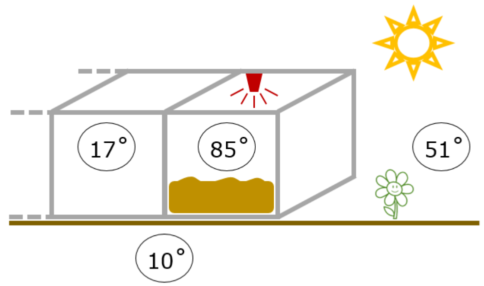
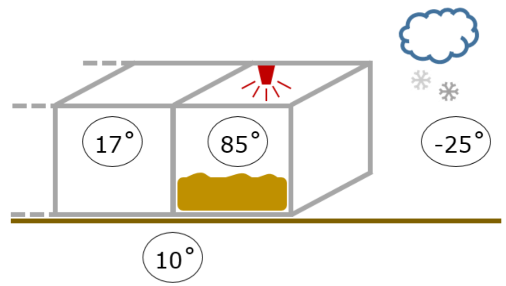
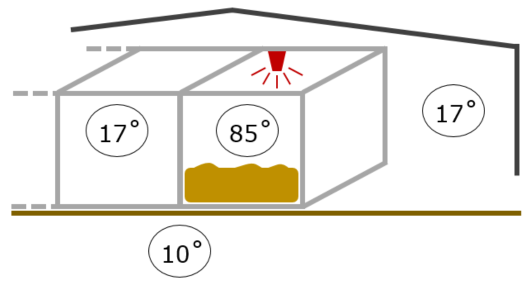
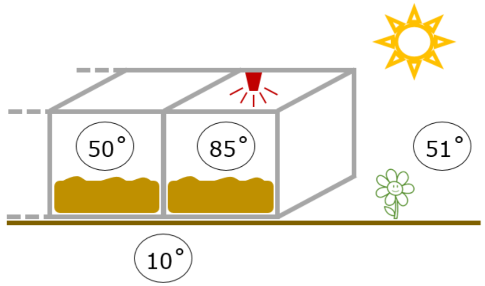
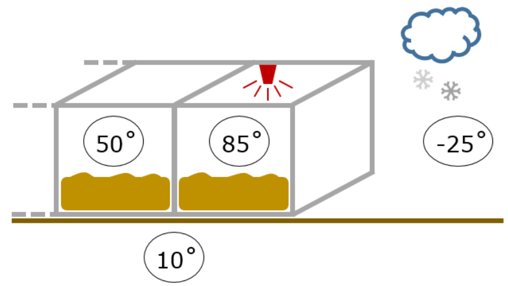
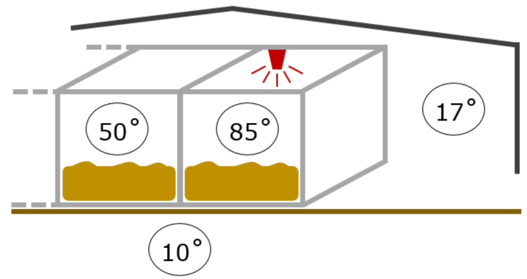
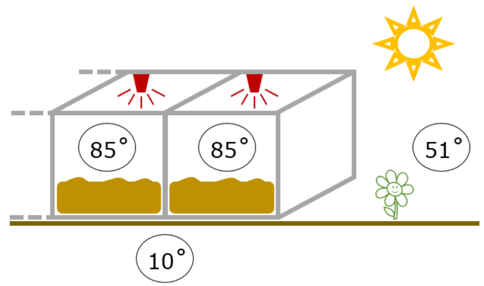
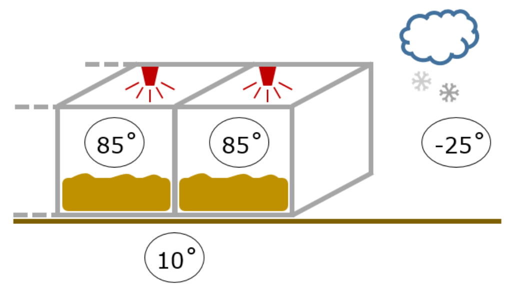
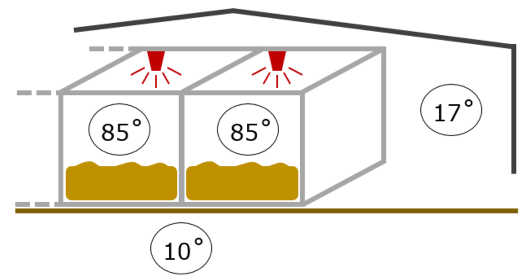
	During composting process		
	A – Summer	**B – Winter**	**C – Inside large hall**
d			
e			
f			

TABLE 11: THE POSSIBLE TEMPERATURE SCENARIOS THAT CAN APPEAR IN THE RIGHT BUNKER DURING AN ERROR.

<table>
<tr><th colspan="4">During an error</th></tr>
<tr><th></th><th>A – Summer</th><th>B – Winter</th><th>C – Inside large hall</th></tr>
<tr><td>g</td>
<td>
</td>
<td>
</td>
<td>
</td></tr>
<tr><td>h</td>
<td>
</td>
<td>
</td>
<td>
</td></tr>
<tr><td>i</td>
<td>
</td>
<td>
</td>
<td>
</td></tr>
</table>

The gradients appearing in the structural elements (roof, outer wall, floor, inner wall) are sorted per structural element and listed again in Table 12, Table 13 and Table 14. In the captions above to the tables is explained were the normative temperatures come from.

TABLE 12: THE TEMPERATURE DIFFERENCE SCENARIOS THAT CAN APPEAR IN THE ROOF OR OUTER WALL. THE TEMPERATURES INSIDE THE COMPOSTING BUNKER (EMPTY, DURING COMPOSTING PROCESS AND DURING AN ERROR) ARE GIVEN BY WTT. THE TEMPERATURES FOR THE SUMMER, WINTER AND INSIDE A LARGE HALL ARE GIVEN BY NEN-EN 1991-1-5 NATIONAL APPENDIX.

Roof or Outer wall			
Outer side / ***Inner side***	A – Summer	B – Winter	C – Inside large hall
Table 9 – Empty bunker	17° to 51° *A-a, A-b, A-c*	17° to -25° *B-a, B-b, B-c*	17° to 17° *C-a, C-b, C-c*
Table 10 – During composting process	50° to 51° *A-d, A-e, A-f*	50° to -25° *B-a, B-b, B-c*	50° to 17° *C-a, C-b, C-c*
Table 11 – During an error	85° to 51° *A-g, A-h, A-i*	85° to -25° *B-a, B-b, B-c*	85° to 17° *C-a, C-b, C-c*

TABLE 13: THE TEMPERATURE DIFFERENCE SCENARIOS THAT CAN APPEAR IN THE FLOOR. THE TEMPERATURES INSIDE THE COMPOSTING BUNKER (EMPTY, DURING COMPOSTING PROCESS AND DURING AN ERROR) ARE GIVEN BY WTT. THE TEMPERATURE FOR THE GROUND IS GIVEN BY NEN-EN 1991-1-5 NATIONAL APPENDIX.

Floor	
Outer side / ***Inner side***	Ground
Table 9 – Empty bunker	17° to 10°
Table 10 – During composting process	50° to 10°
Table 11 – During an error	85° to 10°

TABLE 14: THE TEMPERATURE DIFFERENCE SCENARIOS THAT CAN APPEAR IN THE INNER WALL. THE TEMPERATURES INSIDE THE COMPOSTING BUNKER (EMPTY, DURING COMPOSTING PROCESS AND DURING AN ERROR) AND INSIDE THE ADJACENT BUNKER (EMPTY, DURING COMPOSTING PROCESS AND DURING AN ERROR) ARE GIVEN BY WTT.

Inner wall			
Adjacent bunker / ***Inner side***	a, d, g – Empty bunker	b, e, h – During composting process	c, h, i – During an error
Table 9 – Empty bunker	17° to 17° *A-a, B-a, C-a*	17° to 50° *A-b, B-b, C-b*	17° to 85° *A-c, B-c, C-c*
Table 10 – During composting process	50° to 17° *A-d, B-d, C-d*	50° to 50° *A-e, B-e, C-e*	50° to 85° *A-h, B-h, C-h*
Table 11 – During an error	85° to 17° *A-g, B-g, C-g*	85° to 50° *A-h, B-h, C-h*	85° to 85° *A-i, B-i, C-i*

6.2.2. EQUATIONS AND PARAMETERS

The temperature gradients appearing in the structural components are calculated using Equation 21 and Equation 2 (see also Figure 6 mentioned in Section *3.5. Creep, relaxation and transitional thermal strain*)

$$\text{Rtotal}\ [m^2\text{K/W}] = (\frac{1}{\text{U}}) = \text{Ri} + \text{Rc} + \text{Ro} = \frac{1}{\alpha\text{i}} + \frac{\text{h}}{\lambda} + \frac{1}{\alpha\text{o}} \quad (21)$$

$$\Delta\text{Tseperate layer}\ [^\circ] = \frac{\text{Ri}\ \mathit{or}\ \text{Rc}\ \mathit{or}\ \text{Ro}}{\text{Rtotal}} * (\text{T1} - \text{T4}) \quad (22)$$

The parameters from the equations are explained below. The values for the parameters in different scenarios can be found in Table 15 and Table 16.

- Ri [m^2K/w]:
  This value depends on the material on the inside of the structural element; so inside the bunker. The material on the inside can be either air, when the bunker is empty, or compost, when the composting process is in progress or when an error occurs. Because compost resembles a combination of water and ground, the R belonging to ground & water is taken as the Ri of compost from NEN-EN 1068. The value of air depends on whether the air find itself inside or outside a building, where airflow lowers the Ri-value.
- Ro [m^2K/w]:
  This value depends on the material outside the structural element. The outside can consist of air, compost (when the outside finds itself inside a bunker next door in case of an inner wall) or ground (when the structural element is a floor). Also here depends the value of air on whether the air find itself inside or outside a building.
- λ [W/m°C]:
  Depends material of the structural element. The structural elements now only contain concrete. Later on, when insulation is explored as a solution, the values for the used insulation also need to be used here too.

- h [m]:
  The thickness of the structural element. The possible structural elements are: inner wall, outer wall, floor and roof (these can also be found in Table 12, Table 13 and Table 14).

TABLE 15: THE VALUES OF THE MATERIAL RELATED PARAMETERS. THESE ARE USED TO CALCULATE THE TEMPERATURE GRADIENTS APPEARING IN THE CASE STUDY BUNKER IN SWISTTAL. THE RI AND RO AND TAKEN FROM NEN-EN 1068.

Parameter	Material	Value	Scenario
Ri	Air (inside): Compost (water & ground):	0.13 m^2K/w 0.00 m^2K/w	Table 9 Table 10 and Table 11
Ro	Air (outside): Air (inside): Ground: Compost (water & ground):	0.04 m^2K/w 0.13 m^2K/w 0.00 m^2K/w 0.00 m^2K/w	Columns A & B Row a, d and g All scenarios Row b, c, e, f, h and i
λ	Concrete:	2.0 W/m˚C	

TABLE 16: THE THICKNESSES OF THE DIFFERENT STRUCTURAL ELEMENTS. THE APPEARING TEMPERATURE GRADIENTS DEPENDS ON THE THICKNESS.

Parameter	Structural element	Value	Table
h	Outer wall: Roof: Floor: Inner wall: *(Door:)*	0.40 m 0.28 m 0.59 m (0.30 + 0.29) 0.30 m *(0.20 m)*	Table 12 Table 12 Table 13 Table 14 *(-)*

6.2.3. CALCULATED TEMPERATURE GRADIENTS

The general scenarios from Table 9, Table 10 and Table 11 are used to study the temperature gradients that can appear in the case study situation. First all the temperature gradients appearing in the structural elements of *all* the scenarios are calculated. The results of these calculations can be found in Chapter *13. Appendix C: All calculated temperature gradients*. The temperature gradients that are part of Scenario 1 Extreme scenario (Scenario B-g in Table 11) are coloured blue in the appendix and when they are part of the common scenario, they are coloured green. Assumed is that the temperature in the concrete stays the same, because the composting time (2 – 3 weeks) is far longer than the interim time (1 day).

6.2.4. TWO NORMATIVE CASE STUDY SCENARIOS

From all the calculated scenarios the most extreme is going to be used as normative thermal load in the calculations. This from now on called *Scenario 1 Extreme* contains the most extreme temperature gradients that can appear in the concrete composting bunkers. This extreme situation is rare and occurs only several times a year. Scenario 1 Extreme appears when the inside of the bunker reaches extreme temperatures, while the surrounding bunkers are empty and the season outside is winter (Table 11, scenario B-g).
Important to mention is that the outer wall of bunker IX is partially build inside the large hall and partially outside. This wall has thus two different temperature gradients (85˚ to -25˚ and 85˚ to 17˚). The inner wall between bunker V and

VI is twice as thick as the other inner walls. The temperature gradient over this wall is thus different from the other inner walls. The calculated temperature gradients can be found in Table 17.

TABLE 17: THE TEMPERATURE GRADIENTS APPEARING IN EXTREME NORMATIVE SCENARIO. T1 IS THE TEMPERTURE INSIDE THE BUNKER AND T4 IS THE TEMPERATURE OUTSIDE THE BUNKER.

Scenario B-g: Scenario 1 Extreme winter	
Structural element	**Temperature gradient**
Roof	T1 = 85.00 T2 = 85.00 T3 = -00.56 T4 = -25.00
Outer wall *(The outer wall of bunker IX is partially outside and partially inside a large hall)*	T1 = 85.00 T2 = 85.00 T3 = -06.67 T4 = -25.00 *T1 = 85.00* *T2 = 85.00* *T3 = 43.79* *T4 = 17.00*
Floor	T1 = 85.00 T2 = 85.00 T3 = 10.00 T4 = 10.00
Inner wall *(The inner wall between bunker V and VI is twice as thick as a normal inner wall)*	T1 = 85.00 T2 = 85.00 T3 = 48.57 T4 = 17.00 *T1 = 85.00* *T2 = 85.00* *T3 = 37.56* *T4 = 17.00*

Because Scenario 1 Extreme doesn't occur on a daily basis, the most extreme common scenario is given as possibility for comparison (Table 18). In this common scenario a normal composting process temperature is present, while outside it is winter (Table 10, scenario B-d). The surrounding bunkers are still empty.

TABLE 18: THE TEMPERATURE GRADIENTS APPEARING IN COMMON NORMATIVE SCENARIO. T1 IS THE TEMPERTURE INSIDE THE BUNKER AND T4 IS THE TEMPERATURE OUTSIDE THE BUNKER.

Scenario B-d: Common winter	
Structural element	**Temperature gradient**
Roof	T1 = 50.00 T2 = 50.00 T3 = -08.33 T4 = -25.00
Outer wall *(The outer wall of Bunker IX is partially outside and partially inside a large hall)*	T1 = 50.00 T2 = 50.00 T3 = -12.50 T4 = -25.00 *T1 = 50.00* *T2 = 50.00* *T3 = 30.00* *T4 = 17.00*
Floor	T1 = 50.00 T2 = 50.00 T3 = 10.00 T4 = 10.00
Inner wall *(The inner wall between bunker V and VI is twice as thick as a normal inner wall)*	T1 = 50.00 T2 = 50.00 T3 = 32.32 T4 = 17.00 *T1 = 50.00* *T2 = 50.00* *T3 = 26.98* *T4 = 17.00*

The temperature gradients of Scenario 1 Extreme appearing in the concrete layers (the difference between T2 and T3) are going to be implemented in Scia Engineer. This scenario is thus going to be used to calculate the stress and forces that appear in the case study bunkers, which create the cracks in the concrete.

6.2.5. CONCLUSION RESEARCH QUESTION 2

There are twenty-seven temperature scenarios that can occur in a concrete composting bunker of WTT. This bachelor thesis will use the most extreme scenario in the calculations to look at the influence of the temperature on the concrete (Scenario 1 Extreme). The Eurocode is followed in determining the temperatures in all these scenarios.

It would be clearer if WTT would provide the building companies with all these twenty-seven temperature scenarios. They could give the right temperatures and how often and how long certain temperatures can occur. This way the building companies don't need to puzzle and guess which rule in the Eurocode applies. These temperature scenarios apply all over The Eurocode is used for many types of buildings and it is hard to determine which rules apply to this specific situation of the concrete bunkers. Also, WTT then could point out which and how many normative temperature scenario(s) need to be used in the calculations.

