CHALMERS

FE-Analysis of a Beam-Column Connection in Composite Structures exposed to Fire

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design

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Cover:
On the left is a picture of a PCs corbel prototype and to the right the modelled corbel showing temperature distribution.

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ABSTRACT

The PCs corbel is a prefabricated beam-column connection produced by Peikko. Today the connection is only used in concrete columns where it has been proven to be a well functioning solution. Peikko wants to further develop the product by using it in a new context, together with a composite column, which in this case means a concrete filled steel tube. However, before modifying the PCs corbel and applying it in this type of column, research must be done. This master thesis focuses on how the load bearing capacity of the PCs corbel is affected by exposure to fire. Steel loses stiffness at relatively low temperatures and therefore when used in this kind of construction it must be investigated if the capacity of the system is high enough even at elevated temperatures.

The aim of this thesis is therefore to study if the benefits of using the PCs corbel can be transferred to the new composite system. One main objective is to investigate the extent to which the column cross section affects the behavior of the connection at elevated temperatures. Two types of cross sections are analyzed: circular and rectangular.

A finite element model was established in the software Abaqus, in this model both static and thermal simulations were performed. The thermal simulation ended in a temperature distribution after 60 minutes of fire and all material properties changed according to this. The following mechanical simulation uses these changed material properties in a static analysis to study the stress distribution in the connection and the surrounding structural elements. Bond slip between steel and concrete and the non-linear behaviour of concrete are not taken into account.

The simulations show that the cross section of the column is of minor importance in this study. Columns with circular and rectangular cross section, and with almost identical cross sectional area, were analyzed and the difference was found to be small enough not to be governing the fire design. As the temperature rises stress redistribution can be observed from the steel shell to the concrete core.

It should be noted that this is a pre-study for further investigations according development of the PCs corbel, but from the results presented no reasons can be seen why this development should not continue.

Key words: Composite column, concrete, steel, thermal analysis, static analysis, PCs corbel, finite element modeling, Abaqus

FE-analys av pelar-balk koppling avsedd för samverkanskonstruktioner utsatta för brand
Examensarbete inom Masterprogrammet Structural Engineering and Building Performance Design

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SAMMANFATTNING

PCs konsolen är en prefabricerad pelar-balk koppling som produceras av Peikko. Idag används kopplingen endast i armerade betongpelare där den har visat sig vara en framgångsrik produkt. Peikko vill nu vidareutveckla PCs konsolen för att kunna använda den i samverkanspelare. Förändring av PCs konsolen kräver utredningar avseende till exempel hur bärförmåga påverkas. Detta examensarbete fokuserar på hur kopplingens bärförmåga påverkas av brand. Stål förlorar sin styvhet redan vid relativt låga temperaturer därför är denna studie motiverad.

Syftet med examensarbetet är att studera om PCs konsolens positiva egenskaper kan utnyttjas i det nya systemet. En annan av huvuduppgifterna är att utreda i vilken omfattning pelarens tvärsnitt påverkar kopplingens beteende vid förhöjda temperaturer. Två olika tvärsnitt analyseras: cirkulärt och rektangulärt.

Finita element modeller skapades i Abaqus där både statiska och termiska simulationer genomfördes. Den termiska simulationen avslutades efter 60 minuters brand vilket resulterande i en temperaturspridning som i sin tur leder till förändring av materialegenskaperna. Efterföljande mekaniska simulering använder de förändrade egenskaperna för att studera spänningsfördelningen. Vidhäftning mellan stål och betong samt icke linjära egenskaper hos betongen har inte beaktas i modellen.

Simuleringarna visar att skillnaden mellan tvärsnitten är marginella. Pelare med liknade tvärsnittsarea men med olika tvärsnittstyper studerades och skillnaden var tillräckligt liten för att inte vara avgörande vid branddimensionering. Resultaten visar också en tydlig omfördelning av spänningar från det omgivande stålskalet till den inre betongkärna.

Det skall förtydligas att examensarbetet är en förstudie för vidareutvecklingen av PCs konsolen. Resultaten presenterade i denna rapport påvisar dock inga tydliga hinder mot dessa planer.

Nyckelord: Samverkanspelare, betong, stål, termisk analys, statisk analys, PCs konsol, finita element modellering, Abaqus

Contents

Preface

This master thesis was carried out at the Department of Structural Engineering at Chalmers University of Technology in cooperation with Peikko Sverige AB.

A special thanks to our supervisor and examiner Mohammad Al-Emrani, Associate Professor at the Department of Structural Engineering for guidance and expertise. Also thanks to our co-supervisor Fredrik Larsson, Associate Professor at the Department of Applied Mechanics, for his expertise and help with interpreting the results.

The idea to this project was presented by Peikko and we are grateful for giving us the opportunity to do this as a master thesis. Special thanks to Eric Bengts, Jason Martin and Kenneth Sühl which is those we have had contact with at the company.

Bijan Adl-Zarrabi, Assistance Professor at the Department of Civil and Environmental Engineering, who contributed with his knowledge in fire design which was invaluable for our thesis.

A special thanks also to our opponents Christoffer Isaksson and Markus Johansson for their interest and comments on the report. Also thanks to our roommates this semester, Martin Persson and Sebastian Wogelberg, for good cooperation and contribution to a nice atmosphere in the office.

Göteborg May 2011

Joakim Kvist, Daniel Näkne

Notations

Roman letters

h_c	Convection coefficient
T_0	Initial temperature
T_a	Ambient temperature
T_s	Surface temperature
t	Time
q_c	Convective heat flux
q_r	Radiation heat flux

Greek letters

γ_c	Partial safety factor
ε	True strain
ε_a	Emissivity of ambient
ε_{nom}	Nominal strain
ε_s	Emissivity of surface
σ	True stress
σ_b	Stephan-Boltzmann's constant
σ_{nom}	Nominal stress
σ_{Rd}	Stress capacity
ϕ	Shape factor, radiation

Abbreviations

CFCHS	Concrete Filled Circular Hollow Section
CFHS	Concrete Filled Hollow Section
CFRHS	Concrete Filled Rectangular Hollow Section
EC	Eurocode
PCs	Peikko Corbel short

1 Introduction

Reducing the costs is one of the most important things in the competitive building sector of today. Use of standard solutions for different cases similar to each other can reduce working hours both in design and construction stage, which saves money for the actors. With a standard solution there is also a higher chance that all components have the same high quality and the risk for unforeseen errors are kept to a minimum.

This master thesis is focusing on one such standard solution. A connection detail in steel used to connect a beam to a column for composite steel concrete structures. The studied detail is called the PCs corbel and is produced by Peikko AB. PCs stand for 'Peikko Corbel short'.

Due to the high thermal conductance of the steel the corbel will act as a reversed thermal bridge during fire. This can affect the properties of the concrete core and lead to a decreased load bearing capacity of the connection.

1.1 Background

The idea to this master thesis was presented by Peikko Sverige AB. They are producers and developers of prefabricated building components, mainly in steel constructions. The component studied in this thesis is a connection detail between composite steel concrete columns and beams, called PCs corbel, see Figure 1.
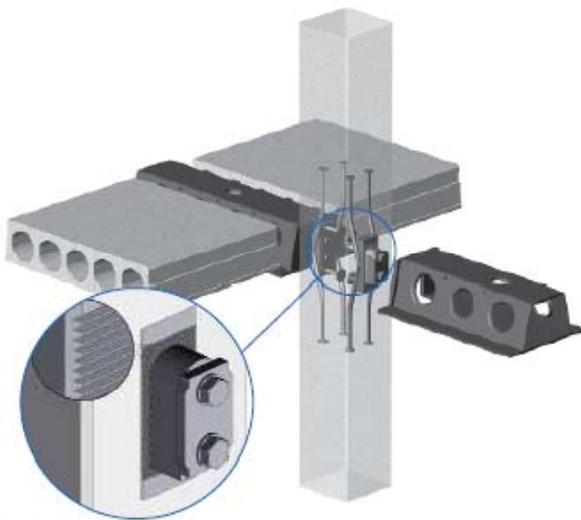
Figure 1: Illustration of a PCs corbel placed in a column

The PCs corbel is today only used in reinforced concrete columns. But as a step towards making this corbel a standard solution even for composite steel concrete columns a computer analysis of its fire behaviour has to be performed.

Changes of the corbel design are made to adapt the corbel to a composite column. The steel shell of the column makes it possible to remove the anchorage bars and replace their function with both welds around the corbel and a U-shaped steel plate. Welds and U-shaped plate have the purpose to transfer the shear forces to the steel shell and concrete core respectively.

An investigation about the most favourable column cross section of two given alternatives is also an issue, one circular and one rectangular. These cross section types will further on be

referred to as CFCHS and CFRHS, short for Concrete Filled Circular Hollow Section and Concrete Filled Rectangular Hollow Section or CFHS when both types are represented. See cross sections in Appendix A. The comparison regards the behaviour under fire and heat distribution through the corbel and the column.

For accurate simulation results it is important to know how the material properties change when temperature raises.

1.2 Aim and Objectives

The aim of this master thesis is to investigate if the new modified PCs corbel is an efficient solution when considering fire design. It should in addition tell to what extension the corbel design affects the heat distribution into the column, and if the strength is reduced due to this.

Other objectives are:

- To investigate if the column cross section shape affects the heat distribution in the areas close to the connection.
- To provide a base for further investigations and development of this specific corbel and similar products regarding fire design.

1.3 Method

Initially a literature study is performed to get a better knowledge about the behaviour of composite structures in general and especially under fire. Studies about the interaction between the structural components and the materials bonding when exposed to elevated temperatures are done for better modelling results.

To get a realistic picture of how the connection is working both before and after fire is a FE-model established and analyses are performed in the software Abaqus. The modelling results are then analysed concerning both thermal results and stress redistribution due to the thermal distribution.

Comparisons are made and based on the results a discussion about design and suitability to use the modified PCs corbel in this situation is initiated.

1.4 Limitations

The fire behaviour studied is according to fire class R60, which means that the corbel should have enough capacity to carry the loads throughout 60 minutes of fire.

The PCs corbel is available in several different sizes. This report focuses one of them, called PCs-3.

Stirrups are excluded in the Abaqus model. Stirrups are placed more dense close to the corbel, this to hold the cross section together as the outer steel shell loses its capacity when exposed to elevated temperatures. It is possible that these stirrups also can have a small effect on the temperature distribution since steel transfer heat considerably faster than concrete. However, due to the complexity of the model it would lead to an exclusion of these bars are justified. Stresses will nevertheless be checked and analyzed to see where stirrups are needed.