6.3. The influence of thermal loading on concrete bunkers

To study the influence of the large temperature differences on the concrete construction, Scenario 1 Extreme is implemented in SCIA Engineer. Besides that the other present loads (listed and calculated in Chapter *12. Appendix B: Calculation of the forces working on the case study bunker*s) are implemented in order to get a clear view on the role of the temperature in the complete situation. Eventually the normal stresses caused by the extreme thermal load (Scenario 1 Extreme) and all the loads are calculated and discussed.

In the next chapter the calculated normal stresses will be compared to the tensile normal stress the concrete can handle, which is very low compared to the compression the concrete can handle. The tensile normal stress of the concrete will also be used in order to optimize the researched solution in the next research goal in the next chapter.

6.3.1. Implementation

All the loads are put into SCIA Engineer: the own weight of the concrete housing, the weight of the content, the machines, the wind load, the snow load, the live load (people). On top of that the normative temperature gradients (Scenario 1 Extreme) are implemented in SCIA Engineer. This bachelor thesis looks at the influence of the temperature on *concrete*. This means the inner and outer resistance aren't included (between T1 and T2 and between T3 and T4), but only the temperature gradient appearing in the concrete (the difference between T2 and T3 taken from Table 17).

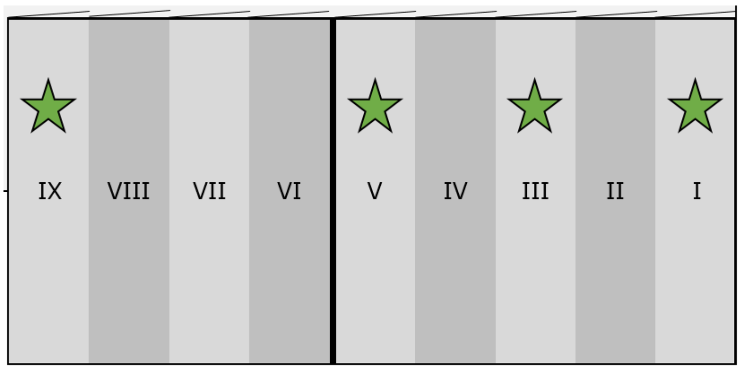


Figure 9: The four bunker types in the case study in Swisttal.

As mentioned in Subsection *6.1.4. Layout and dimensions case study bunkers*, there are four types of bunkers in the case study situation. To study the temperature gradients in the different bunker types, the bunkers I, III, V and IX will be used in the simulation and filled with feedstock (Figure 9). The influence of the normative temperature scenario on the four bunker types is going to be researched.

All the nine bunkers are modelled into SCIA Engineer according to the dimensions mentioned in Subsection *6.1.4. Layout and dimensions case study bunkers*. There is assumed that all the structural elements are connected to fixed supports, because this is the most common support used in these type of constructions (B. Van Ens, personal communication, April 25, 2017).
The original modulus of elasticity of the used concrete type C35/45 is 35,439 N/mm^2. According to NEN-EN 1992-1-1 a lower stiffness (modulus of elasticity) of the concrete may be assumed, if thermal effects play a role. The modulus of elasticity can go in the direction of the 4,000 N/mm^2 when thermal effects play a role, but this bachelor thesis will use a modulus of elasticity of 15,000 N/mm^2

to be safe (B. Van Ens and K. Kerkhof, personal communication, June 15, 2017).

6.3.2. LOAD COMBINATIONS

The temperature scenario has a certain influence on the construction and this is going to be displayed and discussed. With the extreme temperature load and all the other loads (calculated in Chapter *12. Appendix B: Calculation of the forces working on the case study bunkers*), the normative load combination is going to be established. This load combination represents the most unfavourable combination of loads on the construction (Table 19). Also the influence of only the thermal load is going to be calculated. Both results, only thermal load Scenario 1 and the normative load combination, are going to be displayed and compared.

There are two ways to calculate the dimensions necessary for a safe construction: Ultimate Limit State (ULS or in Dutch: UGT) and Serviceability Limit State (SLS or in Dutch: BGT). The ULS is related to the minimum safety of people, the construction and the content of the construction. This means the most extreme, inconvenient loads are placed on the construction and the construction must be able to handle it without failing. The SLS is related to the operatively of a construction, the comfort of the used and the appearance of the construction. This means the most common forces are placed on the construction and the construction must be able to handle them without creating obstacles for people or the arising of too big deformations.

Thermal effects only play a role in the SLS according to NEN-EN 1992-1-1. They are only taken into account in the ULS when the effects are significant (for example when second order effects or fatigue play a role). In the ULS large cracks indicate the failing of the construction. When such large cracks appear in the concrete, the stiffness of the concrete decreases and the modulus of elasticity decreases. The size of stress caused by the temperature depends on the stiffness of the concrete. When the stiffness and modulus of elasticity decrease, the stresses caused by the temperature decrease and thus the thermal load disappears. Letting such big cracks appear in the concrete isn’t possible, because the reinforcement is then exposed. The chemical composting process can then attack the reinforcement beneath the concrete, which can result in a failing construction. The ULS is thus not suitable for this situation and thus the normative load combination will be calculated in the SLS.

In Table 19 the loads are sorted per type. The own weight of the construction and the machines are the only permanent loads. Because the thermal load is researched in this bachelor thesis, the thermal load is pointed out as dominant variable load. Both are multiplied with a load factor of 1.0. The other variable loads are multiplied with 1.0 Ψ_0.

TABLE 19: THE LOAD COMBINATION WITH SCENARIO 1 EXTREME AND THE THERMAL LOAD OF SCENARIO 1 EXTREME ARE CALCULATED IN THE SLS ACCORDING TO NEN-EN 1990. THE G REPRESENTS THE PERMANENT LOADS AND THE Q REPRESENTS THE VARIABLE LOADS.

Load type	Loads	Load factor
Permanent	Own weight; the machines	1.0
Dominant variable load	Thermal load: Scenario 1 Extreme	1.0
Simultaneous variable loads	Weight of the content; the snow load; the wind load; the live load	1.0 Ψ_0

When permanent loads and variable loads are combined in one scenario, the factor Ψ may be used with the variable loads. With this factor the low frequent variable loads are reduced, because they occur less often. The used Ψ_0 factor per variable load type can be found in Table 20.

TABLE 20: THE Ψ FACTOR PER VARIABLE LOAD TAKEN FROM NEN-EN 1990.

No.	Load type	Ψ_0-factor
2	Content (Compost and liquid)	1.0
5	Snow	0.5
6	Wind	0.6
7	Live load	1.0

The stresses per structural element will be given in the X and Y direction in the appendix. This coordinate system (X and Y) is determined locally per structural element. The coordinate systems are positioned in a way that the following applies: the Y direction follows the direction of the longest side of the structural element and the X direction follows the short side of the structural element, perpendicular to the Y. An example of the outer wall is given in Figure 10: the Y follows the long side and the X follows the short side. The X and Y direction of the normal stress indicate how the structural element is modelled. When the normal stress is calculated in the X direction (short side), the structural element is seen as a relatively short beam in the X direction with a certain profile width and length in the YZ plane. The Y direction (long side) is modelled as a long beam with a relatively small profile in the XZ plane.

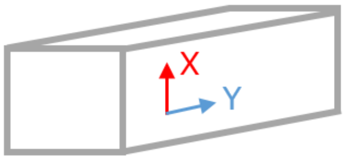


FIGURE 10: THE X AND Y DIRECTION ON THE OUTER WALL.

6.3.3. RESULTS AND DISCUSSION

With SCIA Engineer the normal stress (N/mm^2) in the concrete is calculated for normative load combination and for the thermal load case: Scenario 1 Extreme. All the results can be found in Chapter *14. Appendix D: The normal stresses calculated by SCIA Engineer*, Table 34. The left column of the table gives the stress caused only by the thermal load case Scenario 1 Extreme. The right column gives the stress caused by the normative load combination.

A comparison and discussion about the results will be given below. The discussion below applies to Table 34 in the appendix. The colour scale in every normal stress figure stays the same: -12 to 12 N/mm^2. This way the figures are easier to compare. The positive numbers (reddish) represent the *tensile* normal stress and the negative numbers (blueish) represent the *compressive* normal stress.

In general the normal stress calculated in the X direction is smaller than in the Y direction. The stress calculated in the Y direction is larger, because the Y direction is longer and the stress has to overcome this length.
The minor differences to this general conclusion arise due to the fact that this simulation in SCIA Engineer contains a *whole* 3D construction and not only *individual* structural elements. The loads on the whole construction influence each other and some stresses may lift each other or magnify each other.

Inside the filled bunkers normal compressive stresses and on the outside tensile normal stresses arise. Because the differences between the left and the right column in Table 34 are small, there can be concluded that the compressive and tensile normal stresses are mostly caused by the thermal load.
The normal stress in bunkers which aren't filled with feedstock, stays in most cases neutral. Only in the roofs and floors of the unfilled bunkers large tensile stresses arise in the Y direction. The thermal loads working on parts of the whole construction apparently cause large tensile stresses in the unfilled bunkers.

The difference between the normal stress caused by only the thermal load (left column of the tables in the appendices) and the stress caused by the normative load combination (right column of the tables in the appendices) is small. From this can be concluded that the influence of the temperature is large compared to the other loads. The difference between the normal stress caused by only the thermal load and the stress caused by the normative load combination, is slightly bigger in the roofs than in the other structural elements. This is caused by the machines placed on top of the roof; they add extra stress.

6.3.4. CALCULATION CHECK

The calculation check is used, to check if the SCIA Engineer model gives realistic results. For this Equation 7 is used. The parameters and the equation are taken from Chapter *3. Theoretical framework*.

$$\sigma t\ [N/mm^2] = Ec\ \varepsilon t\ =\ Ec\ \alpha c\ \Delta T \tag{7}$$

$$With\ \alpha c\ [m/m * K] =\ 10 * 10^{-6}$$
$$And\ Ec\ [N/mm^2] =\ 15{,}000$$

To use this equation, the structural elements are simplified to a dimensionless beam, instead of a plate shape. The results will give an indication about the *maximum* normal stresses arising in the construction, because this formula simplifies the structural plate shaped elements to dimensionless beam. In reality the stress is smaller, because the stress can spread through the plate. The results calculated by hand are given in Table 21. If the stress calculated by hand is found as maximum in the figures calculated by SCIA Engineer, the values from SCIA Engineer are accepted and a positive check is given in the last column.

TABLE 21: THE CALCULATION CHECK FOR SCENARIO 1 EXTREME. PER STRUCTURAL ELEMENT THE MAXIMUM TENSILE STRESS IS CALCULATED. THE 'CHECK' COLUMN INDICATES IF THE CALCULATION CHECK ACCEPTS OR REJECTS THE RESULTS CALCULATED BY SCIA ENGINEER.

Structural element	Temperature gradient (ΔT)	Calculated normal stress by hand	Check
Roof	T2 = 85.00 T3 = -00.56	12.8 N/mm^2	✓
Outer wall	T2 = 85.00 T3 = -06.67	13.8 N/mm^2	✓
Outer wall of bunker IX	*T2 = 85.00* *T3 = 43.79*	6.2 N/mm^2	✓
Floor	T2 = 85.00 T3 = 10.00	11.3 N/mm^2	✓
Inner wall	T2 = 85.00 T3 = 48.57	5.5 N/mm^2	✓
Inner wall between bunker V and VI	*T2 = 85.00* *T3 = 37.56*	7.1 N/mm^2	✓

Generally the calculation by hand matches with the figures produced by SCIA Engineer. The differences are caused by the fact that the calculation by hand simplify the construction to individual beams, while Scia Engineer takes the *whole* construction into account.
The normal stresses calculated by Scia Engineer in the roofs and the inner walls are a bit lower, than the stresses calculated by hand. In the outer walls and floors are the calculated stresses a bit higher, than when they are calculated by hand.

6.3.5. CONCLUSION RESEARCH QUESTION 3

The influence of the most extreme temperature scenario is displayed by the tensile normal stress caused by the temperature. The tensile normal stress is chosen as parameter, because the tensile stress the concrete can take, is very small. The cracking of the concrete is thus caused by too large tensile stresses. The tensile stresses caused by the most extreme temperature scenario are calculated, so that they can be compared to the tensile stress the concrete can handle. The maximum tensile stress found is 12 N/mm^2 and this stress is for a major part caused by only the thermal load. Inside the filled bunkers compressive stresses arise and outside tensile stresses arise. The stresses in the empty bunkers next door generally stay neutral. Only in the roofs and floors of the unfilled bunkers large tensile stresses arise in the Y direction. This underscores the fact that a whole construction needs to be taken into account, because individual structural elements can influence each other, which results in stresses in other places than initially expected. In the next research question possible solutions are going to be proposed to prevent the cracking.

The Eurocode is used in determining if the influence of the temperature should be calculated in the ULS or SLS. If WTT prescribes which temperature scenario(s) need(s) to be used in the calculations, they could also state if this or these scenario(s) should be calculated in the ULS or SLS and which crack width requirement the scenario(s) should meet. This way the right temperatures are used and their influence is compared to the right requirements.

6.4. Conclusion first research goal

In this chapter the over- and under-designing by the building companies has been researched, because they don't know how to handle the large temperature differences caused by the composting environment. Two manuals and one report are compared to each other and analysed.
There has been concluded that the guidelines in the manuals are too broad and that the general and specific manual don't match. The guidelines need to be specified and there needs to be explained why these guidelines are required by WTT. This way the building companies know which requirements they have to meet and why. Then they can apply the right assumptions and calculation to their specific project circumstances.
The biggest difference between the calculation report made by Grotemeier Ingenieure and the calculations made in this bachelor thesis, lies in the used temperatures. Some of them are estimated higher by Grotemeier Ingenieure than the Eurocode prescribes and some of them are lower than the Eurocode prescribes. Further research needs to be done after the *real* temperatures that influence the concrete composting bunkers.

Next, all the twenty-seven possible temperature scenarios that can occur in the concrete composting bunkers were portrait. The most extreme temperature scenario was further used in the calculations as a normative temperature scenario (Scenario 1 Extreme).
It is unclear which temperature scenarios and which belonging temperatures need to be taken into account. This bachelor thesis took the temperatures from the NEN-EN norms, but these norms are very safe. The NEN-EN norms don't include this specific type of construction and give very large temperatures to calculate with. The fact that the right temperatures aren't clear and the building companies don't know which scenarios should meet which requirement, creates uncertainty and differences between the calculation reports of the building companies.
There needs to be an agreement on which temperatures need to be used for these special constructions. WTT could provide the building companies with the twenty-seven possible temperature scenarios containing the right temperatures and how often they occur per year. Then they could say which scenarios need to be taken into account, if these scenarios need to be calculated in the ULS or SLS and which crack requirement they would need to meet. This way WTT ensures that the right temperatures are used and that they are compared to the right requirements. WTT prevents this way that the norms in certain countries don't meet *their* requirements of a safe construction.

Finally, the tensile normal stress caused by the most extreme temperature scenario was calculated. The maximum tensile normal stress found is 12 N/mm^2 and the thermal load causes most of this normal stress. Inside the filled bunkers compressive normal stress and outside tensile normal stress was found. The empty bunkers had almost no normal stresses to deal with, except for the roofs and floors of the unfilled bunkers. Tensile normal stresses arose here in the Y direction. These weren't directly caused by the thermal loads on the roofs and floors, but they have been thus caused by loads working on other parts of the construction. This underscores that individual structural elements can influence each other and thus a whole construction needs to be taken into account.

7. OPTIMIZED SOLUTIONS

The problems regarding the over- and under-designing of the building companies have been analysed. After that there was zoomed in on the temperature differences.
The tensile normal stresses caused by the thermal loads have been calculated and they will be used to suggest and optimize possible solutions to the problems WTT has. First, all possible solutions are listed. Second, one of the solutions will be further explored: insulation.

7.1. POSSIBLE SOLUTIONS

The normal tensile stress (calculated in Section *6.3. The influence of the thermal loading on the concrete bunkers*) is going to be compared to the maximum tensile stress the concrete can handle. Eventually a list of possible solutions is going to be given. The situation to which the solutions can be applied depends on the cause of the cracking. If the maximum tensile normal stress the concrete can handle is exceeded, because the *thermal* load is too high, insulation can be a solution. If the *other* loads cause this exceedance, other (more constructive) solution types need to be used.

7.1.1. THE THREE CRACKING SITUATIONS

The type of solution that can be used to solve the cracking of the concrete depends on the cause of the cracking. Research question 3 (Section *6.3. The influence of the thermal loading on the concrete bunkers*) has looked at the influence of the thermal load on the construction. Also, the influence of the other loads working on the nine case study bunkers is modelled and calculated. The influence of these loads on the construction is presented in form of normal stress.

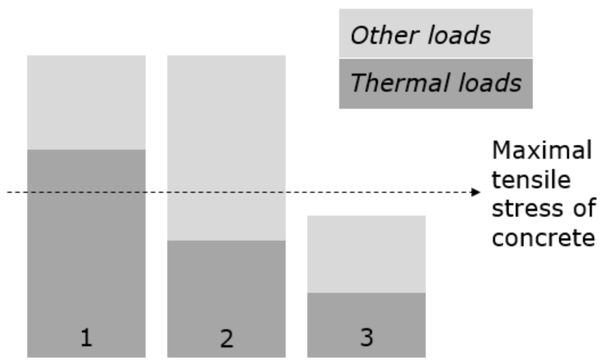


FIGURE 11: THE THREE LOAD SITUATIONS THAT CAN RESULT IN TENSILE STRESS THE CONCRETE CAN'T HANDLE (LARGER THAN 3.21 N/MM²).

Three cracking situations can arise due to the loads on the construction (Figure 11):

1) All the loads (including the thermal load) create a tensile stress too big for the concrete to handle. When only the thermal load works on the construction, this is also too much for the concrete.
   Solution options:
   Reduce the *thermal* tensile stress with for example insulation. The stress caused by the other loads can be further reduced with constructive solutions (for example reinforcement).

2) All the loads (including the thermal load) create a tensile stress too big for the concrete to handle. However, in contrast to situation 1, the thermal stress isn't too large for the concrete to handle.

Solution options:
Insulation as a solution doesn't work. Only constructive solutions, which reduce the impact of the other loads, can help.

3) The tensile stress is not too big for the concrete to handle.
Solution options:
All is well.

First there is researched which situation applies to this case study. With this information, solutions are going to be listed to prevent the occurrence of too large tensile stresses.

7.1.2. COMPARISON TENSILE STRESS

The maximum *tensile* normal stress the concrete C35/45 can handle is 3.21 N/mm^2, calculated with Equation 4 (taken from Chapter *3. Theoretical*). To test situation 1 from Figure 10, the tensile stresses caused by Scenario 1 Extreme are compared to the maximum tensile strength the concrete can handle (3.21 N/mm^2). The results can be found in Chapter *15. Appendix E: Comparison tensile normal stress*.

For the red coloured parts the tensile normal stress is too large to handle. The green coloured parts can handle the stress caused by the thermal load Scenario 1 Extreme. The blue coloured parts aren't of importance, because *compressive* normal stress arises here. In the red parts the occurring tensile stresses are too big for the concrete to handle, so the concrete will crack and this needs to be solved. As can be seen in the figures, major parts of all the structural elements are coloured red. Cracking situation 1 from Figure 10 is thus applicable here.

7.1.3. ALL POSSIBLE SOLUTIONS

Different solutions can be researched when too large stresses occur as can be seen in Table 22. Over-designing is a solution which is now used by some building companies to prevent the concrete from cracking. Insulation is the first solution that will be researched in Section *7.2. First researched solution: insulation*, to see if this solution can be applied in the concrete composting bunkers of WTT.

TABLE 22: LIST OF POSSIBLE SOLUTIONS TO THE PROBLEM WTT HAS WITH THE CRACKING OF THE CONCRETE.

Solution	Description	Applicable situation
Over-designing (e.g. thicker walls)	*Enlarge the dimensions and the amount of reinforcement used. This solution is now used by the building companies.*	2
Insulation	*Apply (more) insulation, in order to reduce the thermal load on the concrete.*	1
Reinforcement	*Use (more) reinforcement to take the tensile forces and stresses caused by the loads.*	1, 2
Dilatation holes	*Leave room for the concrete to expand. Corbels can be used for example.*	1
Thinner walls	*When thin concrete walls are used, the temperature gradient over the concrete walls becomes smaller.*	1
Support type	*Don't used fixed supports, but pinned (and roller) supports to leave room for the construction to expand.*	1

7.1.4. CONCLUSION RESEARCH QUESTION 4

When the tensile normal stresses are larger can the tensile stress the concrete can handle (3.21 N/mm^2), the solutions possible to solve this depend on the cause. Three situations are distinguished and it is established that the first situation applies here: the thermal load *and* the other loads both create tensile normal stresses that are larger than 3.21 N/mm^2. Insulation is one of the possible solutions to this. The other solutions can be found in Table 22.

7.2. First researched solution: insulation

Of all solutions listed in Table 22, insulation is going to be explored first as a solution to the large thermal load. Concluded before was that in situation 1 the colour red dominates and thus major parts of the concrete construction have to deal with tensile normal stresses larger than 3.21 N/mm^2. Insulation can be used as a solution to solve this problem.

7.2.1. Determination optimum

Applying insulation results in a lower temperature gradient in the concrete structural elements. A lower temperature gradient results in lower tensile normal stresses. The insulation is optimized by looking at the resulting (reduced) tensile normal stresses occurring in the concrete.

The goal is to reduce the tensile normal stresses caused by Scenario 1 Extreme. When the tensile normal stresses are lower than 3.21 N/mm^2, no cracks will appear due to the temperature. WTT doesn't want deep cracks in the concrete layer, because the chemical substances released during the composting process can attack the reinforcement lying beneath the concrete layer through these cracks (Braam & Lagendijk, 2011). The reason to research insulation first is that insulation doesn't cause cracks in the concrete, while reinforcement can only work when the concrete is cracked. Cracks are a risk in a composting environment, so a solution without cracks is preferred. The optimum is determined by reducing the tensile normal stress caused by Scenario 1 Extreme to 3.21 N/mm^2. The insulation must thus neutralize the tensile normal stress caused by the thermal load.

7.2.2. Implementation

Finding the optimal amount of insulation depends on the type of insulation used and thus how low the belonging heat resistance coefficient (λ) is. It also depends on the thickness of the insulation layer. Three insulation types are implemented in the construction and the (reduced) normal stresses are calculated with SCIA Engineer. When the stresses in the construction are lower than 3.21 N/mm^2, the optimized thickness of the insulation is found.

The chosen insulation materials and the belonging heat resistance coefficient (λ) can be found in Table 23. These three insulation materials are chosen, because they are the most common insulation types used and they can all handle the high temperatures arising in the composting bunkers. The optimal thickness for each insulation type is going to be given as result.

Table 23: The heat resistance coefficient (Λ) of the three chosen insulation types.

Insulation material	Λ (Linden, Erdsieck, Gaalen, & Zeegers, 2013)
Mineral wool	0.041 W/m˚C
Polystyrene (expanded)	0.035 W/m˚C
Polyurethane foam (PUR)	0.021 W/m˚C

The insulation materials are implemented on the outside of the concrete construction, because this way the insulation isn't affected by the chemicals in the composting environment.

7.2.3. RESULTS AND DISCUSSION

After an iterative process the optimal thickness of the insulation is approached. There is found that in general the maximum temperature gradient the concrete can handle is around 65 °C to 85 °C (with a calculation check it is confirmed that the resulting normal stress caused by this gradient is 3 N/mm^2). If this temperature gradient is placed on every structural element, by implementing insulation, the tensile stresses remains lower than 3.21 N/mm^2. The insulation type, thickness and the different thicknesses of the concrete per structural element influence the temperature gradient and are thus the parameters used in the iterative process.

In Table 24, Table 25, Table 26 and Table 27 the results can be found. Per structural element (respectively roof, outer wall, floor, inner wall) each optimal thickness for the three insulation types is given with the belonging temperature gradient remaining in the concrete. In Table 25 and Table 27 two thicknesses are given. These are the insulation thicknesses for the outer wall of bunker IX and the inner wall V and VI. As mentioned before, this outer and inner wall have different dimensions from the other outer and inner walls and are thus mentioned separately.

TABLE 24: THE THICKNESS OF THE INSULATION LAYER RESULTS IN A LOWER TEMPERATURE GRADIENT IN THE CONCRETE OF THE *ROOFS*. THREE DIFFERENT THICKNESSES ARE GIVEN, BELONGING TO THREE DIFFERENT TYPES OF INSULATION. THE COMBINATION OF THE GIVEN INSULATION TYPE WITH THE GIVEN THICKNESS RESULTS IN A THERMAL LOAD AND TENSILE NORMAL STRESSES THE CONCRETE CAN HANDLE.

Thickness concrete: roof [mm]	ΔT over the concrete
Mineral wool	
25 mm	T2 = 85.00 °C T3 = 65.50 °C
Polystyrene (expanded)	
20 mm	T2 = 85.00 °C T3 = 64.51 °C
Polyurethane foam (PUR)	
15 mm	T2 = 85.00 °C T3 = 67.78 °C

TABLE 25: THE THICKNESS OF THE INSULATION LAYER RESULTS IN A LOWER TEMPERATURE GRADIENT IN THE CONCRETE OF THE *OUTER WALLS*. THREE DIFFERENT THICKNESSES ARE GIVEN, BELONGING TO THREE DIFFERENT TYPES OF INSULATION. THE COMBINATION OF THE GIVEN INSULATION TYPE WITH THE GIVEN THICKNESS RESULTS IN A THERMAL LOAD AND TENSILE NORMAL STRESSES THE CONCRETE CAN HANDLE.

Thickness concrete: outer wall [mm]	ΔT over the concrete
Mineral wool	
40 mm 15 mm	T2 = 85.00 °C T3 = 66.90 °C *(Outer wall IX: T3 = 65.46 °C)*
Polystyrene (expanded)	
30 mm 15 mm	T2 = 85.00 °C T3 = 64.95 °C *(Outer wall IX: T3 = 67.07 °C)*
Polyurethane foam (PUR)	
20 mm 10 mm	T2 = 85.00 °C T3 = 66.55 °C *(Outer wall IX: T3 = 68.13 °C)*

TABLE 26: THE THICKNESS OF THE INSULATION LAYER RESULTS IN A LOWER TEMPERATURE GRADIENT IN THE CONCRETE OF THE *FLOORS*. THREE DIFFERENT THICKNESSES ARE GIVEN, BELONGING TO THREE DIFFERENT TYPES OF INSULATION. THE COMBINATION OF THE GIVEN INSULATION TYPE WITH THE GIVEN THICKNESS RESULTS IN A THERMAL LOAD AND TENSILE NORMAL STRESSES THE CONCRETE CAN HANDLE.

Thickness concrete: floor [mm]	ΔT over the concrete
Mineral wool	
40 mm	T2 = 85.00 °C T3 = 67.59 °C
Polystyrene (expanded)	
30 mm	T2 = 85.00 °C T3 = 65.80 °C
Polyurethane foam (PUR)	
20 mm	T2 = 85.00 °C T3 = 67.26 °C

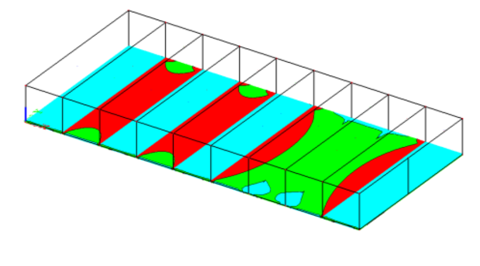
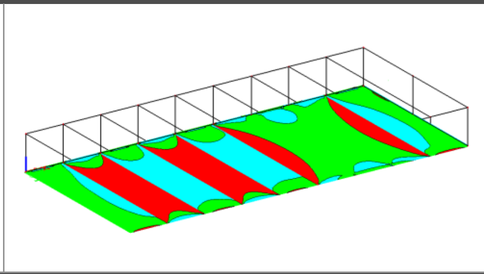
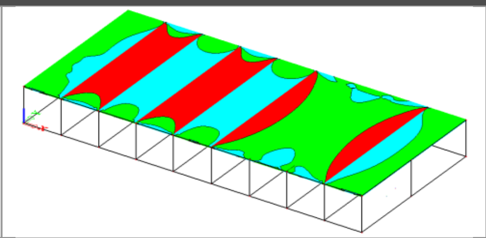
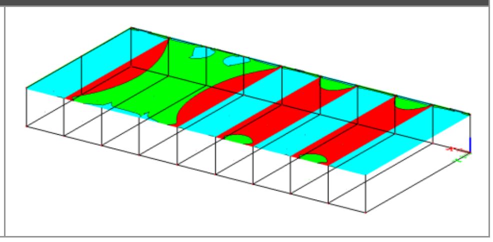
Implementing insulation on the inner walls is difficult. The insulation needs to be protected from the feedstock by concrete. A solution is to implement the insulation in the middle of the concrete layer. However, then the concrete layer may have too little space left, if also reinforcement needs to be placed inside the concrete. Of all the structural elements, the inner walls need to deal with the smallest temperature gradient, but the tensile normal stresses are still too large to handle in some places for the concrete. Measures are therefore necessary and perhaps another solution than insulation is cheaper or easier to implement. This can be further researched in a follow-up study.

TABLE 27: THE THICKNESS OF THE INSULATION LAYER RESULTS IN A LOWER TEMPERATURE GRADIENT IN THE CONCRETE OF THE *INNER WALLS*. THREE DIFFERENT THICKNESSES ARE GIVEN, BELONGING TO THREE DIFFERENT TYPES OF INSULATION. THE COMBINATION OF THE GIVEN INSULATION TYPE WITH THE GIVEN THICKNESS RESULTS IN A THERMAL LOAD AND TENSILE NORMAL STRESSES THE CONCRETE CAN HANDLE.

Thickness concrete: inner wall	ΔT over the concrete
Mineral wool	
10 mm 30 mm	T2 = 85.00 °C T3 = 65.53 °C *(Inner wall V and VI: T3 = 67.44 °C)*
Polystyrene (expanded)	
10 mm 20 mm	T2 = 85.00 °C T3 = 66.97 °C *(Inner wall V and VI: T3 = 64.63 °C)*
Polyurethane foam (PUR)	
5 mm 15 mm	T2 = 85.00 °C T3 = 65.31 °C *(Inner wall V and VI: T3 = 67.17 °C)*

The insulation type and the belonging thickness of the insulation given in the tables above, reduce the initial thermal load. The remaining tensile normal stresses are lower than 3.21 N/mm^2. Only in the roofs and floors of the not filled bunkers the tensile normal stress stays too large (Table 28). The obvious solution then is to keep the temperature inside all bunkers the same and constant. There can be assumed that the temperature inside the bunkers stays the same all the time, because the bunkers are emptied and filled again in one day. There can thus be assumed that the remaining red parts won't arise, if the bunkers are filled regularly.

TABLE 28: THE REMAINING TENSILE NORMAL STRESSES IN THE ROOFS AND FLOORS OF THE BUNKERS AFTER THE INSULATION IS IMPLEMENTED.
RED: CONCRETE *CANNOT* TAKE THE TENSILE NORMAL STRESS, CAUSED BY THE TEMPERATURE.
GREEN: CONCRETE *CAN* TAKE THE TENSILE NORMAL STRESS, CAUSED BY THE TEMPERATURE.
BLUE: THE COMPRESSIVE NORMAL STRESS.

Floor		
Y		
Roof		
Y		

7.2.4. CONCLUSION RESEARCH QUESTION 5

Insulation is researched as a solution, because this solution doesn't create cracks in the concrete. Cracks in the concrete layer can be a possible danger for the underlying reinforcement layer, because the chemical composting environment can attack the reinforcement. This can result in a construction failure.

The optimal amount of insulation is determined by looking at the tensile normal stresses in the concrete. When insulation is applied, the temperature gradient becomes smaller and thus the thermal load on the concrete becomes smaller. When the insulation neutralizes the tensile normal stress caused by the thermal load to 3.21 N/mm^2, the optimum is found. The optimal amount of insulation depends on the type and thickness of the insulation. The optimal thickness of three commonly used types of insulation (mineral wool, expanded polystyrene, polyurethane foam) is found.
The optimal thickness is found for the four structural elements (roof, outer wall, floor, inner wall). Insulation can't be placed on the inner walls, without protecting the insulation against the chemical composting environment. The required insulation thickness for the inner walls are thus calculated, but extra measurements are necessary when insulation on the inner walls will be implemented.
The thicknesses of the three insulation types, reducing all the normal stresses to 3.21 N/mm^2, can be found in Table 24, Table 25, Table 26 and Table 27. Only the tensile normal stresses in the Y direction in the roofs and floors of the empty bunkers remain. As concluded before, these tensile normal stresses aren't caused by only the thermal load on these structural elements and thus can't be solved by applying insulation.