2 Literature Review

This chapter intends to summarize the basic knowledge needed to understand the extent of the issue regarding modelling, problem description and interpretation of results.

2.1 Composite Structures

Composite structures mean that multiple materials work together as a single structural component. One common composition in construction context is steel and concrete, which in this report will be referred to as 'composite structures'.

The use of composite structures comes initially from the idea to protect steel columns from fire by encasing them in concrete. This encasing was first considered just as cover. When calculating the capacity of the column the concrete was neglected. It was later found that the effective slenderness ratio of the encased column was significantly increased which also gives a positive effect to the buckling resistance (Johnson 2004).

Today composite structures are used for many different purposes. For fast erection of a floor slab it is quite common to use a corrugated steel sheet as a permanent formwork. Composite columns are often used when there is a need for slim construction, for example of aesthetic reasons. Other reasons could be structural members with an increased risk for accidental loads, such as impact from traffic, earthquake or fire (Shanmugam & Lakshmi 2001). The use of composite structures can also reduce building time. For example there is no need for formwork when enclosing steel is used. Instead the steel works as formwork for the concrete to be casted into (INSDAG 2011).

One of the most important benefits with using composite steel and concrete building components is that the strength of a given cross-section can be increased without changing the outer dimensions. For example the column in a multi-storey building can have the same dimension on all floors, even if the columns near ground level carry higher loads. This since the material composition of the column core can be changed to a higher concrete strength, combined with a higher amount of reinforcement or other modifications. This way of designing gives a unanimity which can be appreciated from an architectural detailing point of view (INSDAG 2011).

Another positive effect, which is an important part in this report, is the fire protection the concrete gives the steel. For optimal fire performance the steel should be enclosed by the concrete, but even with the steel exposed on the outside the load bearing strength is increased compared to a structure in pure steel, this due to the concretes high thermal mass (Purkiss 1996). Read more about material behaviour in elevated temperatures in Chapter 2.2.

The analyses presented in this report are made on concrete filled steel tubular columns with either cylindrical or rectangular shape. Which basically is a reinforced concrete column enclosed by a thin steel shell.

2.1.1 Possible Failure Modes for Composite Columns

During normal conditions a composite column failure mode depends mainly on its slenderness. For short length columns a combination of concrete crushing and yielding in the steel defines the failure mode. Intermediate columns failure mode is instead partial yielding in the steel and a combined crushing and cracking failure of the concrete. Very slender columns are most likely to fail in buckling or global instability (Shanmugam & Lakshmi 2001).

The external steel shell can also fail in local buckling, but compared to only steel columns the capacity with reference to local buckling is increased. It should be noted that if the criteria in Figure 2 are fulfilled there is no considerable risk for local buckling (EC 1994-1-1 2005).
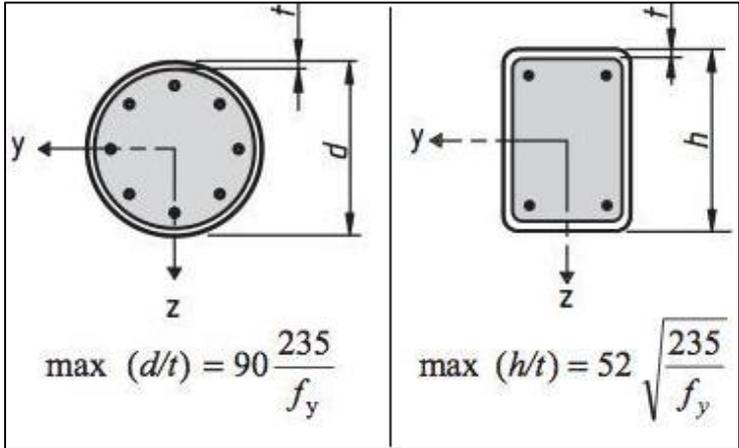

Figure 2: Slenderness calculations according to (EC 1994-1-1 2005)

2.2 Behaviour of Steel and Concrete at Elevated Temperatures

Several concrete and steel properties change with increased temperature, for example Young's modulus and thermal conductivity. Both of these properties decrease considerably when exposed to temperatures developed in a fire, which makes them important to consider.

Curves and diagrams presented in this chapter are all following the standard definitions used in Eurocode.

2.2.1 Steel

Common knowledge about structural steel is that it loses both stiffness and strength at relatively low temperatures, especially considering temperatures developed during a fire. This can be seen when plotting the relative Young's modulus against steel temperature, see Figure 3. The properties vary depending on how the steel is treated, hot rolled steel show a slightly higher capacity during fire than cold rolled. Reinforcement steel can be either hot or cold rolled depending on quality. The hot rolled reinforcement steel B500BT, used in this thesis, is one of the most used qualities in concrete structures today.
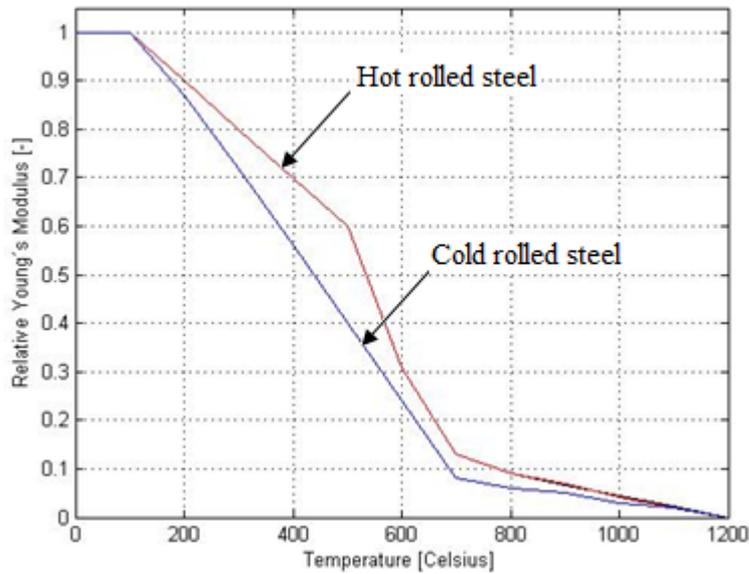
Figure 3: Relative Young's modulus vs. temperature, hot rolled and cold rolled steel (EC 1993-1-2 2005)

Yield strength of steel is also highly depending on the temperature. Up to $400\,^{\circ}C$ it is considered to be constant, but after this limit decreases rapidly, see Figure 4.
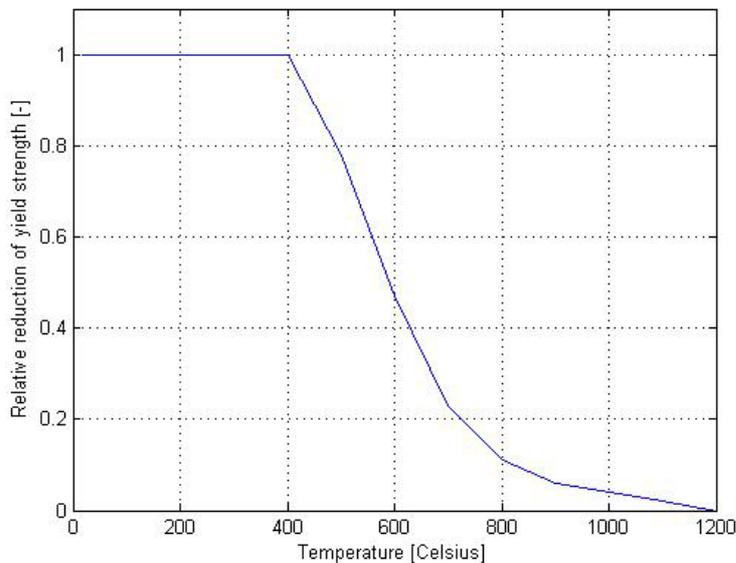
Figure 4: Relative yield strength vs. temperature for steel (EC 1993-1-2 2005)

The thermal conductivity of steel is also temperature dependent. In Eurocode the temperature dependence is considered to be linear up to $800\,^{\circ}C$ and then be constant 27.3 W/m$^{\circ}$C, see Figure 5.
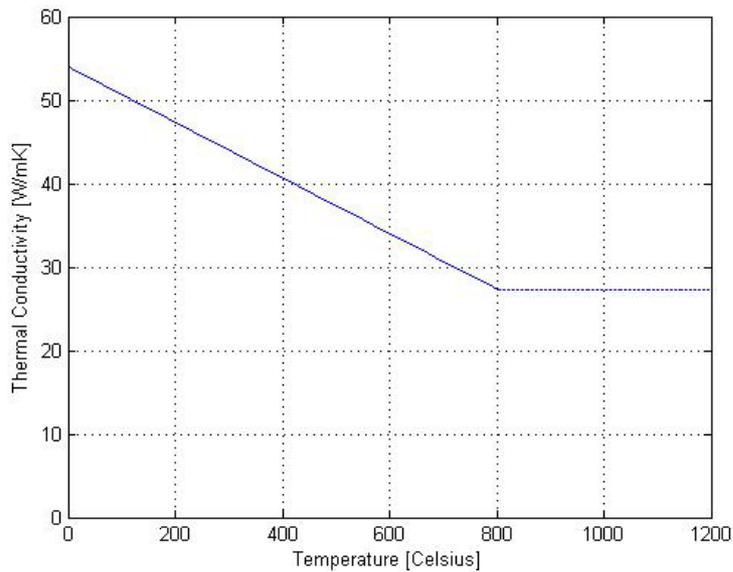
Figure 5: Thermal Conductivity vs. temperature for steel (EC 1993-1-2 2005)

Specific heat capacity is a measurement on how much energy it takes to increase one kilogram of a specific material one degree Celsius. For steel the specific heat capacity can be approximated a constant value of 600 J/kg$^{\circ}$C for all temperatures except around 735°C where discontinuity occurs, see Figure 6. One explanation to this discontinuity is that a phase transition takes place in the steel around these temperatures (Burström 2007).
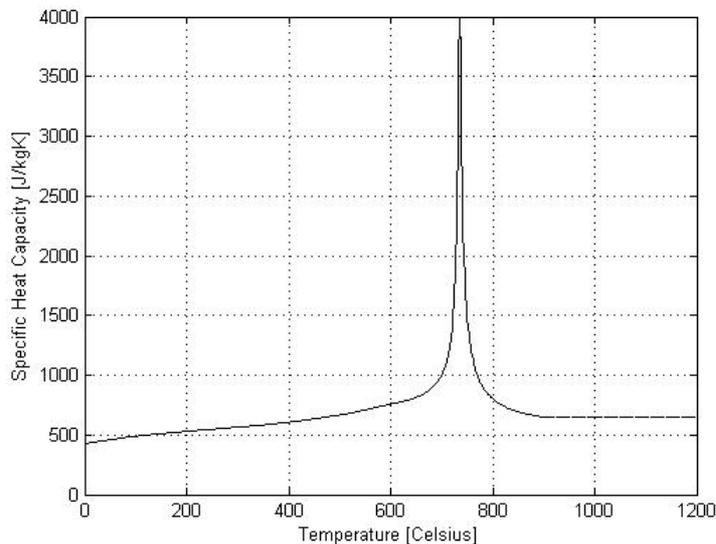
Figure 6: Specific heat capacity vs. temperature for steel (EC 1993-1-2 2005)

2.2.2 Plastic Behaviour of Steel

Plastic deformations occur when stresses are higher than the yield strength of the material, which means that the elastic deformations are exceeded. Plastic deformations are therefore remaining even after unloading the structure.