The calculated insulation layers of all insulation types on all structural elements lie between 5 mm and 40 mm. Grotemeier Ingenieure has used 80 mm of insulation, only on the outer walls and not on the roof or floor. Their insulation layer is much thicker and they don't explain why. They have used the same heat resistance coefficient as the first insulation type used in this bachelor thesis: mineral wool. The temperatures used by Grotemeier Ingenieure aren't much bigger and sometimes even smaller than the temperatures used in this bachelor thesis. The temperature gradient appearing over the outer walls are even smaller (75 ˚C to -12 ˚C instead of 85 ˚C to -25 ˚C). There is not explained by Grotemeier Ingenieure why this type and thickness of insulation is used and no explanation can be found by this bachelor thesis. The insulation layer used in another, comparable case study, located in Ennigerloh, Germany, has an insulation layer of 100 mm on the outer walls. This even bigger than the insulation layer used in Swisttal. It appears that the building companies don't know how much influence the temperatures on the construction have and how much insulation they need to solve this.

Which type of insulation will be used, can depend on the cost. When the calculated thicknesses are multiplied by the surface (m^2) and the cost per m^3, the lowest results indicates the most advantageous the insulation type. When more solutions are researched, they need to be compared to each other in the same way (necessary volume multiplied by the cost per m^3). The best solution can then be chosen based on the cost or for example on the amount of cracks they create.

"The more insulation does not necessarily mean the better. Optimum economic thickness of insulation can be defined as the thickness of insulation for which the cost of the added increment of insulation is just balanced by increased energy savings over the life of the project (principle of diminishing returns)."

Al-Homoud (2004)

7.3. Conclusion second research goal

The type of solution that can be applied, depends on the cause of the problem. There is stated that the thermal load alone already creates tensile stresses that are too large for the concrete to handle (larger than 3.21 N/mm^2). Because insulation doesn't need to create cracks in the concrete to be able to work, like reinforcement does, this solution in researched first. When insulation is used, the temperature gradient and the thermal load become smaller and the tensile normal stresses become lower. Three types of insulation have been researched and the thickness of the insulation layer is optimized by reducing these tensile normal stresses to 3.21 N/mm^2.

The optimal thickness of the three insulation types on the four structural elements lies between the 5 mm and 40 mm. This is lower than the insulation layer of 80 mm calculated by Grotemeier Ingenieure. They used mineral wool also as an insulation type and the temperatures used in their calculations aren't all larger than the temperatures used in the calculations of this bachelor thesis. There is no explanation on why the insulation layer is this thick and this confirms that building companies how to solve the influence of the thermal load on the bunkers using insulation.

The type of insulation that will be used, can depend on the thickness multiplied by the surface (m^2) and by the cost per m^3. This way the types of insulation can be compared to each other and the type with the highest return can be chosen. When more solutions are researched, they can be compared to each other in the same way. Other parameters to compare the solutions to each other can be for example: the amount of cracks they create, the durability or the sustainability of the solution.

8. CONCLUSION AND DISCUSSION

Two major conclusion that are interesting for WTT are drawn from this research. With these conclusions WTT can improve the communication with their building partners about the specifics of the bunker constructions and search for on optimal solution for the appearance of cracks in their concrete composting bunkers.

The given manuals of WTT don't match and the given guidelines in the manuals are too broad. Specific guidelines with explanation will increase the understanding of the building companies about the new and different circumstances that come with building a concrete composting bunker. Especially the temperatures need to be specified. WTT can give all the twenty-seven temperature scenarios that can appear in a concrete composting bunker, including the right temperatures. These real temperatures need to be measured and tested, so that the building companies don't need to puzzle anymore which norms are applicable when they are building a concrete composting bunker. Out of all these possible scenarios the most important scenario(s), for example the most extreme or the most common, need to be linked to a certain requirement, for example the crack width. WTT can also give if the calculation needs to be done in the ULS or SLS.

The biggest problem of WTT is the large tensile normal stress creating cracks in the concrete. Over-designing is now used by the building companies to solve this or sometimes under-designing occurs, when the building companies don't know how to take the composting environment into account. This bachelor thesis has proposed different types of solutions to this problem of WTT. Insulation has been the first solution which was further researched to neutralize the thermal load. The optimal thickness of the insulation layer for the case study in Swisttal is found and appears to be two to sixteen times lower than the thickness Grotemeier Ingenieure, the designing building company of the case study bunkers in Swisttal, has used. An explanation on which they based their choice for insulation thickness isn't given. The over-designing is thus seen in the amount of insulation used by Grotemeier Ingenieure. Also important to mention is that the insulation is only implemented on the outer walls and not on the roof or the floor of the bunkers.
The combination of not knowing the real temperatures that need to be used in the calculation and choosing a thickness of the insulation layer without proper explanation, creates uncertain circumstances.

An important footnote is that the tensile normal stresses are used to optimize the solutions and draw conclusions from there, aren't the only forces arising due to the thermal load. In Figure 12 shows that besides tensile and compressive stresses, also bending moments arise. This bending moment is not taken into account in this bachelor thesis. This bending moment is smaller than the normal stress, but its precise influence is something to further research.

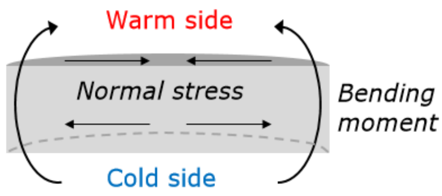


FIGURE 12: THE NORMAL STRESS AND BENDING MOMENT CREATED BY THERMAL LOADING.

9. RECOMMENDATIONS

The conclusions and recommendations made in this bachelor thesis draw general statements about the concrete composting bunkers using the results from the analysis about one case study in Swisttal. To confirm these conclusions, more case studies need to be used and researched in order to check if the drawn conclusions are generally applicable.
This bachelor thesis is specifically focused on the composting systems of WTT, but their anaerobic digestion systems are also placed inside concrete composting bunkers. A part of the research done may be applicable there too.

The cause of the appearance of cracks can be researched by looking at the size and location of the cracks. In the beginning of the internship WTT has been asked if pictures of the cracks were available. Because most building companies over-design the composting bunkers, the appearance of cracks has been stopped and no photos of the cracks were available. In order provide WTT with other solutions than over-designing, the specific cause of the cracks needs to be found. The advice to a follow-up study is to get photos of some cracks.

Designated as major cause for the appearance of cracks is the large temperature differences over the concrete construction, but other causes can also play a role. The composting environment can contain a lot of moisture or chemical substances that can influence the concrete in a bad way. The cracks could also already be embedded in the concrete construction right after the concrete is poured. During the hydration the concrete shrinks, because of water evaporation. When freshly poured concrete shrinks, while it’s attached to something, cracks can appear in the connection between the two parts. Solutions to this can be the usage of a different type of cement (Blast furnace cement (Dutch: CEM III / Hoogovencement) instead of Portland cement) or a different type of concrete. A prefab construction can also be used (for example the in Dutch called *schilwanden*). These other possible causes are now left outside the scope of this bachelor thesis and can be further researched in a follow-up study.

During the calculation the modulus of elasticity is reduced from 35,439 N/mm^2 to 15,000 N/mm^2 (according to NEN-EN 1992-1-1). The reason is that the shrinkage of concrete, caused by water evaporation, and cracks, caused by the loads, reduced the stiffness of the concrete. Known is that a modulus of elasticity of 15,000 N/mm^2 is still very large, so further research can be done after the real, reduced modulus of elasticity.

All the norms used in this bachelor thesis are European and sometimes specifically Dutch. There is tried to keep the assumptions and conclusions as general as possible, because WTT operates all over the world and they thus have to deal with all sorts of norms. The European norms are very safe, while other countries might use less strict norms. Some of those norms will be very safe and some will be unsafe, which can result in a failing construction and a negative view on the systems of WTT. These difference need to be taken into account when the conclusions from bachelor thesis are used and when further research is done.

There are also other solutions possible regarding the insulation in the floor. The floor consists of two parts: a constructive floor and the spigot floor. When insulation is applied in the floor, this can be placed between those two floor types, allowing the spigot floor to crack. When the spigot floor is allowed to crack, the temperature gradient over the concrete becomes smaller, because the concrete layer becomes in essence thinner (B. Van Ens, personal communication, June 15, 2017). Another idea is that the ground can be seen as an insulation layer (Figure 13). When the resistance of the outer walls are larger than the resistance of the light brown piece of ground, the heat will try escape through the ground. The heat will seak the path of the least resistance. The light brown ground can then be seen as an insulation layer (B. Entrop, personal communication, April 19, 2017). Thus, by appliying insulation on the walls and using the ground as insulation, the temperature gradients in the walls and in the floor both reduce.

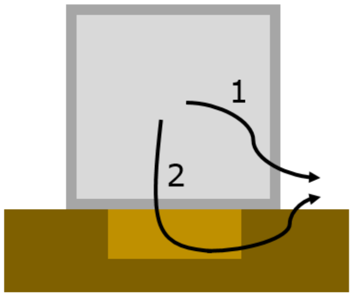


FIGURE 13: THE RESISTANCE ARROW 1 MEETS IS LARGER THAN THE RESISTANCE ARROW 2 MEETS. THIS WAY THE LIGHT BROWN GROUND CAN BE SEEN AS AN EXTRA INSULATION LAYER.

The NEN-EN norms give rules that design a construction for a life cycle length of fifty years. However, the concrete composting bunkers of WTT only have a life cycle length of twenty years. This is not included in the NEN-EN norms, but this can have an influence on how the calculation results must be used.
When the life cycle length of the concrete composting bunker is actually shorter than for which it is designed, the cracks at the end of the life span of twenty years are small and by far wouldn’t result in a failing construction. The calculated results (for a life span of fifty years) are thus safer than necessary. It is not possible to make a precise calculation for a life cycle length of twenty years, because there are no calculation rules for this given in the NEN-EN norm. This can thus be further researched in a follow-up study.

Acknowledgements

I want to thank some people for their support and contribution to this bachelor thesis.

Thanks to dr. I. Stipanovic and dr. ir. S. Miller for being my supervisors from the University of Twente during my bachelor thesis.

Thanks to ing. B. van Ens for being my supervisor from Tauw during my bachelor thesis. Also thanks to my colleagues at Tauw for their support and assistance.

Thanks to ir. C. Stelwagen for being my first contact person from WTT during my bachelor thesis. Also thanks to ing. E. Jansen of Lorkeers from WTT for your support and assistance.

Author: E. M. R. (Esmee) Koopman

10. REFERENCE LIST

Al-Homoud, M. S. (2004). The Effectiveness of Thermal Insulation in Different Types of Buildings in Hot Climates. *Journal of Building Physics*.

BEKON GmbH. (2017, april 13). Errichtung einer Tunnelkompostierungsanlage Kompostwerke Rhein-Sieg: Grundriss OG.

BEKON GmbH. (2017, april 13). Errichtung einer Tunnelkompostierungsanlage Kompostwerke Rhein-Sieg: Layout.

BEKON GmbH. (2017, april 13). Errichtung einer Tunnelkompostierungsanlage Kompostwerke Rhein-Sieg: Schnitte.

BetonLexicon. (n.d.). *Warmtegeleiding*. Retrieved from BetonLexicon Het woordenboek voor de betonwereld: http://betonlexicon.nl/W/Warmtegeleiding/

Braam, C., & Lagendijk, P. (2011). *Constructieleer gewapend beton.*

Breugel, K. v., Veen, C. v., & Walraven, J. (1996). *Betonconstructies onder Temperatuur- en Krimpvervormingen.*

Castillo, C. (1987). *Effect of transient high temperatures on high-strength concrete.* Houston: Rice University.

Cement&BetonCentrum. (2016). *Vervormingseigenschappen*. Retrieved from Cement&BetonCentrum: http://www.cementenbeton.nl/materiaal/materiaaleigenschappen/vervormingseigenschappen

Chen, L., Haro, M. d., Moore, A., & Falen, C. (2011). *The Composting Process.* Moscow: University of Idaho Extension.

Delincé, D., & Parmentier, B. (2004). *Staal-betonconstructies Deel 2: controle van de gebruiksgrenstoestanden volgens Eurocode 4.* Zaventem: WTCB.

Hager, I. (2013). Behaviour of cement concrete at high temperature. *Bulletin of the Polisch Academy of Sciences: Technical Sciences*, 10.

KompostWerke Rhein-Sieg. (2016). *EU-weite Ausschreibung zur Errichtung einer Tunnelkompostierungsanlage am Standort Swisttal-Miel.* Swisttal.

Linden, A. C., Erdsieck, P., Gaalen, L. K.-V., & Zeegers, A. (2013). *Building Physics.* ThiemeMeulenhoff.

Mindeguia, J., Pimienta, P., Hager, I., Laborderie, C., & Carré, H. (2006). Experimental study of transient thermal strain and creep of an ordinary concrete at high temperatures. *Fourth International Workshop: Structures in Fire*, (p. 13). Aveiro, Portugal.

NEN. (2001). *NEN-EN 1068 (nl).*

NEN. (2011). *NEN-EN 1991-1-5 (nl).*

NEN. (2011). *NEN-EN 1992-1-1 (nl).*

NEN. (2012). *NEN-EN 1990 (nl).*

Orosz, Á. (1980). Effects of temperature upon reinforced concrete cooling towers. *Periodica Polytechnica*, 13.

Pace, M. G., Miller, B. E., & Farrell-Poe, K. L. (1995, October). *The Composting Process.* Logan: Utah State University.

Saad, M., Abo-El-Eneini, S., Hanna, G., & Kotkatat, M. (1996). Effect of temperature on physical and mechanical properties of concrete containing silicia fume. *Cement and Concrete Research*, 7.

Sagel, R., Dees, W. C., Geest, F. P., & Braam, C. R. (2010). *GTB 2010 Complete uitgave.* Gouda: Betonvereniging Gouda.

Waste Treatment Technologies. (2015). *Spigotfloor installation description.* Almelo.

Waste Treatment Technologies. (2016). Biological techniques. Almelo, Overijssel, The Netherlands. [*Movie*]

Waste Treatment Technologies. (2016). *Technical Specifications CIVIL DESIGN.* Almelo.

Waste Treatment Technologies. (2017, februari 16). Ersten Entwurf Swisttal-Miel: Explosionszeichnung Spigotboden.

Waste Treatment Technologies. (2017, februari 16). Ersten Entwurf Swisttal-Miel: Layout.

Waste Treatment Technologies. (n.d.). *Project Announcement: Swisttal-Miel – Germany – New tunnel composting facility*. Retrieved from WTT: http://www.wtt.nl/project-announcement-swisttal-miel-germany-new-tunnel-composting-facility/

Wollmann, C. L., Breen, J. E., & Kreger, M. E. (1995). Temperature induced deformations in match cast segments. *PCI Journal - Precast Concrete Institute*, 10.

11. APPENDIX A: TERMINOLOGY

A list of exact definitions is made to be sure that the reader has a clear view on what is meant when certain terms are used.

3D simulation program	*A series of instructions put into a computer in order to create a mathematical representation of a three-dimensional object and calculate the forces and deformations in the three-dimensional object.*
Building companies	*Partners of WTT, that build the concrete housing of their waste treatments systems. Sometimes they are located in the country of the building site, because then they can respond better to the local rules and building methods.*
Case study	*A particular person, group or situation, which can be analysed over a period of time. In this bachelor thesis a composting bunker in Swisttal, Germany will be used as a case study.*
Concrete housing	*The concrete bunkers where the composting systems are stalled in and were the composting process takes place.*
Compost	*Decayed organic material used as a fertilizer for growing plants.*
Composting process	*Processing source separated organic waste or municipal solid waste into a mixture of various decaying organic substances.*
Composting system	*All the systems, among others the aeration system, the percolation system and the spigots, in this case developed by WTT to compost the source separated organic waste or the municipal solid waste.*
Composting environment	*The humid and heated climate inside the concrete bunker, created by the composting process.*
Constructive (solutions)	*Creating a structural solution, by for example creating dilatation holes, using hinges, creating thicker or thinner walls.*
Cracks (in the concrete)	*Due to stress in the concrete, the concrete has split leaving a deep crack or a shallow scratch or something in-between.*
Even load	*An equally distributed surface or line load.*
FEM	Finite Element Method *A numeric method used in structural analyses to calculate among others bending moments, axial forces, torsion and shear forces and*

	deformations.
Fixed support	*A support type that can take horizontal and vertical forces.*
Hydration process	*Chemical reactions in the concrete that result chemical bonds with water while creating heat. The speed of this process decreases over time.*
Line load	*A distributed load on a line (in Dutch: q-last). The unit is N/m.*
Municipal solid waste	Rubbish or garbage. *A waste type consisting of everyday items that are discarded by the public. The composition can differ per municipality. This waste type contains the waste that wasn't separated (Dutch: het afval uit de grijze container).*
to Optimize	*Make the best or most effective use of something regarding the resources. In this bachelor thesis the solutions will be optimized in the eleven weeks available and with the methods described in methodology. In consultation with the supervisors the precise end stadium of the optimization will be determined during the research.*
to Over-design	*Using a large safety marge to be sure the construction won't fail. This results in the use of extra materials; extra concrete and extra reinforcement.*
Pinned support	*A support type that can take horizontal and vertical forces and a momentum.*
Point load	*A load placed on one point in the construction. The unit is Newton.*
Roller support	*A support type that can only take horizontal forces.*
Source separated organic waste	*Waste that is separated into the following categories: paper, yard and food debris (Dutch: blauwe, groene container).*
Spigot	*In the floor embedded facilities connected to ventilation channels in the floor of the concrete bunker. These spigots are used to blow the air through the concrete floor.*
Structural element	*A part of the whole construction. For example a wall, floor, roof or door.*
Surface load	*A distributed load on a surface. The unit is* N/m^2.

Uncontrollable appearance of cracks (in the concrete)	*The distance between the cracks, the crack amount, depth and width. Due to compressive and tensile forces, small cracks appear in the concrete over time. Cracks in the concrete aren't an immediate problem, as long as they are regulated.*
to Under-design	*Using a too small safety marge or no safety marge, because there is no knowledge about how certain things need to be taken into account in the calculation. This results in failure of the construction.*
Trapezoid load	*A surface or line load, which is not distributed equally but has a slope in it.*
WTT	Waste Treatment Technologies *The client of this bachelor thesis. A company which builds waste treatment systems.*

12. APPENDIX B: CALCULATION OF THE FORCES WORKING ON THE CASE STUDY BUNKERS

Table 29 gives the loads that work on the nine case study bunkers in Swisttal, Germany, as mentioned in Subsection *6.1.4. Layout an dimensions case study bunkers*. In the second column the loads can be found. In the third column the values that are needed to calculate the forces are given. The fourth column gives the calculated force and how it will be modelled in SCIA Engineer. Figure 14 gives the locations and the size of the machines loads.

TABLE 29: THE LOADS AND THE RESULTING FORCES THAT WORK ON THE COMPOSTING BUNKER IN SWISTTAL. THE ANGLE OF REPOSE OF THE FEEDSTOCK (Φ = 30˚) IS ESTIMATED BASED ON THE VALUES OF SUBSTANCES THAT COULD BE IN THE FEEDSTOCK. WHEN THE SURFACE IS GIVEN, FIRST THE WIDTH (HORIZONTAL SIDE IN FIGURE 14) AND THEN THE LENGTH (VERTICAL SIDE IN FIGURE 14) ARE GIVEN. NOTE: WTT HAS SPECIFIED THAT THE FEEDSTOCK IS ONLY FILLED UP TO 4.5 M (WHILE THE HEIGHT OF THE BUNKER IS 5 M). THE PERCOLATION LIQUID HOWEVER FILLS THE BUNKER 100% (UP TO 5 M). THE SNOW, WIND AND LIVE LOAD ARE TAKEN FROM NEN-EN 1991-1, -3, -4.

No.	Load	Values	Implemented in SCIA Engineer
1	Own weight:		
1a	Concrete housing (C35/45)	Density: 2,500 kg/m^3	SCIA Engineer calculates the own weight, using the density and the dimensions of the concrete housing.
2	Content		
2a	Feedstock	Density: 800 kg/m^3 Maximum height: 4.5 m	*Vertical even surface load:* 800 * 4.5 * 9.81 = 35,316 N/m^2
2b		Angle of repose: φ = 30˚	*Horizontal trapezoid surface load:* 35,316 * (1-sin(φ)) = 17,658 N/m^2
2c	Percolation liquid	11 *10^{-3} kg/m^3 * 5 m	*Vertical even surface load (negligible compared to feedstock):* 11 *10^{-3} * 5.0 * 9.81 = 540 *10^{-3} N/m^2
3	Machines:		
3a	Air cleaner	Weight: 6,000 kg Surface: 5.0 m * 4.5 m	*Vertical even surface load:* 6,000 / (5.0 * 4.5) * 9.81 = 2,616 N/m^2
3b	Large fan	Weight: 1,500 kg Surface: 2.7 m * 3.0 m	*Vertical even surface load:* 1,500 / (2.7 * 3.0) * 9.81 = 185 N/m^2

3c	Tubular fan with support	Weight: 300 kg Surface: 1.5 m * 2.0 m	*Vertical even surface load:* 300 / (1.5* 2.0) * 9.81 = 981 N/m^2
3d	Fresh water storage	Weight: 90,000 kg Surface: 25.6 m * 2.85 m	*Vertical even surface load:* 90,000 / (25.6 * 2.85) * 9.81 = 12,101 N/m^2
3e	Process water storage	Weight: 80,000 kg Surface: 25.6 m * 2.50 m	*Vertical even surface load:* 80,000 / (25.6 * 2.50) * 9.81 = 12,263 N/m^2
3f	Concrete container water storage	Density concrete C35/45: 2500 kg/m^3 Measurements: can be taken from Figure 14.	*Vertical even line load:* (2,500 * 9.81) / 1.2 = 20,437 N/m
3g	Water skid	Weight: 1,500 kg Surface: 1.65 m * 4.0 m	*Vertical even surface load:* 1,500 / (1.65 * 4.0) * 9.81 = 227 N/m^2
3h	Air skid	Weight: 1,000 kg Support points: 4	*Four vertical point loads:* (1,000 * 9.81) / 4 = 2,453 N
4	Thermal load	Answered in Section *6.2. The temperature gradients scenarios*.	Temperature gradients are put on the walls, floor and roof
5	Snow load	Given by NEN-EN 1991-3.	*Vertical even surface load:* 560 N/m^2
6	Wind load	Given by NEN-EN 1991-4.	*Horizontal even surface load:* 0 to 4 m: 490 N/m^2 4 to 5 m: 540 N/m^2 5 to 5.7 m: 580 N/m^2 *The highest wind load (580 N/m^2) will be placed on the long side and short side of the construction.*
7	Live load (people on the roof)	Given by NEN-EN 1991-1.	*Vertical even surface load:* 2,000 N/m^2

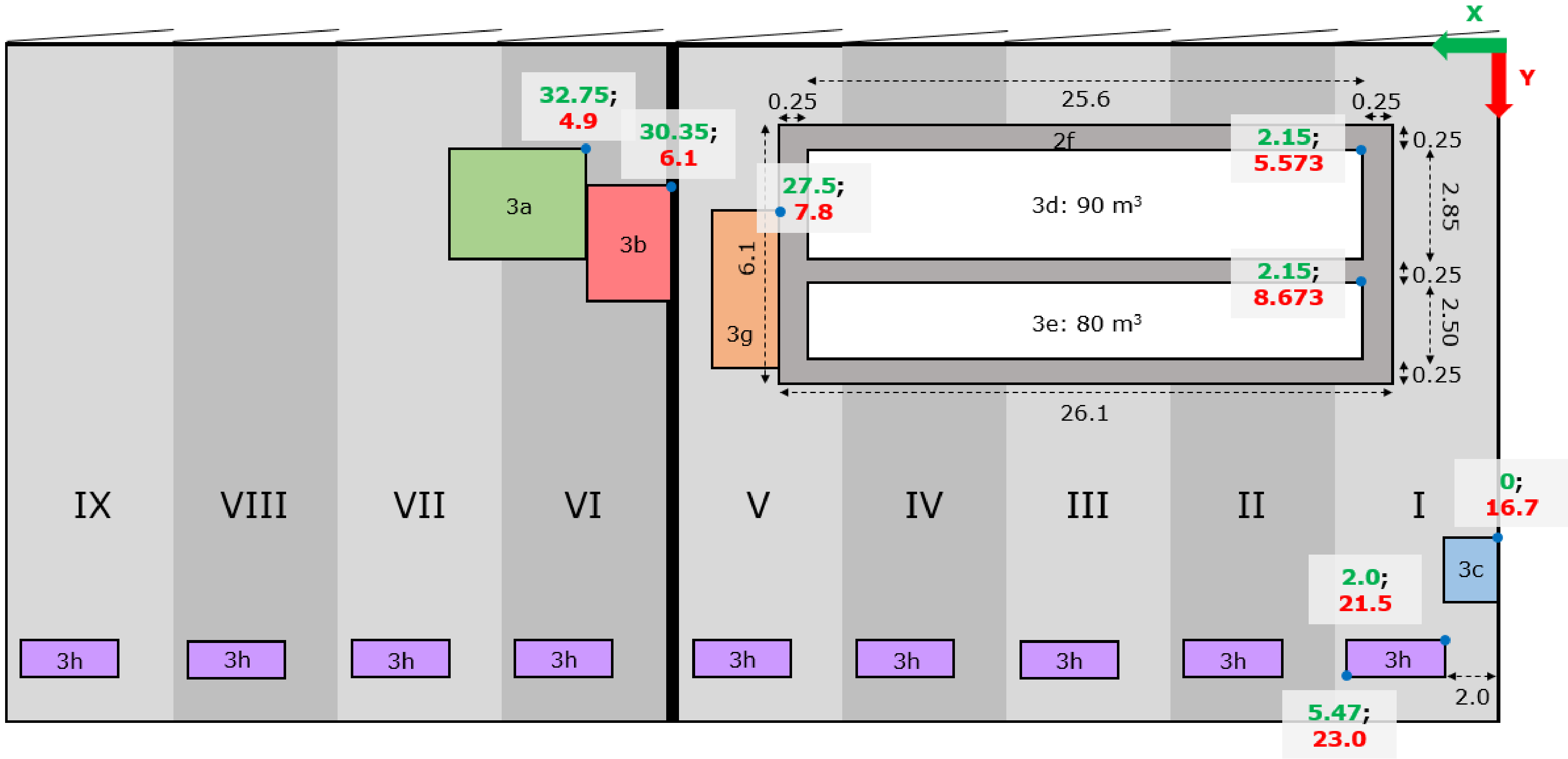


FIGURE 14: THE LOCATIONS OF THE MACHINE LOADS AND THE DIMENSIONS OF THE CONCRETE STORAGE CONTAINER OF THE FRESH WATER AND PROCESS WATER. THE HEIGHT OF THE CONCRETE STORAGE CONTAINER IS 1.2 M.

13. APPENDIX C: ALL CALCULATED TEMPERATURE GRADIENTS

In the tables below, all the possible temperature scenarios with the belonging temperature gradients are given. Each table covers one of the four structural elements: roof, outer wall, inner wall or floor. In the last column the temperature gradient working on the concrete can be found. The blue coloured rows are parts of Scenario 1 Extreme, while the green coloured rows are part of the common scenario, which can be used as comparison by the reader.

TABLE 30: ALL THE TEMPERATURE GRADIENTS IN APPEARING IN THE ROOF. THE BLUE ROW IS USED IN THE EXTREME SCENARIO (B-G). THE GREEN ROW IS USED IN THE COMMON SCENARIO (B-D).

Structural component: Roof				
Scenario	**Inner side**	**Outer side**	**Temperature gradient [˚]**	**ΔT in concrete [˚]**
A-a, A-b, A-c	Empty	Summer	T1 = 17.00 T2 = 31.26 T3 = 46.26 T4 = 51.00	T2 – T3 = -15.00
A-d, A-e, A-f	During composting process	Summer	T1 = 50.00 T2 = 50.00 T3 = 50.78 T4 = 51.00	T2 – T3 = -00.78
A-g, A-h, A-i	During an error	Summer	T1 = 85.00 T2 = 85.00 T3 = 58.56 T4 = 51.00	T2 – T3 = +26.44
B-a, B-b, B-c	Empty	Winter	T1 = 17.00 T2 = -00.61 T3 = -19.58 T4 = -25.00	T2 – T3 = +18.97
B-d, B-e, B-f	During composting process	Winter	T1 = 50.00 T2 = 50.00 T3 = -08.33 T4 = -25.00	T2 – T3 = -58.33
B-g, B-h, B-i	During an error	Winter	T1 = 85.00 T2 = 85.00 T3 = -00.56 T4 = -25.00	T2 – T3 = -85.56
C-a, C-b, C-c	Empty	Inside a large hall	T1 = 17.00 T2 = 17.00 T3 = 17.00 T4 = 17.00	T2 – T3 = 00.00
C-d, C-e, C-f	During composting process	Inside a large hall	T1 = 50.00 T2 = 50.00 T3 = 32.89 T4 = 17.00	T2 – T3 = +17.11
C-g, C-h, C-i	During an error	Inside a large hall	T1 = 85.00 T2 = 85.00	T2 – T3 = +35.26

			T3 = 49.74 T4 = 17.00	

TABLE 31: ALL THE TEMPERATURE GRADIENTS IN APPEARING IN THE OUTER WALL. THE BLUE ROW IS USED IN THE EXTREME SCENARIO (B-G). THE GREEN ROW IS USED IN THE COMMON SCENARIO (B-D).

Structural component: Outer wall				
Scenario	**Inner side**	**Outer side**	**Temperature gradient [˚]**	**ΔT in concrete [˚]**
A-a, A-b, A-c	Empty	Summer	T1 = 17.00 T2 = 28.95 T3 = 47.32 T4 = 51.00	T2 – T3 = -18.37
A-d, A-e, A-f	During composting process	Summer	T1 = 50.00 T2 = 50.00 T3 = 50.83 T4 = 51.00	T2 – T3 = +00.83
A-g, A-h, A-i	During an error	Summer	T1 = 85.00 T2 = 85.00 T3 = 56.67 T4 = 51.00	T2 – T3 = +28.33
B-a, B-b, B-c	Empty	Winter	T1 = 17.00 T2 = 17.00 T3 = 18.00 T4 = -25.00	T2 – T3 = +01.00
B-d, B-e, B-f	During composting process	Winter	T1 = 50.00 T2 = 50.00 T3 = -12.50 T4 = -25.00	T2 – T3 = +62.50
B-g, B-h, B-i	During an error	Winter	T1 = 85.00 T2 = 85.00 T3 = -06.67 T4 = -25.00	T2 – T3 = +91.67
C-a, C-b, C-c	Empty	Inside a large hall	T1 = 17.00 T2 = 17.00 T3 = 17.00 T4 = 17.00	T2 – T3 = 00.00
C-d, C-e, C-f	During composting process	Inside a large hall	T1 = 50.00 T2 = 50.00 T3 = 30.00 T4 = 17.00	T2 – T3 = +20.00
C-g, C-h, C-i	During an error	Inside a large hall	T1 = 85.00 T2 = 85.00 T3 = 43.79 T4 = 17.00	T2 – T3 = +41.21

TABLE 32: ALL THE TEMPERATURE GRADIENTS IN APPEARING IN THE FLOOR. THE BLUE ROW IS USED IN THE EXTREME SCENARIO (B-G). THE GREEN ROW IS USED IN THE COMMON SCENARIO (B-D).

Structural component: Floor				
Scenario	**Inner side**	**Outer side**	**Temperature gradient [˚]**	**ΔT in concrete [˚]**

Table 9	Empty	Ground	T1 = 17.00 T2 = 14.86 T3 = 10.00 T4 = 10.00	T2 – T3 = +04.86
Table 10	During composting process	Ground	T1 = 50.00 T2 = 50.00 T3 = 10.00 T4 = 10.00	T2 – T3 = +40.00
Table 11	During an error	Ground	T1 = 85.00 T2 = 85.00 T3 = 10.00 T4 = 10.00	T2 – T3 = +75.00

TABLE 33: ALL THE TEMPERATURE GRADIENTS IN APPEARING IN THE INNER WALL. THE BLUE ROW IS USED IN THE EXTREME SCENARIO (B-G). THE GREEN ROW IS USED IN THE COMMON SCENARIO (B-D).