As the temperature of steel raise, several physical effects take place. One of the most important is the decrease of the yield strength, which means that in a fire plastic deformations

will be initiated earlier than for steel at room temperature and the plastic deformations will therefore be larger than it would be at a normal case.

In Eurocode the yield stress is assumed to be constant up to 300°C but decreasing afterwards for higher temperatures, see Figure 7. Note that only the plastic phase is plotted, the elastic deformation up to the yield strength, $\varepsilon=0.02$ is excluded.
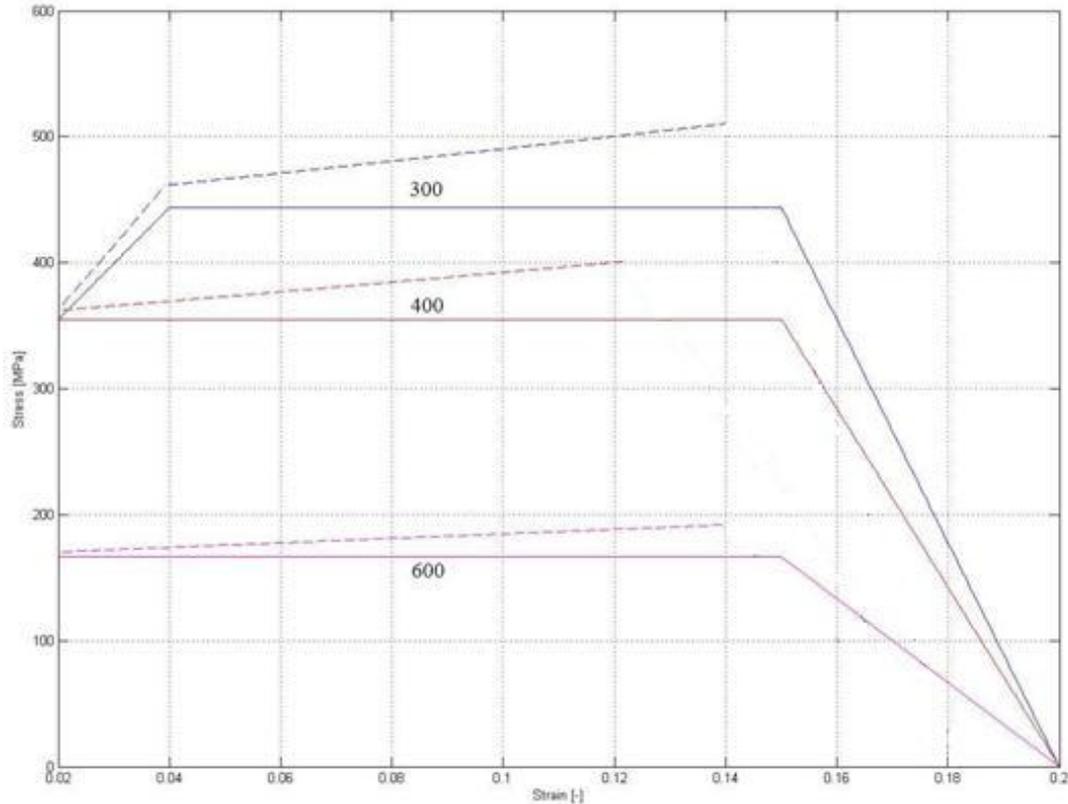
Figure 7: Plastic Stress-Strain curves (solid line) and True stress–True strain curves (Dotted lines)

As can be seen in Figure 7 does the steel continue to strain-harden all the way to fracture, which means that the stress needs to increase for producing more deformation, compare the plateau for the solid line to the dotted lines small increase in the figure above. Taking this strain-hardening into account give the so called 'True stress-True strain curve' (Key to Metals 2011).

The true stress σ is defined in Equation 1 and true strain in Equation 2:

$$\sigma = \sigma_{nom}(\varepsilon_{nom} + 1) \qquad\qquad (1)$$

$$\varepsilon = ln(\varepsilon_{nom} + 1) \qquad\qquad (2)$$

In Figure 7 the nominal values are represented by a solid line and they are from Eurocode standards.

2.2.3 Concrete

When concrete is heated it loses capacity due to both chemical and physical reactions that affect the composition of the ingredients. Below some temperature intervals are listed and the main changes are summarized.

- 100-200°C: The free water evaporates and the vapour pressure is increased. The strength of the cement paste is constant and the aggregates increase in volume deepening on type. No drastic change in structural strength.

- 200-500°C: The free water is now evaporated and the chemical bound water starts to separate from the cement paste. This leads to a contraction of the cement paste, even though the cement itself expands during the temperature increase. The reduction of the concrete strength, at this stage, is highly depending on the aggregate type. The structural strength is reduced more rapidly in this temperature interval (Svensk Byggtjänst 1994).

- 500-900°C: Calcium hydroxide, which is a component in the cement paste, starts to separate into water vapour and lime stone. During this temperature interval the largest contribution to the concrete strength comes from the aggregates. This is the interval where the concrete strength is decreased in the most rapid way.

- 900-1200°C: There is no water left to evaporate and there is no interaction between the concrete components. The concrete structure has lost over 90 % of its original capacity.

During the entire heating process micro cracks can occur due to different behaviour and geometry of the ingredients (Betongvaruindustrin 2007). The high vapour pressure built-up when the concrete is heated can lead to spalling of the concrete cover. In a CFHS the steel shell will stop the concrete cover to fall off, but it do not change the fact that the vapour pressure is significantly increased. According to Plos[1], there is a need for small holes in the shell to let some of the vapour out which prevents the column from damage. These holes are often placed near the top and bottom of the column. Due to the reactions explained, the material properties will change, which is shown in changes such as Young's modulus, thermal conductivity and specific heat capacity.

Young's modulus for concrete is reduced when exposed to high temperatures, see Figure 8. As for most materials concrete loses a large part of its capacity when the temperature is increasing, but due to high thermal mass the temperature will increase relatively slow. The heat buffering properties gives a positive effect since the temperature raise will be postponed over a longer period of time.

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[1] Mario Plos, Department of Structural Engineering Chalmers, 2011-02-24
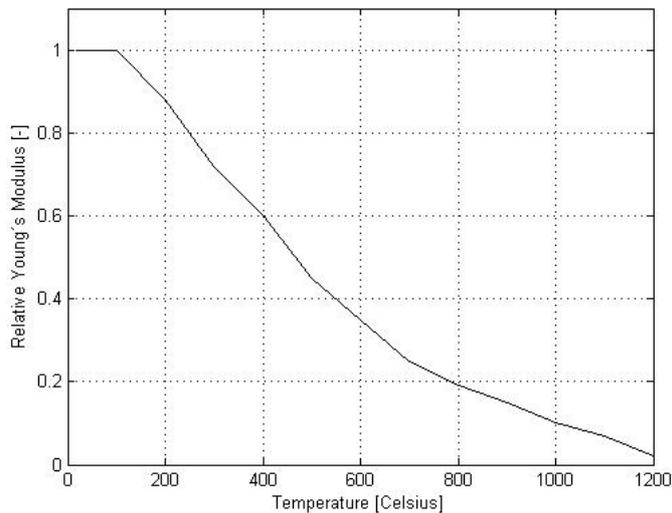
Figure 8: Young's modulus vs. temperature for concrete

The thermal conductivity for concrete at room temperature is normally 1.7 W/m$^{\circ}$C, to be more accurate one should say that it differs depending on the concrete composition from about 1.4 to 2.0 W/m$^{\circ}$C, mainly depending on the aggregate type.

Thermal conductivity is decreasing with increasing temperature, and difference between concrete compositions becomes less significant, see Figure 9.
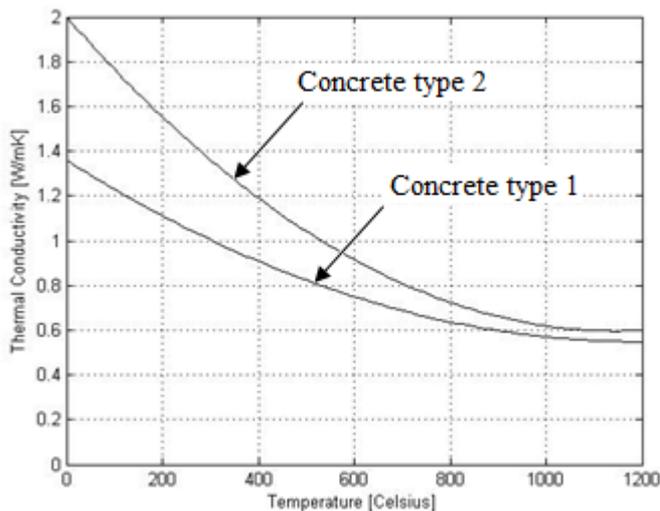
Figure 9: Thermal conductivity vs. temperature for concrete (EC 1992-1-2 2005)