Structural component: Inner wall				
Scenario	**Inner side**	**Outer side**	**Temperature gradient [˚]**	**ΔT in concrete [˚]**
A-a, B-a, C-a	Empty	Adjacent bunker: Empty	T1 = 17.00 T2 = 17.00 T3 = 17.00 T4 = 17.00	T2 – T3 = 00.00
A-b, B-b, C-b	During composting process	Adjacent bunker: Empty	T1 = 50.00 T2 = 50.00 T3 = 32.32 T4 = 17.00	T2 – T3 = +17.68
A-c, B-c, C-c	During an error	Adjacent bunker: Empty	T1 = 85.00 T2 = 85.00 T3 = 48.57 T4 = 17.00	T2 – T3 = +36.43
A-d, B-d, C-d	Empty	Adjacent bunker: During composting process	T1 = 17.00 T2 = 32.32 T3 = 50.00 T4 = 50.00	T2 – T3 = -18.00
A-e, B-e, C-e	During composting process	Adjacent bunker: During composting process	T1 = 50.00 T2 = 50.00 T3 = 50.00 T4 = 50.00	T2 – T3 = 00.00
A-f, B-f, C-f	During an error	Adjacent bunker: During composting process	T1 = 85.00 T2 = 85.00 T3 = 50.00 T4 = 50.00	T2 – T3 = +35.00
A-g, B-g, C-g	Empty	Adjacent bunker: During an error	T1 = 17.00 T2 = 48.57 T3 = 85.00 T4 = 85.00	T2 – T3 = -36.43
A-h, B-h, C-h	During composting process	Adjacent bunker: During an error	T1 = 50.00 T2 = 66.25 T3 = 85.00 T4 = 85.00	T2 – T3 = -18.75

A-i, B-i, C-i	During an error	Adjacent bunker: During an error	T1 = 85.00 T2 = 85.00 T3 = 85.00 T4 = 85.00	T2 – T3 = 00.00

14. APPENDIX D: THE NORMAL STRESSES CALCULATED BY SCIA ENGINEER

Table 34 contain the normal stresses that arise. The first table contains the influence of the thermal load Scenario 1 Extreme and the influence of all the loads on the construction. The construction is split into the four structural elements (roof, outer wall, floor, inner wall), to be able to study the influence of the forces on each element separately. The left column of the tables contains the stresses caused by only the thermal load (Scenario 1 Extreme in the first table and Scenario 2 Common in the second table). The right columns contains the stresses caused by all the loads, including the thermal load scenario. The scale of the normal stress figures can be seen in Figure 17. The scale is the same for every figure (-12 to 12 N/mm^2), so that the figures can be compared. The positive numbers (reddish) represent the tensile normal stress and the negative numbers (blueish) represent the compressive stress.

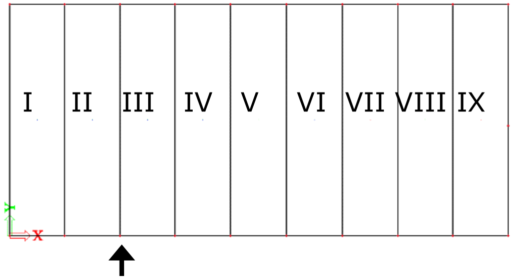


FIGURE 15: THE NINE CASE STUDY BUNKERS FROM THE TOP.

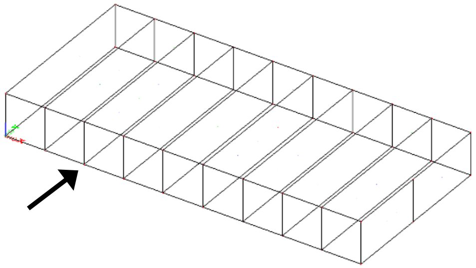


FIGURE 16: THE NINE CASE STUDY BUNKERS FROM THE SIDE (3D PERSPECTIVE).

The stresses are per structural element given in the X and Y direction. The Y direction follows the direction of the longest side of the structural element. The X direction follows the short side of the structural element, perpendicular to the Y. The direction of the stress indicates how the structural element is modelled. When the normal stress is calculated in the X direction, the structural element is seen as a beam in the X direction with a certain profile width and length lying in the Y direction. When the stress is calculated in the Y direction, the beam lies in the Y direction and the profile width in the X direction.

Figure 15 and Figure 16 show the nine case study bunkers from the top and from the side. The black arrow points in every figure in Table 34 to the same point: the floor between bunker II and III.

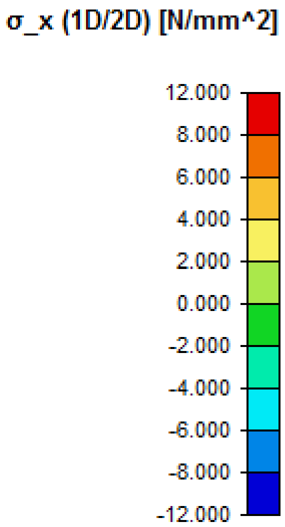
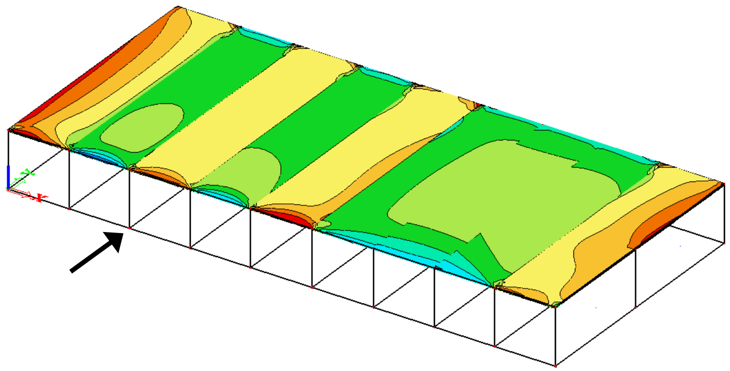
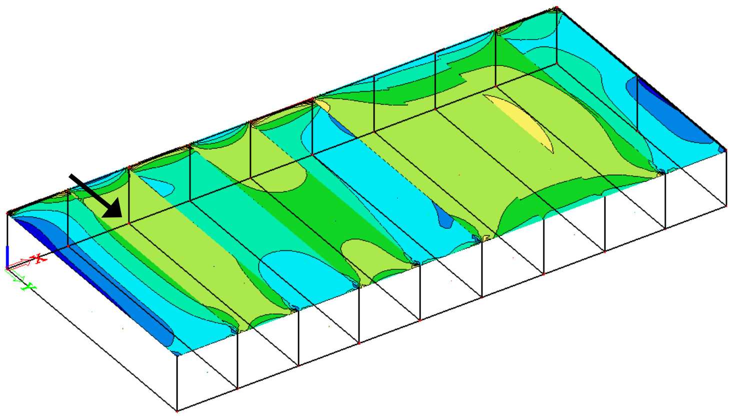
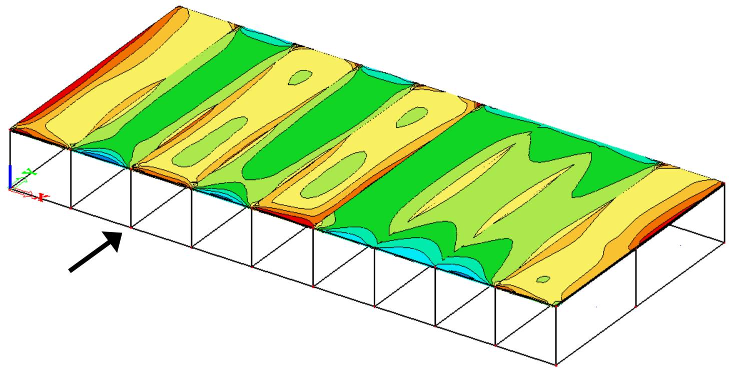
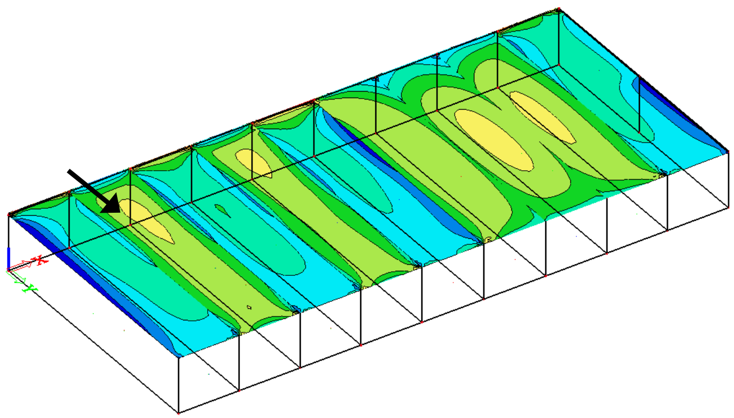
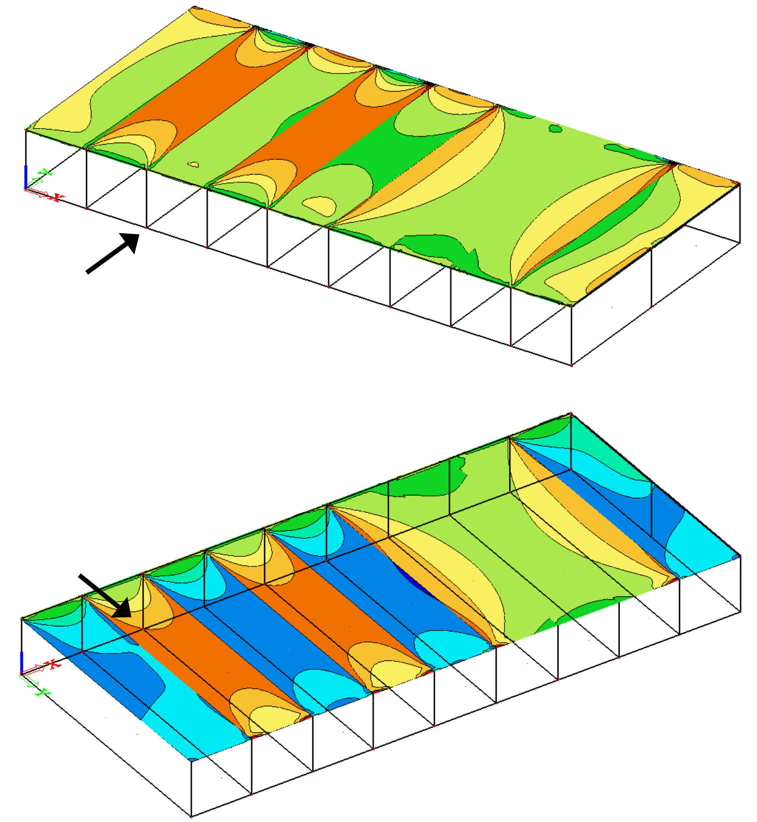
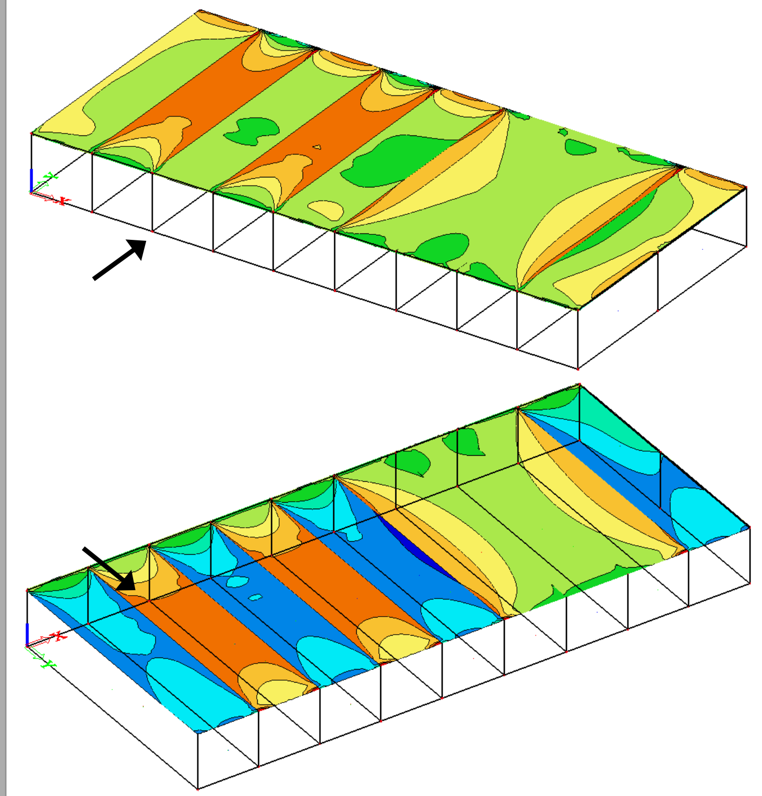
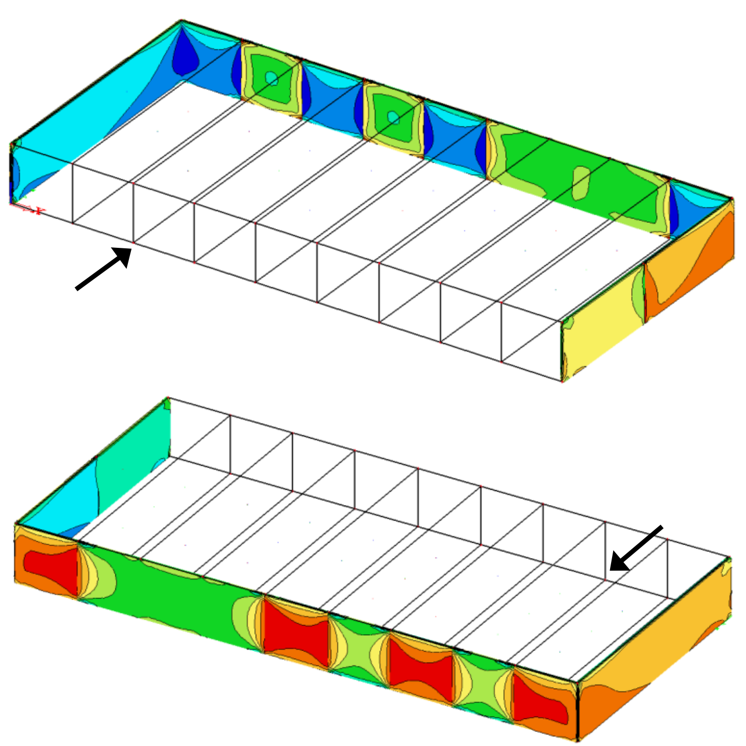
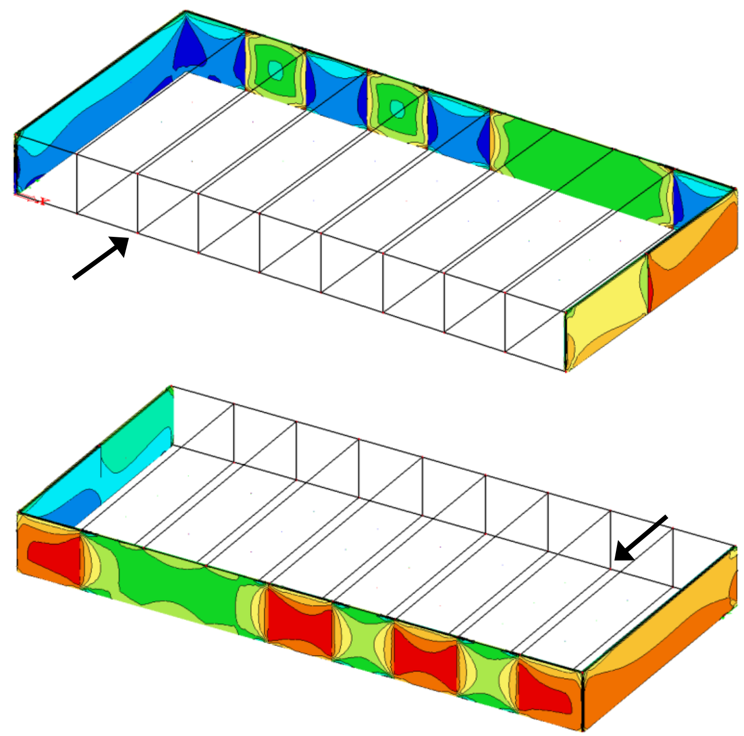