The specific heat capacity for concrete is considerably higher than the one for steel. The capacity is increasing when the material is heated, which must be considered in a fire situation, see Figure 10. The curve represents the specific heat capacity for dry concrete (EC 1992-1-2 2005).
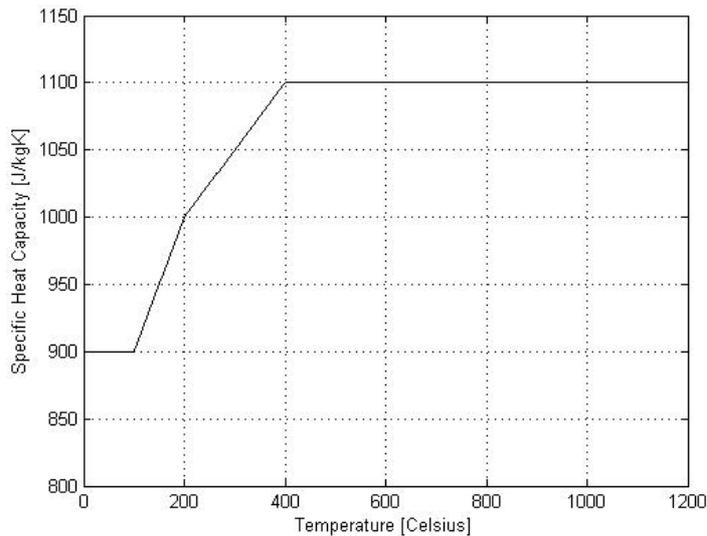
Figure 10: Specific heat capacity vs. temperature for concrete (EC 1992-1-2 2005)

In many situations the characteristic strength of a concrete structure is a better way to describe how the load carrying capacity is reduced during fire than Young's modulus. As mentioned, heated concrete will crack and adopt a non-linear behaviour, which may vary considerably. In Figure 11 the graphs shows the degradation of characteristic strength. The difference in upper and lower bound is mainly depending on aggregate type.
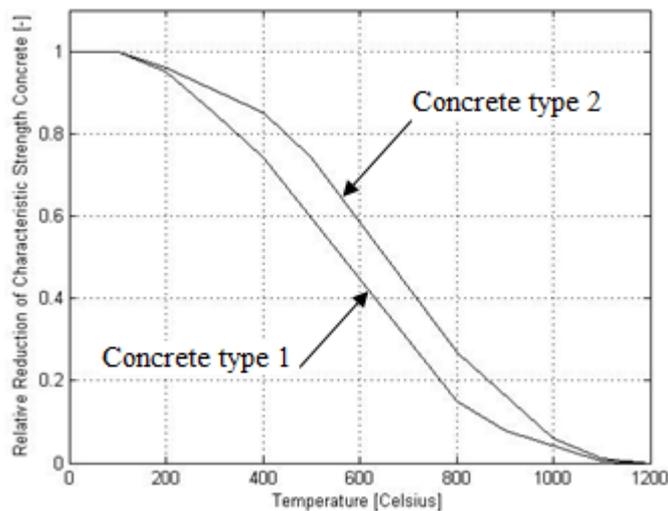

Figure 11: Relative reduction of characteristic strength vs. temperature for concrete with two different types of aggregate (EC 1992-1-2 2005)

2.2.4 Interaction between Steel and Concrete

There are two main mechanical reasons why steel is a good reinforcement material in concrete structures. One is the high tensile capacity of steel which compensates for the low tensile capacity of concrete. The second main reason is that the materials match each other when it comes to thermal elongation, especially around room temperatures, but also for high temperatures, see Figure 12. The three curves represent concrete with different aggregate types and reinforcing steel.
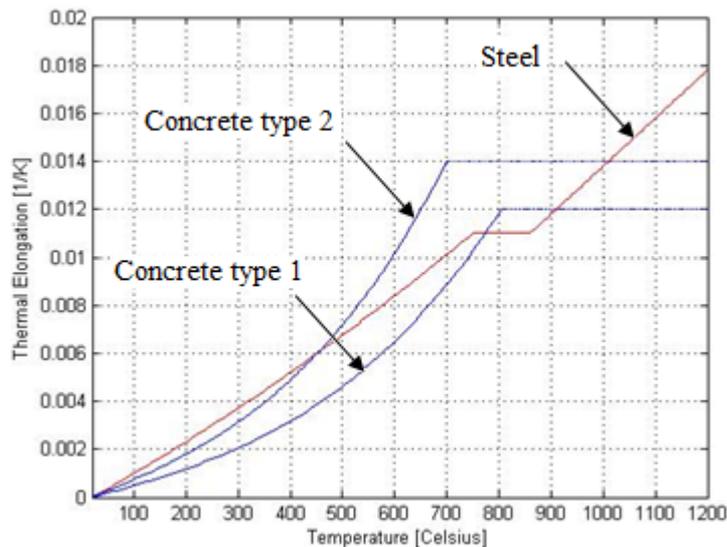
Figure 12: Thermal elongation vs. temperature for concrete (EC 1992-1-2 2005)

The positive effects of having approximately the same elongations are that inner stresses, which might cause cracks, can be avoided. This is essential to keep the bond strength, since the most important factor influencing the bond strength is friction (Zhong et al. 2011). However, avoiding micro cracks entirely at elevated temperatures is not possible. Cracks will change the influence of friction and decrease the bond strength.

When the heat increases both chemical and physical reactions are initiated within the materials. Example of such reactions is water migration and an increased water vapour pressure in the concrete pores. High water vapour pressure might cause cracks which affects the contact area between the steel and concrete. This is one of the reasons why the bond strength decreases (Zhong et al. 2011).

To avoid bond slip, which is a consequence of poor interaction between reinforcement and concrete, the anchorage length needs to be sufficient. This is especially important in case of fire, when the material properties will change, the interaction will decrease and utilization margin of the structure needs to be enough.

For further reading the authors recommend (Purkiss 1996).

2.3 Fire Design

Fire is in Eurocode considered as an accidental load. When structure is exposed to fire it is important to consider both possible load increase, by including changes due to thermal elongation and deformation, and also changes to the structural bearing resistance caused by decrease of material properties. These aspects must be considered when verifying the structural bearing capacity, which is of most importance during the design phase.

Heat from the fire is mainly distributed through radiation. Due to this the best way to protect a structure is by screening it against direct contact with the flame. This method is often used today by enclosing steel columns with gypsum boards or fire protecting paint. Composite CFHS columns uses another method, the concrete's high thermal capacity makes it act like a heat sinker in an early stage of a fire, which keeps the stiffness of the steel (Purkiss 1996).

2.3.1 Heat Transfer

Heat transfer between regions is driven by a temperature gradient. This flow is called heat flux and the direction of the flow is always from hot to cold regions. Heat can be transferred in three different ways; convection, radiation and conduction.

A structure directly exposed to a fire is heated through radiation and convection. Internally the heat is distributed due to conduction. This is true regarding materials with high density, like concrete and steel.

Convection can be either natural or mechanically forced. Natural convective heat distribution is possible due to that air change its density depending on temperature. This causes turbulence in the air which leads to heat transfer to nearby regions. The convective heat flux (q_c) is described by Equation 3 (EC 1991-1-2 2002).

$$q_c = h_c(T_s - T_a) \tag{3}$$

h_c	Convection coefficient, 25 W/m^{2}K (EC 1991-1-2 2002)
T_s	Surface temperature [K]
T_a	Ambient temperature [K]

In opposite to convection, radiation does not depend on a medium for heat transfer. Radiation is instead electromagnetic waves from a region with high energy to a lower energy region. The effect of the radiation is highly depending on the emissivity factor which describes the materials ability to absorb radiated energy. The radiation heat flux (q_r) is described by Equation 4 (EC 1991-1-2 2002).

$$q_r = \phi * \varepsilon_s * \varepsilon_a * \sigma * (T_s^4 - T_a^4) \tag{4}$$

ϕ	Shape factor, usually 1.0 when radiation to ambient temperature and no other surface (EC 1991-1-2 2002)
ε_s	Emissivity of surface
ε_a	Emissivity of ambient, fire usually 1.0 (EC 1991-1-2 2002)
σ	Stephan-Boltzmann's constant, 5.67·10^{-8} W/m^{2}K^4
T_s	Surface temperature [K]
T_a	Ambient temperature [K]

The net heat flux is described as the sum of the two equations 3 and 4.

$$h_{net} = q_c + q_r \tag{5}$$

Both parts are depending on the temperature difference (ΔT) between surface and ambient air. For low temperature the main contribution to the total heat flux is from convection but as the temperature raises the influence from radiation becomes governing.

Conduction is heat transfer between solid materials and is depending on the variables thermal conductivity and thermal heat capacity. Conductance is taking place within each material as well as at the interface between them.

2.3.2 Definition of a Standard Fire

To perform tests and simulations there is need for describing how a fire evolves regarding temperature-time relationship. Therefore several national and international fire test standards have been developed. The most used standard is ISO834 in which the temperature increases over time according to Equation 6 (Purkiss 1996).

$$T = T_0 + 345\log\left(8t + 1\right) \qquad\qquad (6)$$

Where T_0 is the room temperature before fire and t is number of minutes elapsed since fire initiation.

This gives for example that a standard fire generates a temperature of 945°C after 60 minutes, see Figure 13. For more temperatures used for fire design see Table 1.