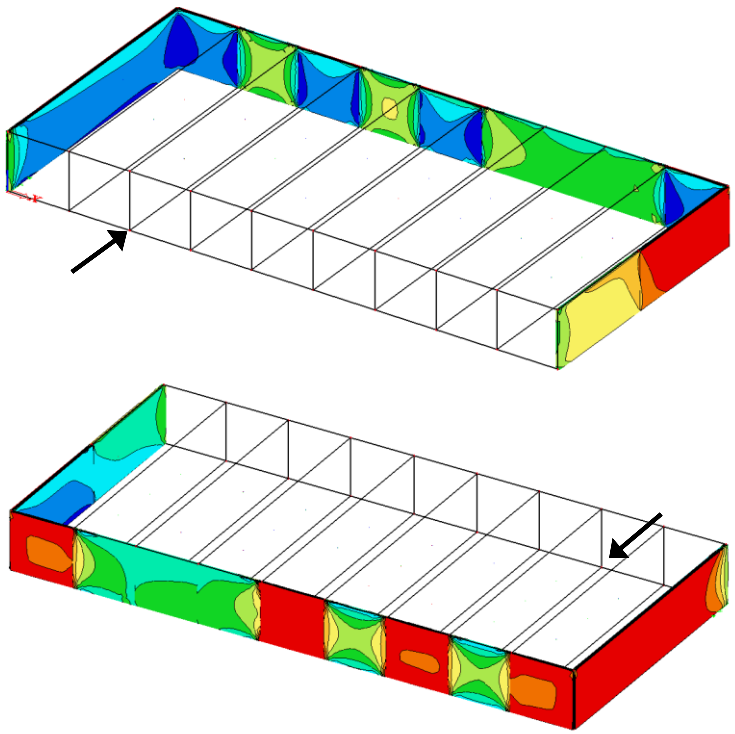
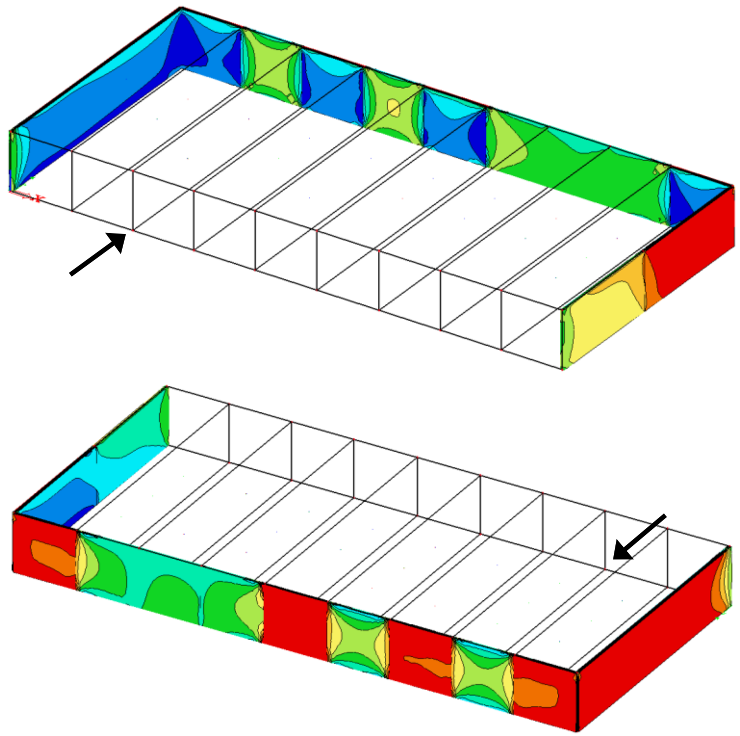
FIGURE 17: THE SCALE OF THE NORMAL STRESS FIGURES IN TABLE 34

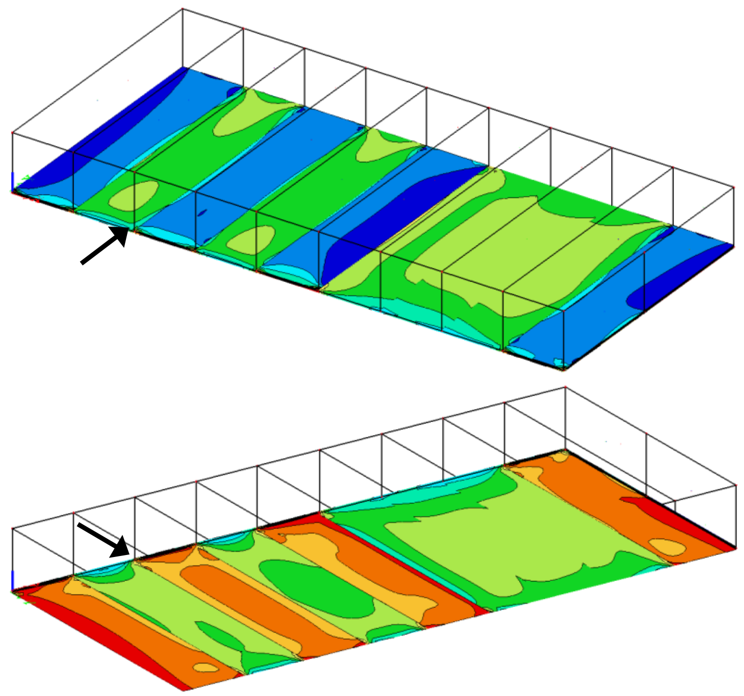
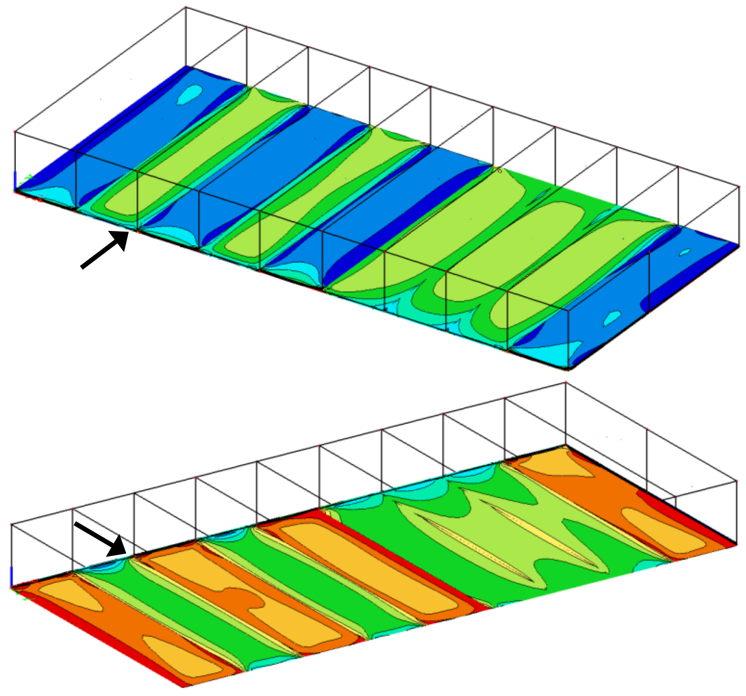
TABLE 34: THE TENSILE NORMATIVE STRESS [N/MM²] ARISING IN THE SCENARIO 1 (THE LEFT COLUMN) AND THE COMBINATION OF ALL LOADS AND SCENARIO 1 (THE RIGHT COLUMN). PER STRUCTURAL ELEMENT, THE ARISING NORMAL STRESSES ARE DISPLAYED WITH COLOURS IN THE X AND Y DIRECTION. THE ARROW IN EVERY PICTURE IS USED FOR ORIENTATION AND POINTS EVERY TIME TO THE FLOOR BETWEEN BUNKER II AND III.

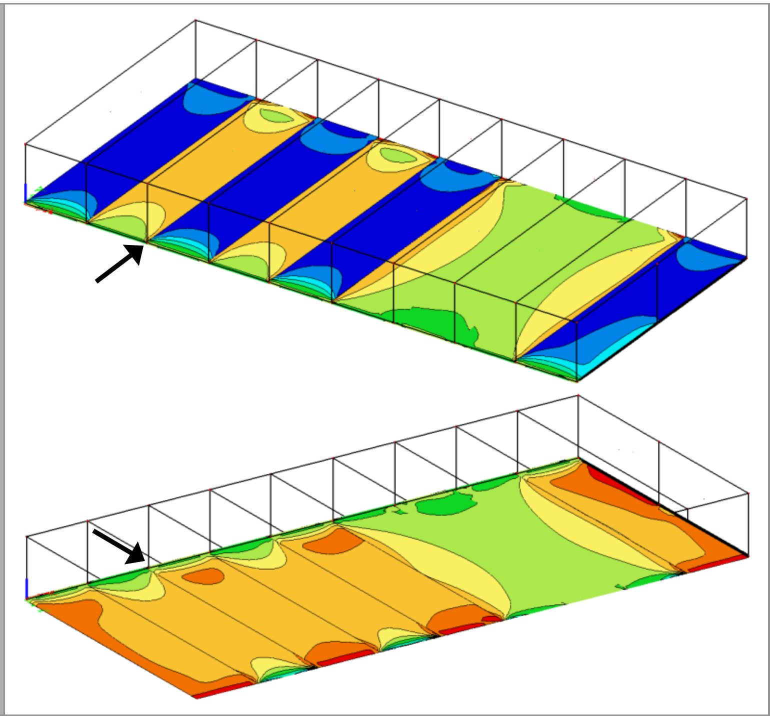
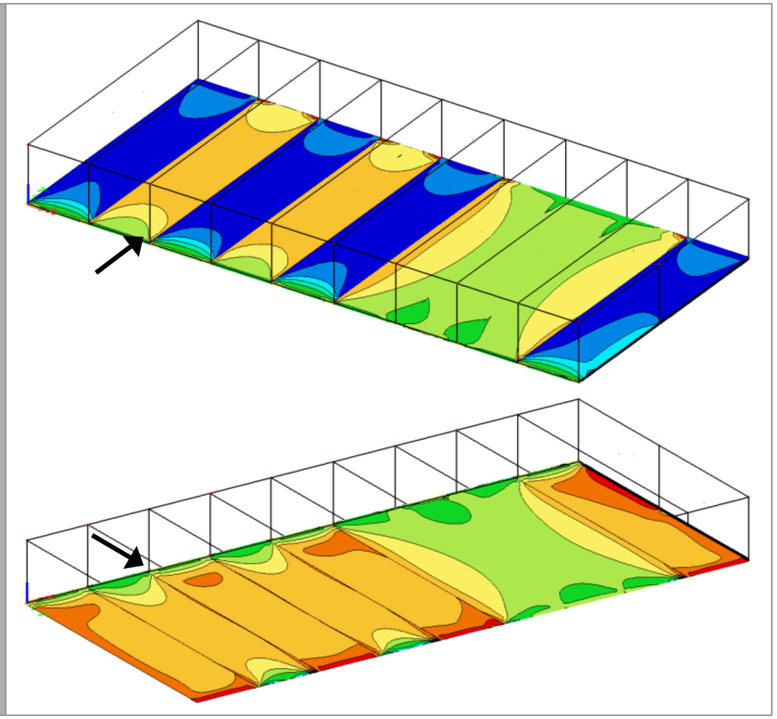
		Load case: Thermal load Scenario 1 Extreme		Normative load combination
Roof	X	 	X	 

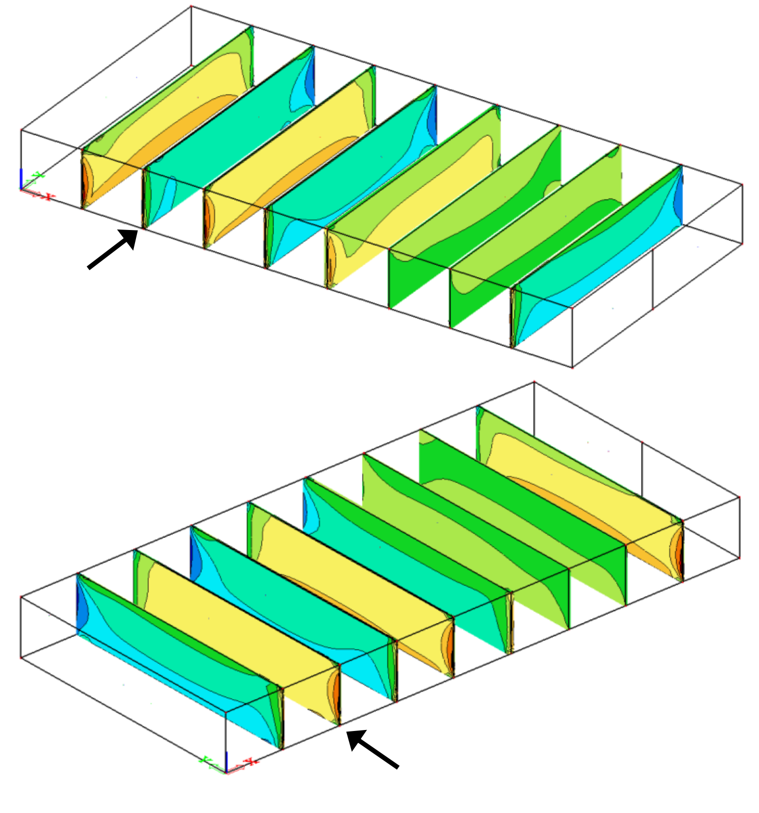
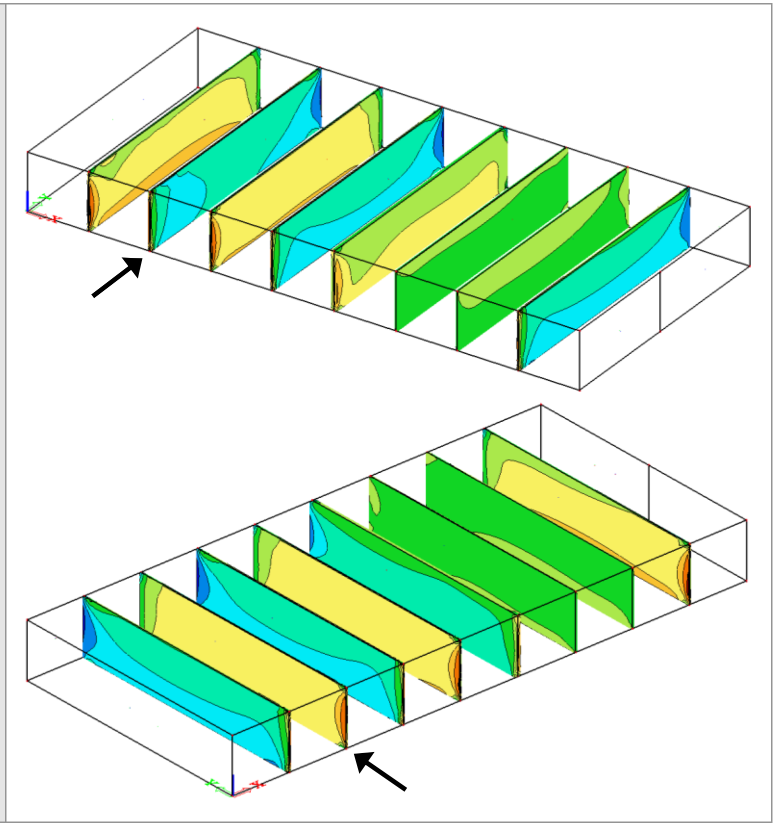
	Y		Y	