Table 1: Standard temperatures used for fire design (Initial temperature T_0=20 °C)

Time [minutes]	30 min	60 min	90 min	120 min	180 min
Temperature [$^\circ$C]	842 $^\circ$C	945 $^\circ$C	1006 $^\circ$C	1049 $^\circ$C	1110 $^\circ$C

The standard fire curve is developed to be used as a preference when testing structural components. But it should be noted that it does not fully follow the behaviour of a real fire, which is much depending on the amount of oxygen and combustible materials available. When there is a shortage of one of these the fire temperature will decay (Betongvaruindustrin 2007). The standard test do not consider this effect, it is instead focusing on the earlier stages of the fire where the temperature increase is most rapid. The logarithmic curve shows increasing temperatures for eternity and is therefore not a relevant approximation after long time. However, it is designed to be on the safe side.
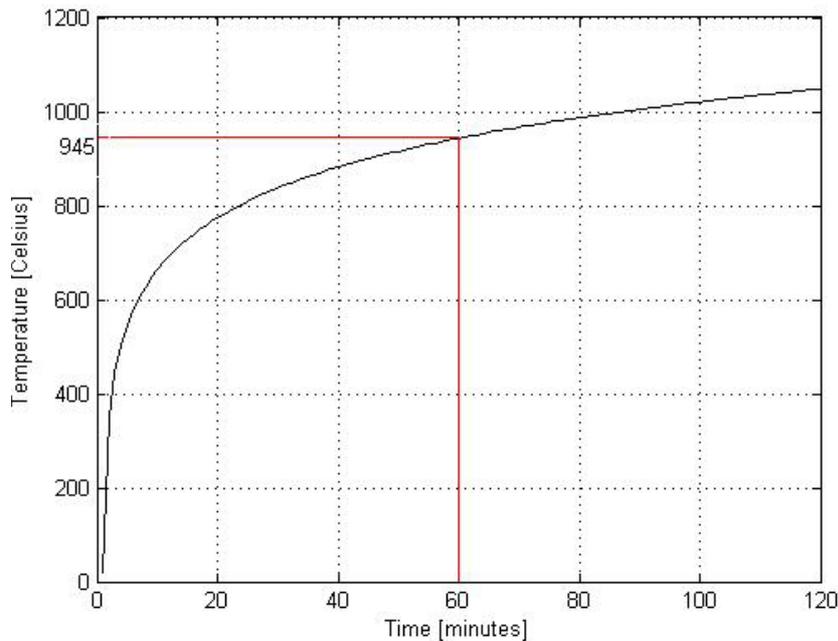
Figure 13: ISO834 standard fire curve

2.3.3 Fire Resistance Classes

Building components are divided in to fire resistance classes depending on how long the properties of a component are expected to sustain fire. Some requirements used to classify is; load bearing capacity (R), insulation (I), smoke leakage (S) etc. The letter is followed by a number, which says how many minutes the criterion is fulfilled during a standardized test (SP 2011). For example; the fire resistance class R60 means that the load bearing capacity should sustain at least 60 minutes of fire. If a member is tested and sustains not more than 59 minutes, the assigned fire resistance class will be R30 until the member is improved and a new test is done (Purkiss 1996).

2.4 Previous studies

Composite structures are used in many countries worldwide. Much research has been done within the subject, both real testing and finite element modelling. For example did (Zha 2002) investigate the temperature spread and critical failure mode in a composite column with an outer steel shell, and found that it was the degradation of material properties in combination with the increased compression stresses that caused the failure of the studied composite column. This study is largely relevant for this thesis to understand what can happen to the system, anyhow is the study not including any irregularity such as the PCs corbel and therefore is the research not fully applicable.

The higher strength of steel columns when encased in concrete or filled with concrete is often mentioned in terms of 'composite action' (Han et.al 2002). What this composite action really is must be a subject for further research, especially when the composite column is exposed to elevated temperatures (Shanmugam & Lakshmi 2002).

3   Description of the System

The PCs corbel is made of steel quality S355 and is used to connect the Deltabeam to the column. The corbel is placed in a formwork with the rest of the reinforcement and is anchored to the column by the in situ casted concrete (Peikko 2008). See drawings in Appendix A.

3.1   PCs Corbel

The PCs corbel is a connection usually used between a concrete column and a Deltabeam.

The supporting part of the corbel can be adjusted both vertically and horizontally, after the anchorage part being fixed to the column. In Figure 14 the non-painted parts of the corbel is casted-in, and the painted are the adjustable support where the Deltabeam is placed. It can also be seen that the top of the support is rounded. This makes the Deltabeam slide in to correct place by its own weight (Peikko 2006). More pictures of the modified PCs corbel are presented in Appendix C.
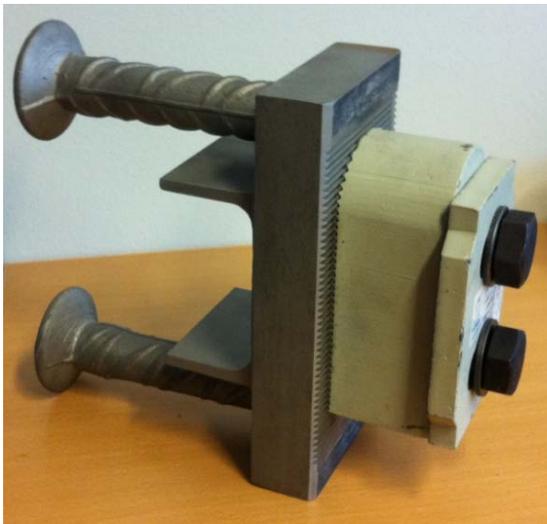
Figure 14: Peikko's PCs-3 corbel

Today the PCs corbel is a standard solution used in reinforced concrete columns. But in the future the goal is to expand the usage to also involve CFHS columns. With the use of CFHS columns the steel shell can contribute to the stiffness of the connection, for example by welding the base plate to the column shell. This new connection method makes a modification of the corbel possible.

The anchorage bars, see Figure 1, are removed and partially replaced by a U-shaped steel plate intended to distribute vertical forces. This steel plate is welded to the back of the base plate. The intension of this modification is to have at least the same performance for the connection as for the original PCs corbel used in a reinforced concrete column.

In this report will the modified PCs-3 corbel from now on will be referred to as the PCs corbel.

3.2 Deltabeam

The PCs corbel is designed to be used with the Deltabeam, see Figure 15. Deltabeam is a registered brand from Peikko, the name comes from its shape which is comparable to the Greek capital letter delta (Peikko 2011). The shape is adapted for easy placement of prefabricated concrete slabs, for example hollow core slabs, resting on the flanges.

After placing the prefabricated slabs and connecting them through the Deltabeam with reinforcement, the system is filled with reinforced concrete for full interaction (Peikko 2008).

Figure 15: Peikko's Deltabeam

Extensive fire testing performed on the Deltabeam shows that, even with the bottom flange unprotected, it is certified for R180, this because of the concrete filling's high thermal mass, as explained in Chapter 2.2.3 (Peikko 2011).

3.3 Corbel Load Distribution

The design load of the PCs3 connection is 300kN, calculated according to Eurocode standards (Peikko 2006). The load is transferred from the Deltabeam through an endplate to the rounded topside of the corbel. The thickness of this endplate varies with beam type. The endplate used with PCs3 corbel is 20 mm thick. Due to the shape of the corbel the load transferring contact surface is approximately 45 mm wide, multiplied with the thickness of the endplate gives an approximate load transferring contact area of 900 mm^2.

The eccentricity of the applied load produces a bending moment within the column. This bending moment creates axial reaction forces in the corbel studs, which leads to tension and compression stresses along the studs respectively within the concrete core, see Figure 16. Due to concretes poor tensile capacity there is a considerable risk that this effect will cause the failure of the connection. This is why stirrups are more concentrated closer to the corbel. The steel shell does also contribute to the prevention of cracking at normal temperatures, but this aspect cannot be included in fire design.
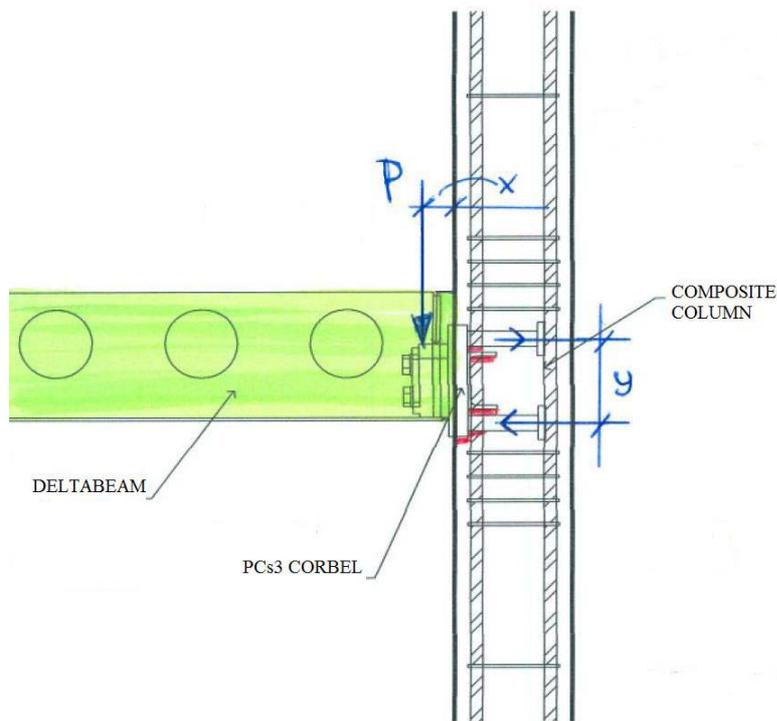
Figure 16: Principal sketch of moment equilibrium for the PCs3 corbel

3.4 Critical Regions

Before performing the computer simulations an assessment regarding the most critical regions and connections were performed. This was done with the purpose to identify possible failure of the corbel connection.

Previous tests performed by Peikko showed two different failure modes, concrete cone failure or yielding of the ribbed base plate (Peikko 2000). The column used in previous tests is a reinforced rectangular concrete column without any steel shell and no elevated temperature. A theory from the authors is that this new model will fail in the corbel. This since steel strength is reduced much more than concrete strength when exposed to elevated temperatures. Especially since the ribbed base plate is only partially protected against fire.

3.4.1 Ribbed Surface

Due to the fast temperature distribution in to the corbel, which is partially exposed to direct fire, the steel properties can change fast. For example the yield strength is decreasing considerably which enhances the risk for plastic behaviour in the ribs and thereby large deformations.

3.4.2 U-plate to Concrete Connection

The purpose of the U-shaped steel plate is to enlarge the contact area between corbel and concrete. Still the risk for local crushing of concrete at the contact zones must be considered if the distribution area is not sufficient.

3.4.3 Studs to Concrete Connection

As mentioned, the load is applied on the edge of the corbel. This will due to the eccentricity cause tension in the upper stud and compression in the lower stud. This will affect the surrounding concrete which can easily crack when tension stresses are created. To prevent this from happening stirrups are placed denser close to the corbel, However, the risk for cracking must still be considered, especially since the temperature development within the stud is expected to be faster than in the surrounding concrete.

4 Computer Modelling

All modelling of the studied system has been performed in the finite element based software Abaqus. An extract from the modelling script created for the simulations is summarized in Appendix E.

Furthermore, all material properties are based on standard values presented in Eurocode (EC 1992 1-2 2005) and (EC 1993 1-2 2005).

4.1 Modelling Plan

First the model has been established by running simplified, decoupled simulations. The main study is then divided into three separate Abaqus-jobs, which are presented in a flowchart, see Figure 17.
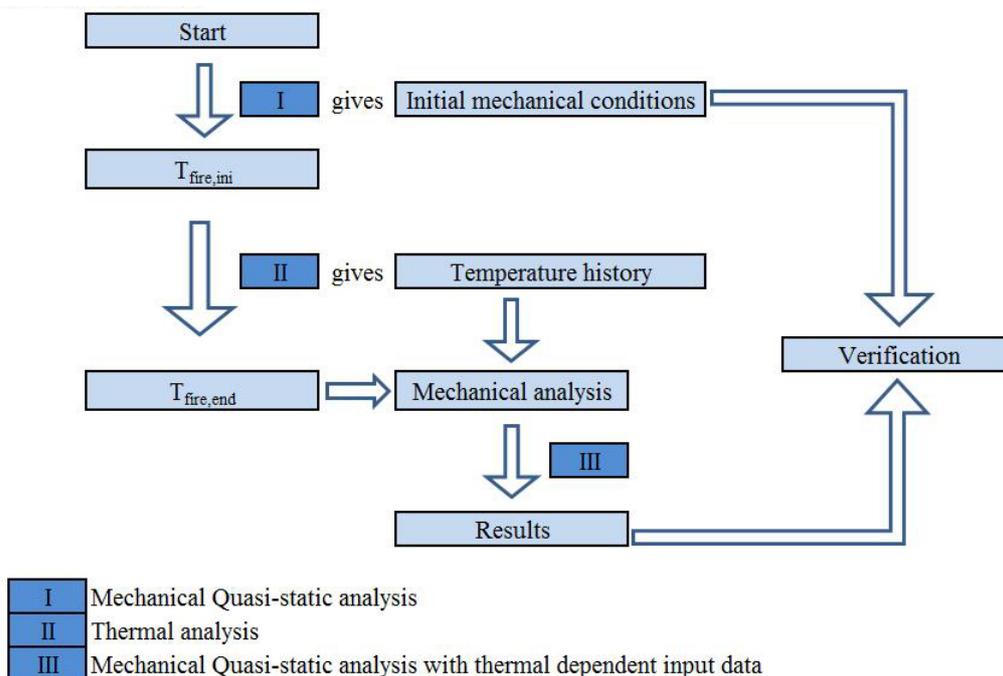
Figure 17: Flow chart over the modelling plan

In the first simulation, only the mechanical load is considered, which means constant room temperature is assumed. The result from this simulation is used for comparison with the final results. The second simulation involves only the thermal load applied as an ambient temperature according to ISO834 standard fire curve. The purpose is to study the temperature distribution through the connection and the column during and after 60 minutes of fire.

The results from the second simulation are regarded as prescribed data when performing the final mechanical simulation. Since Young's modulus, thermal mass capacity and thermal conductivity is temperature dependent these properties will change following the definitions in Eurocode, see Chapter 2.2.

After performing the final simulation, when both static loading and temperature conditions are considered, the results will be compared to the results of the first static simulation and a behaviour analysis will be performed.

This methodology will be used twice, both for CFCHS and CFCRS, in order to be able to compare the performance of the two different cross sections.

4.2 Simplifications in the Modelling Phase

To create a model that describes the geometry of the real PCs corbel exactly is both redundant and time consuming. Therefore, some simplifications are made, but still it should be possible to study all relevant and dangerous parts of the system. The purpose is to later verify these made assumptions by evaluation of the results.

4.2.1 Mechanical simplifications

All load applied from the Deltabeam is transferred from the rounded corbel part to the base plate through the ribbed surface. The only purpose of the bolts is to press the ribbed surfaces together, which means that no external load is transferred through the bolts, and therefore they are neglected in this model. The ribbed surface is replaced with an assumption of full interaction between the two steel parts. This assumption is well motivated since the ribbed surface is designed to fulfil such behaviour. However, this criterion has to be verified.

Also the outer plate in the corbel is omitted. The purpose of this part is to prevent accidents during erection of beams, meaning that the Deltabeam should not slide of the support. In normal situations, the outer plate does not carry any load, and since it is embedded in concrete its contribution to the temperature distribution is assumed to be small.

See comparison between the Abaqus model and the real PCs corbel in Figure 18.
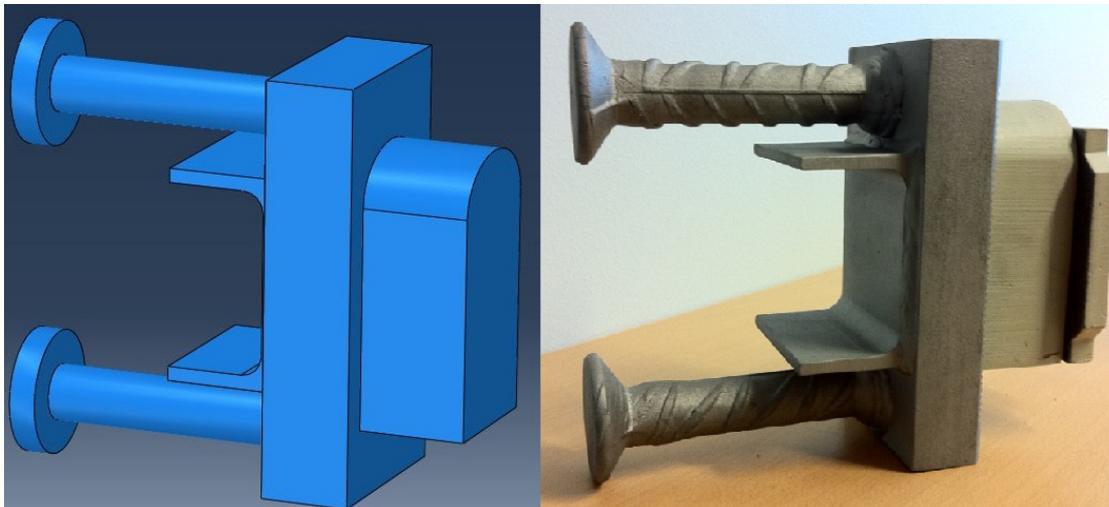
Figure 18: To the left the Abaqus-model, to the right a real specimen

Stirrups in the column are, as well, excluded due to the complexity and time consuming work it would lead to, see Chapter 1.4. To exclude the stirrups could cause higher stresses in the concrete close to the connection, but if stresses high enough to cause cracking of the concrete are detected in this region the conclusion that stirrups are needed can be drawn.

4.2.2 Material simplifications

The specific heat capacity of steel is small compared to concrete, except at around 735°C, where there is a peak in the specific heat capacity for steel, see Chapter 2.2.1. Including this peak in the Abaqus simulation will probably cause convergence problems in the numerically based software. Therefore it was decided to leave it out. The result will be a slightly increased temperature which leads to decreased properties for the steel, but the difference is small and the simulation can be considered to be on the safe side.

4.3 Modelling Steps

4.3.1 Model Generation and Material Properties

The modelling of the connection is made in Abaqus/CAE where each part is drawn separately and then composed to one assembly. All parts are created as 3D solids.

Material properties are defined according to Eurocode, as presented in Chapter 2.2. Young's modulus, thermal conductivity and specific heat capacity are all temperature dependent and are therefore given in tabular form where the property varies with temperature (EC 1993-1-2 2005).

Other material properties which are not considered to be temperature dependent are density and Poisson's ratio, see Table 2.

Table 2: Non-temperature dependent material properties

	Density	Poisson's ratio
Steel	7800 kg/m^3	0.2
Concrete	2300 kg/m^3	0.3

In order to simulate fire on one floor and to be able to study the temperature spread in the vertical direction to the floor above, a screen is used, as shown in Figure 19. This screen is modelled as a homogenous concrete slab with thickness 265 mm. In addition to screening, the concrete's large thermal capacity helps keeping a lower temperature of the steel.
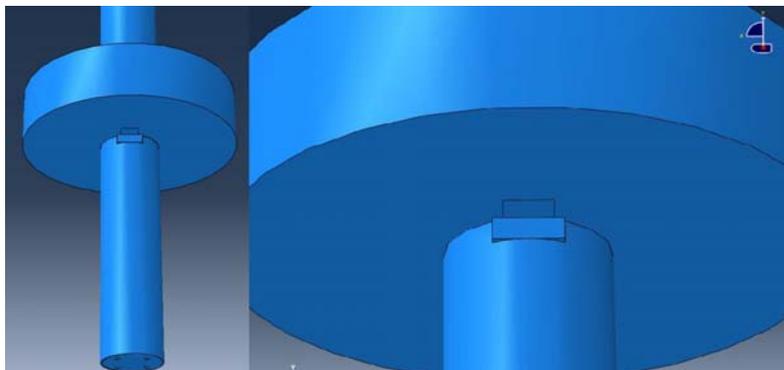

Figure 19: The circular column seen from below, with the concrete screen used to limit the fire

4.3.2 Interaction and Load Application

4.3.2.1 Thermal Loading and Interaction

The thermal load from the fire is defined by an ambient temperature following the standard fire curve ISO834. Heat flux to the structure is due to both radiation and convection, for more detailed information, see Chapter 2.3.1. These two effects are managed separatly in Abaqus, even though they are active on the same surfaces. Convection is defined as a 'film condition' with constant convection coefficient $h_c = 25$ W/m^{2}K. Radiation is defined by the interaction 'surface radiation', and is depending on temperature and emissivity. Radiation becomes governing as the temperature rises, see Chapter 2.3.1. The emissivity is set to 0.8 for both steel and concrete since nothing else is mentioned in the standards, (EN 1991-1-2 2002). Due to that radiation calculations must be performed using temperatures in unit Kelvin, the entire model is defined using this unit (0 K = 273°C).

The interaction properties between assembled parts with the same or different materials are all described by the interaction 'conductance'. In reality, during fire, the conductance between materials decrease with increased temperature. In this simulation the decrease is neglected. Instead the conductance is kept very high compared to the conductance within each separate material, meaning that any possible thermal resistance at the surface between two materials are neglected. This is motivated since the aim of the heat transfer analysis is to obtain a reasonable temperature raise within the connection, but a slightly higher temperature than 'the real case' will only result in a conservative result for the following quasi-static analysis.

The fire is simulated to be on the lower side of the screen and the column, see Figure 19, where parts of the corbel are exposed directly to the fire. Initial temperature for the whole system is considered to be 20°C (293 K).