Outer wall	X		X	

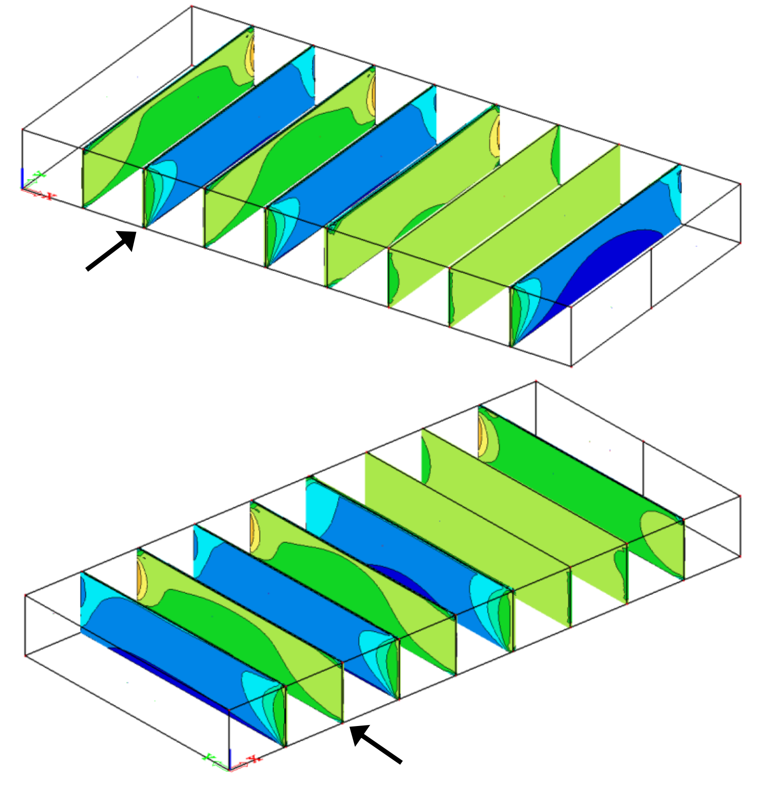
	Y		Y	

Floor	X		X	

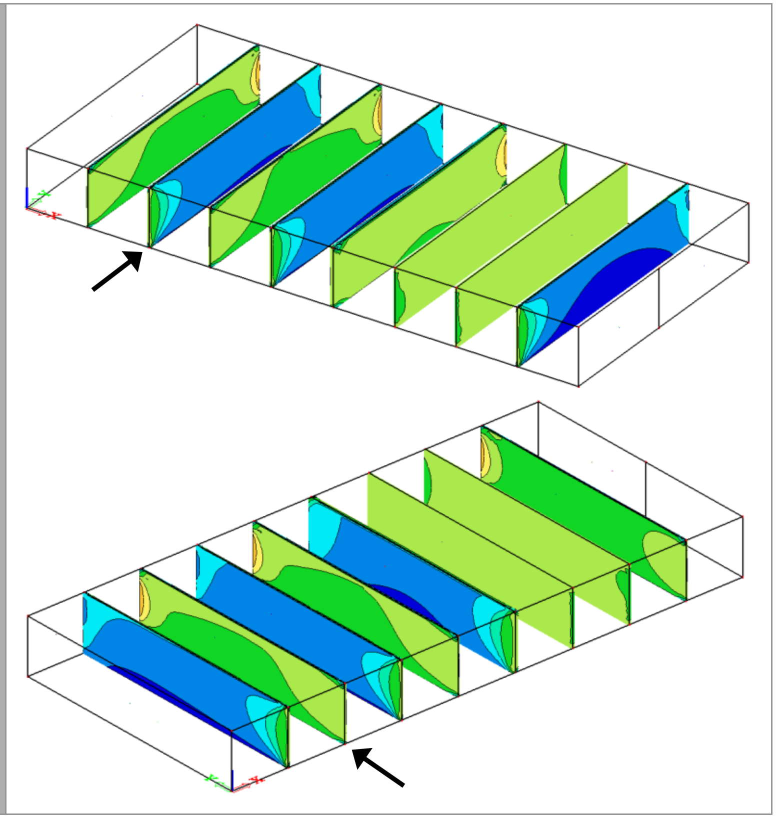
	Y		Y	

Inner wall	X		X	

Y



Y



15. APPENDIX E: COMPARISON TENSILE NORMAL STRESS

The calculated tensile normal stress is compared to the tensile stress the concrete can handle (3.21 N/mm^2). The red colour indicates that the concrete can't handle the tensile stresses caused by the thermal load (Scenario 1 Extreme).

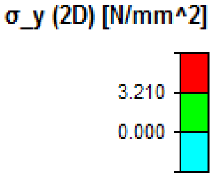
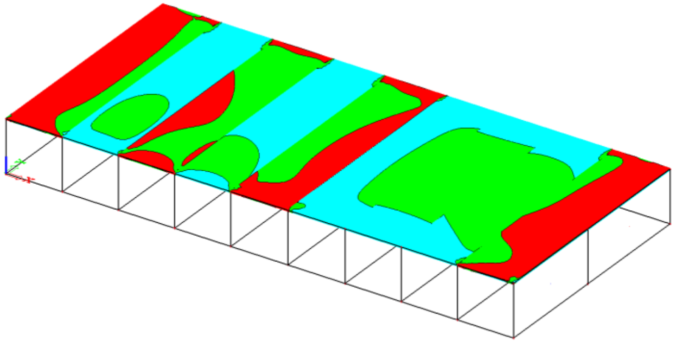
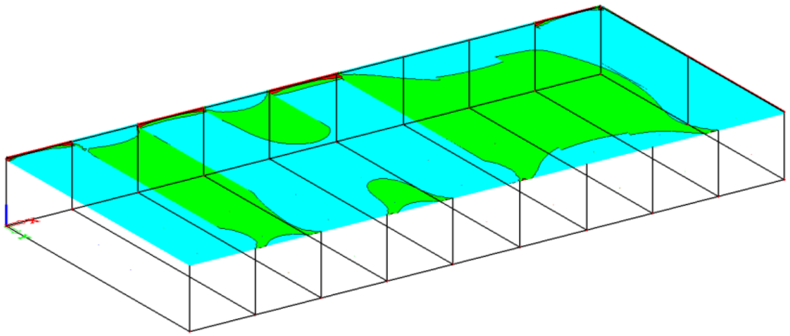
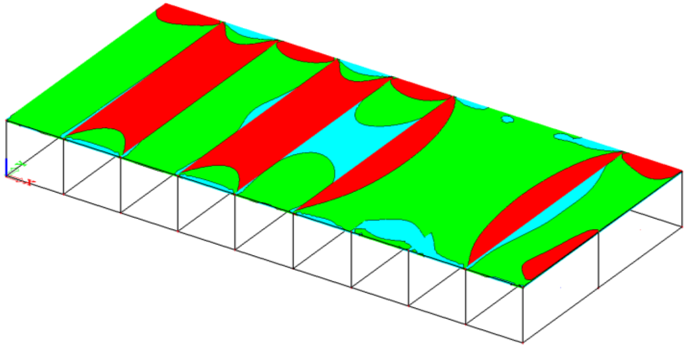
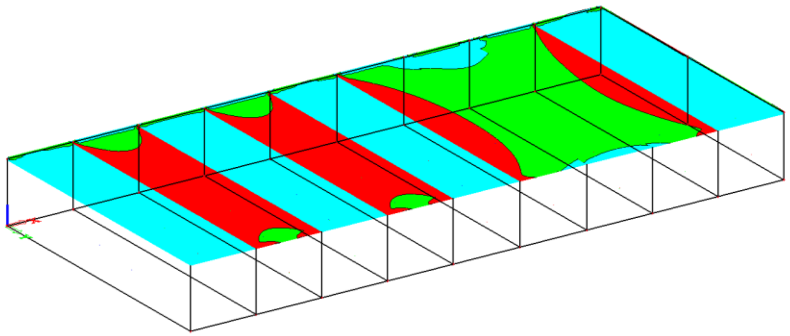
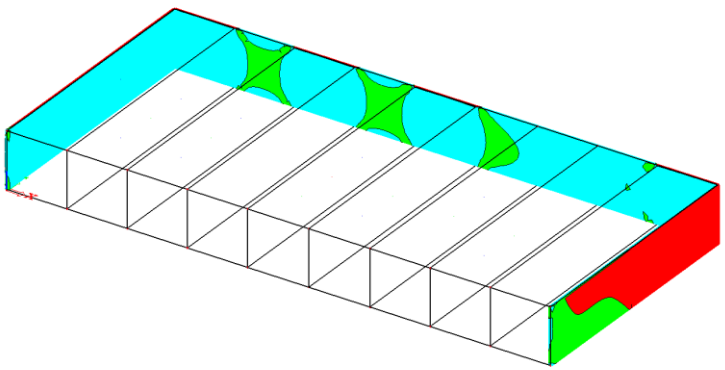
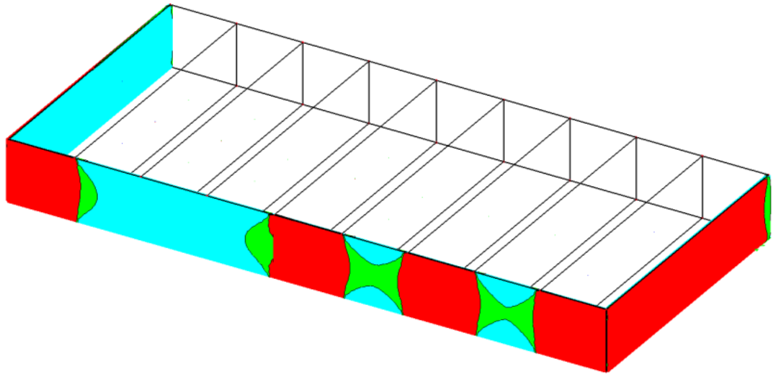
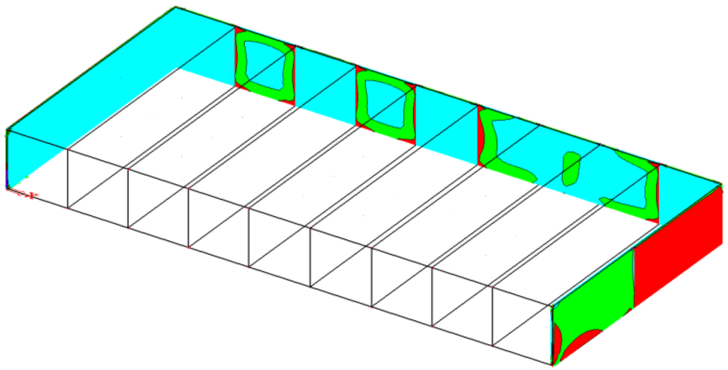
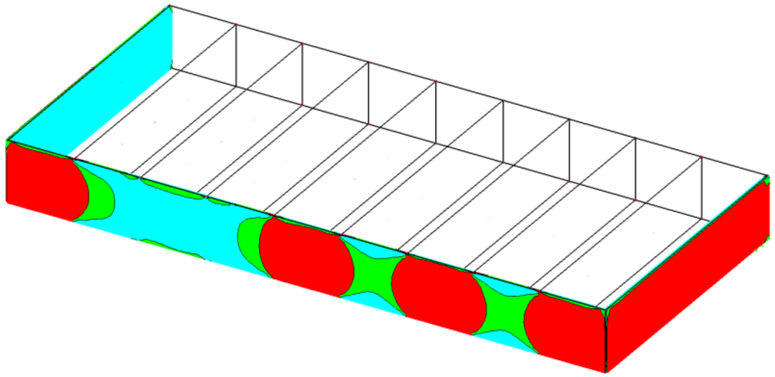
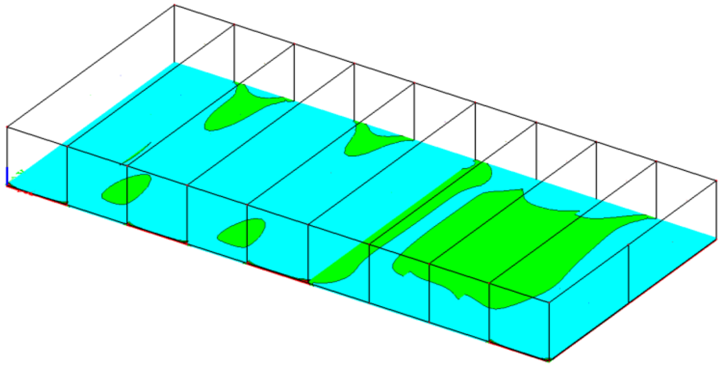
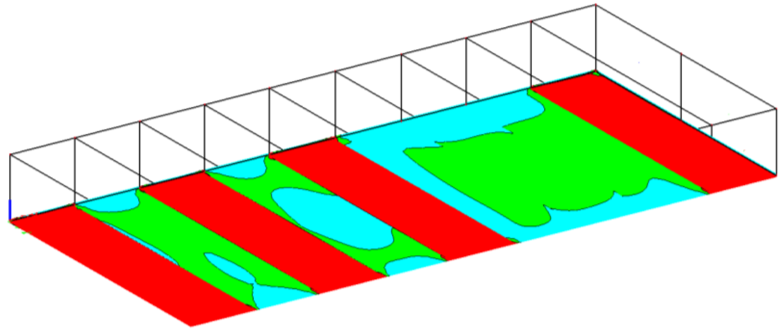
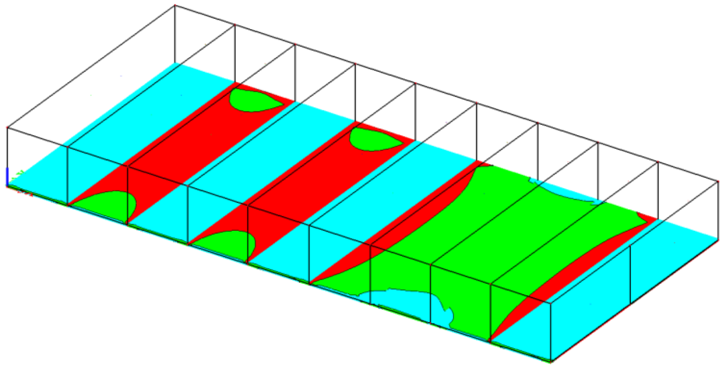
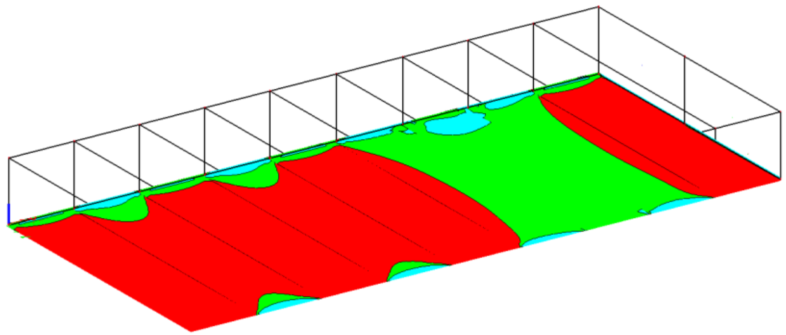


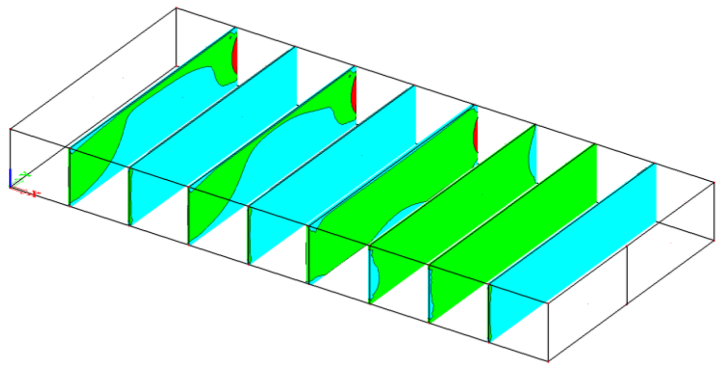
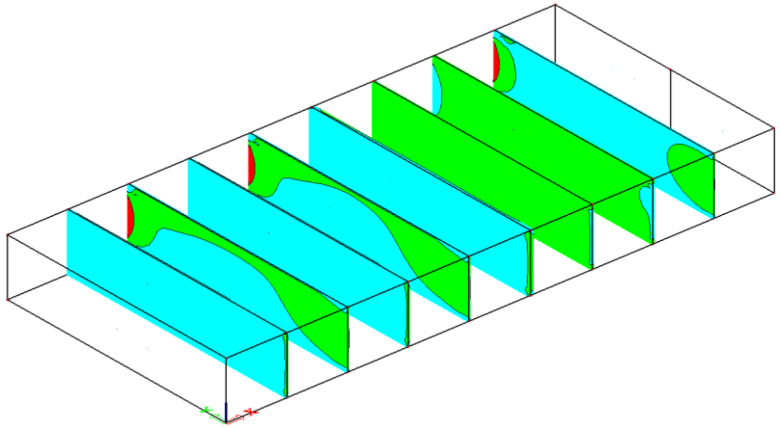
FIGURE 18: THE SCALE DISTRIBUTION.

TABLE 35:
RED: **CONCRETE *CANNOT* TAKE THE TENSILE NORMAL STRESS, CAUSED BY ONLY TEMPERATURE.**
GREEN: **CONCRETE *CAN* TAKE THE TENSILE NORMAL STRESS, CAUSED BY ONLY TEMPERATURE.**
BLUE: **THE COMPRESSIVE NORMAL STRESS.**

		Thermal load: Extreme	
Roof	X		
	Y		

Outer wall	X		
	Y		

Floor	X		
	Y		

Inner wall	X		
	Y