4.3.2.2 Mechanical Loading and Interaction

The load is defined as a pressure load applied in the contact area between the endplate of the Deltabeam and the corbel, see Figure 20. The contact area is approximately 900 mm^2 and the load corresponds to 300kN. It should also be noted that this is the only load active on the column.

A pressure load means that the load are in all points perpendicular to the surface, which in this case means that the load is not fully vertical, but the angle is small enough to be neglected in this model.

Welds connecting the corbel base plate to the column steel shell is replaced with an assumption of full interaction between the steel parts. In a similar way is the interaction between steel parts within the corbel and steel to concrete interface modelled.
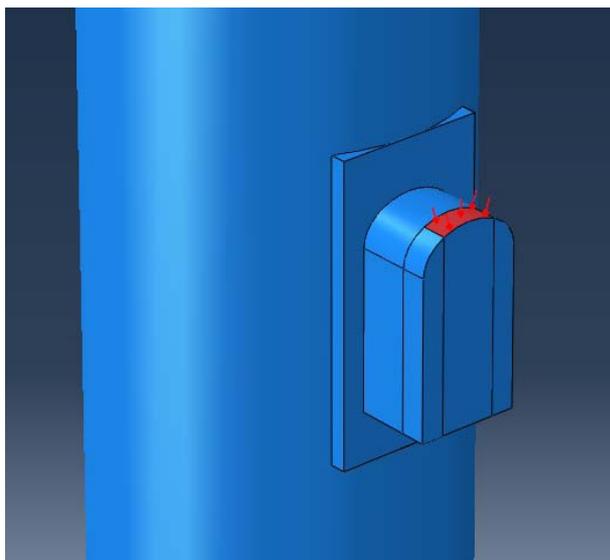
Figure 20: Illustration of the mechanical load application area

4.3.3 Step

In the third analysis, see Figure 17, the connection is studied at every five minute instance, but due to the non-fixed increment size some deviations are inevitable. This will anyhow not affect the final results.

To be able to compare the heat distribution in the two column types, it would be preferable to have a fixed time increment (time step), but due to the non-linear shape of the ISO834 standard fire curve, which can cause convergence problems, this is not possible.

The third analysis is divided into several steps where each step is using temperature distribution data from associated time period and initial deformation data from the previous step. The temperature distribution is retrieved from the thermal analysis and is assigned as a predefined field. 'Predefined field' is a tool in Abaqus which is used for example to assign initial conditions to a region.

4.3.4 Boundary Conditions

To minimize the risk that the results are affected by assigned mechanical boundary conditions, the modelled part of the column is relatively long in comparison to the corbel size. Mechanical boundary conditions preventing displacement are set at the upper and lower edge of the column, see Figure 21.

The column is clamped at both top and bottom because of symmetry reasons. A building using the PCs corbel is usually a multi-storey building and thereby including more than one connection per column.
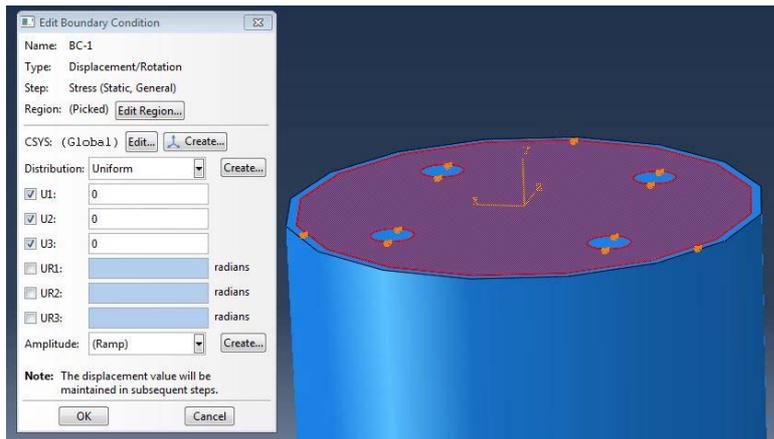
Figure 21: Mechanical boundary condition on the top of the column. The same boundary condition is applied at the bottom part of the column.

4.3.5 Mesh

There are several ways to establish and determine a suitable mesh. How the mesh is established is mainly depending on what kind of results that are expected. Basically, to obtain more precise and accurate results, the elements size should be small and the element type should contain a large number of nodes. It is also preferable that the approximation technique should be of high order. The negative aspect of this is that the simulation can be time consuming and also the mesh can become too complex to work with.

Abaqus contain specific element types for each simulation, for example for thermal analysis. Since the geometry of the corbel connection, including column, is relative complex to establish, the mesh has to be automatic generated. It is the automatic generation that determines what kind of mesh that will be used in present situation, this since, 'mesh by hand' is not an option.

The mesh that is used in all cases contains tetrahedral shaped elements which are either linear or quadratic. Quadratic elements are preferable since they give more accurate results, but due to the irregularities which give a partially distorted mesh is it not possible to use quadratic elements over the entire model. Some parts are therefore meshed with linear elements, each containing 4 nodes compared to 10 nodes per element for quadratic approximation. Furthermore the element size is set to approximately 12 mm.

4.4 Limitations of the Model

To model such a complex connection as the PCs corbel in an exact way is not possible. As mentioned earlier, simplifications are needed. Simplifications will make it easier to model, but it must be considered that it will also affect the results from the simulations.

The most important limitation is that the concrete is modelled as a linear elastic material, which means that redistribution of stress due to cracks in the concrete is not considered in the model. Stresses in the concrete that might cause cracking must be located analogously. Plastic behaviour of steel is included in the model.

The corbel is modelled with full interaction between all steel parts as well as between steel parts and the concrete. This is done in Abaqus by using 'Constraints'. In real case scenario will the base plate of the corbel be welded to the steel shell, but here is the welds left out and

replaced with an assumption of full interaction between corbel and steel shell, this leads for example to an assumption of no slip displacement between the two components. Same condition is applied for the ribbed surface, as mentioned is this one of the regions that must be studied separately since it is identified as a critical region.

Due to simulation technical reasons the results from the thermal simulation has been chosen to be updated every five minute to the temperature dependent mechanical simulation. This is an alternative method to the fully coupled mechanical and thermal simulation which was an option. Effects on the final result are anyway expected to be small since deformation from one step to another is kept.

5 Results

The most important results are presented in this chapter. More figures and illustrations are presented in Appendix D.

If nothing else is mentioned is the presented stresses are so called 'von Mises-stresses', corresponding to the effective stress in the material.

5.1 Reference Simulation

As explained in Chapter 4.1 the purpose of this simulation is to be used as a reference to the final where both thermal and mechanical load is considered. Hence, the propose is to study the change in mechanical response during fire. This analysis has been carried out for both CFHS columns.

Figure 22 shows the stress distribution in a cut through the middle of the connection. The highest stresses are removed from the spectrum, this in order to eliminate local peak values and to make the stress distribution more visible.

The spectrum indicates that, at room temperature, most of the load is transferred through the steel shell. The stress magnitude in the steel shell is almost symmetrical above and below the corbel in both cases.
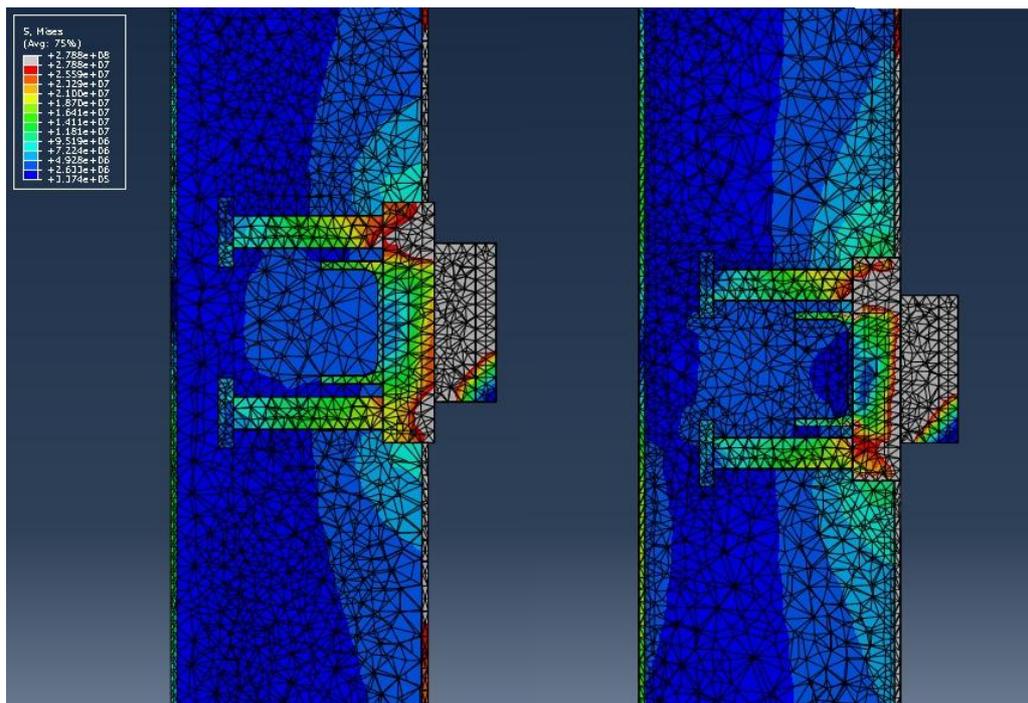

Figure 22: Stress distribution at room temperature. To the left rectangular column and to the right circular column

5.2 Thermal Analysis

The temperature analysis is made with the purpose to study where the highest, and thereby the most dangerous, temperatures will appear. Furthermore, the actual temperature distribution will result in different material properties used in the final quasi-static simulation.

Figure 23 shows an overview of the whole model after 60 minutes of fire. The red surface temperature is 907°C, which is the warmest in the simulation, and the visible part of the corbel has a surface temperature of about 700°C.
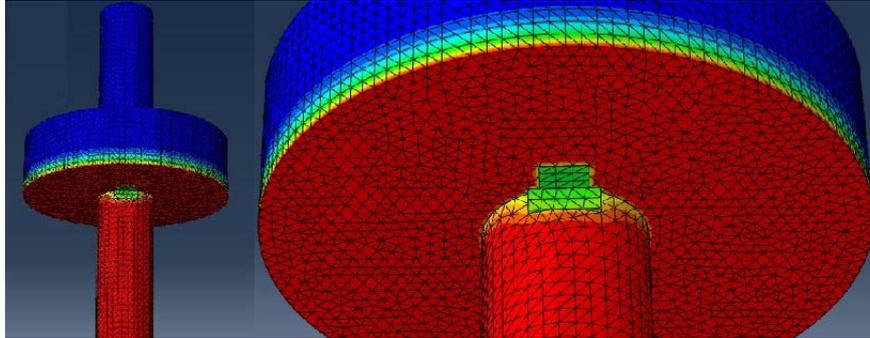
Figure 23:Temperature distribution in the connection after 60 minutes of fire exposure

The temperature distribution can also be studied in a cut through the middle of the connection, see Figure 24. The corbel is on located on the right hand side of the column in the figure.
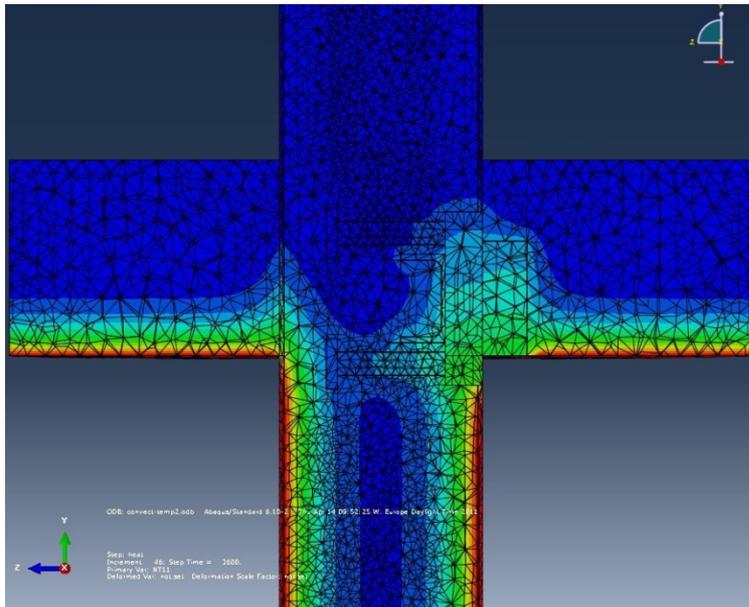
Figure 24: Cut through the middle of the connection in a CFCHS column Temperature distribution after 60 minutes of fire, Red=907°C, Blue=20°C

The true green colour represents about 470°C, and is the highest temperature in the concrete core of the column.

For a more detailed figure, all temperatures below 50°C or above 500°C are eliminated in Figure 25. The black parts have a temperature lower than 50°C and grey parts are warmer than 500°C, which for example shows that the steel shell has a temperature of more then 500°C in

all points exposed to direct fire. The load bearing capacity of steel with this high temperature is small, and therefore can it be assumed that the load bearing capacity of the connection is now depending on the concrete and its bonding to the cast-in corbel parts.

It can also be seen that the steel corbel is spreading the temperatures far more then the concrete, see especially the lower stud. Apart from the column steel shell the corbel is the part with highest overall temperatures.
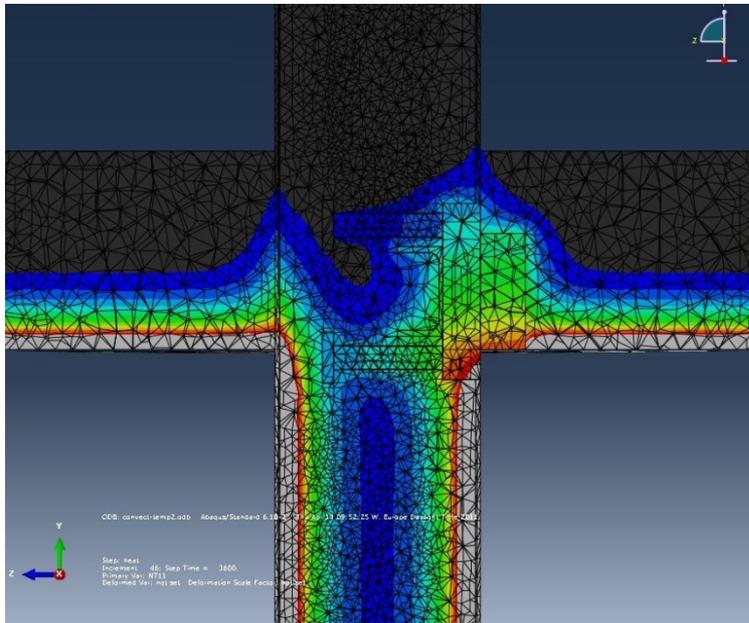

Figure 25: Cut through the middle of the connection in a CFCHS column Temperature distribution after 60 minutes of fire, Red=500°C, Blue=50°C

Figure 24 and 25 are both cuts through the connection in a CFCHS-column. The temperature distribution for a CFRHS-column is similar and is therefore left out in this chapter, but is presented in Appendix D.

Studying the connections where the load is transferred from the PCs corbel to the column is of particular interest. The weld connecting the corbel base plate to the steel shell is new for this design and therefore extra important. The analysis of the CFCHS column show that the temperature is higher than 400°C in 30 percent of the total weld length, which means that full capacity of the weld can only be expected in 70 percent of the weld. It should also be noted that the entire weld has a temperature higher than 100°C, which is the limit where Young's modulus starts to decrease.

Load transfer from the PCs corbel to the column also occurs through the studs to the nearby concrete. Figure 25 shows that the anchorage studs act as a heat bridge in to the column. A more detailed study of the studs are made by measuring the temperatures along the studs, starting at the back of the corbel base plate, see Figure 26. As expected the temperature is higher in the lower stud, and along a short part of the stud the temperature is so high that it will affect the material properties of the steel.
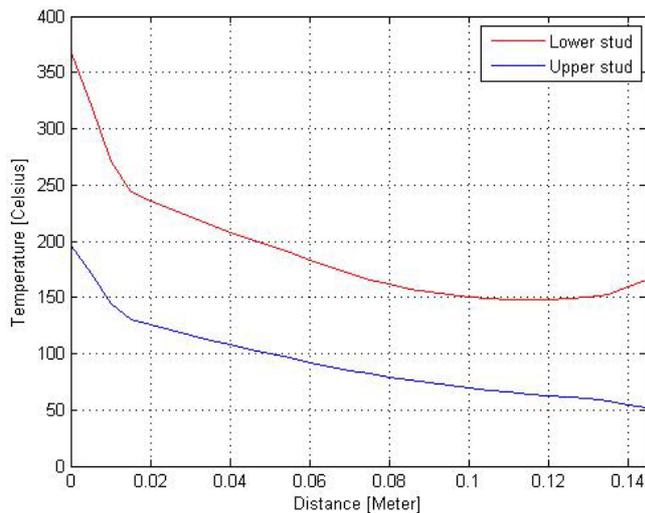
Figure 26: Temperatures along the two studs, starting at the back of the corbel base plate

5.2.1 Thermal Comparison between CFCHS and CFRHS Columns

To make the comparison of the temperature distribution for the two different column cross sections, some reference points are chosen (see Figure 27):

- Node ID 1 is located at the bottom of the rounded corbel part.
- Node ID 2 is located at the bottom of the base plate.
- Node ID 3 is located in the middle of the base plate.
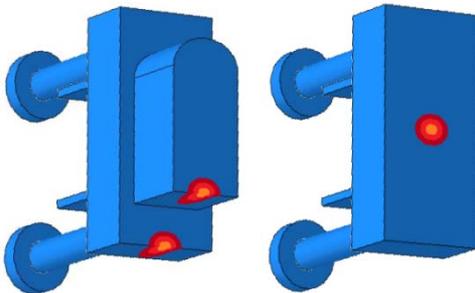
Figure 27: Reference points for comparison between CFCHS and CFRHS columns

As expected, the surrounding concrete has a heat buffering effect which helps the steel to keep a lower temperature and thereby decrease the degradation rate of the steels load bearing capacity, see Figure 28. The three coloured lines show how the temperature increases in the three reference points with time and they are significantly lower than the black line indicating the ISO834 standard fire curve.
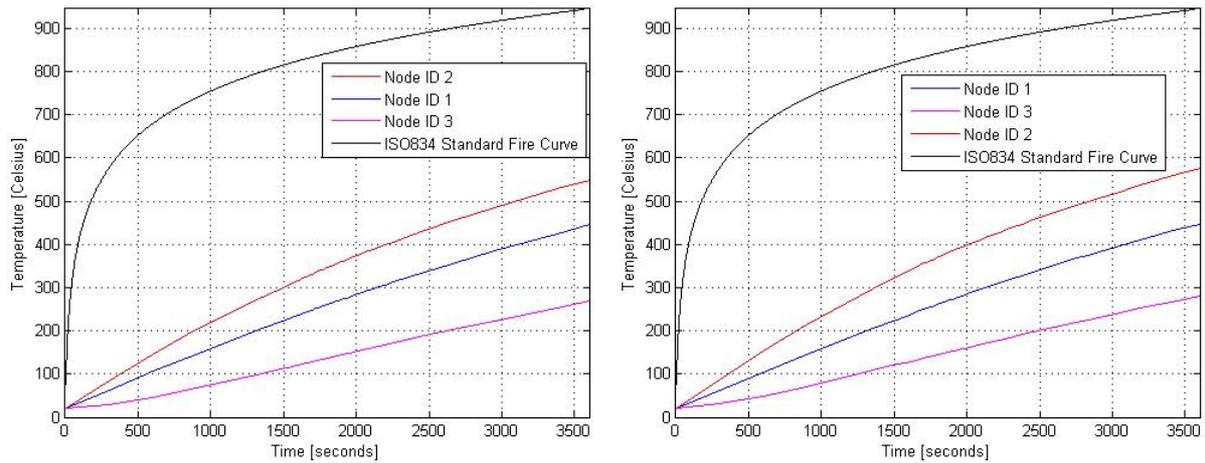
Figure 28: Temperature raise in three different point of the corbel, compared to the ambient temperature, to the left CFRHS and to the right CFCHS.

In the final stage of the simulation the difference between temperatures in the reference points Node ID 1,2 and 3 is $2.5^{\circ}C$, $18.8^{\circ}C$ and $25.7^{\circ}C$ respectively. It should also be noted that the difference in temperature between CFCHS and CFRHS is never larger than in this last stage of the simulation, see graphs Figure 29. The highest temperature in the reinforcement bars are $302^{\circ}C$ for the circular column and $380^{\circ}C$ for the rectangular.
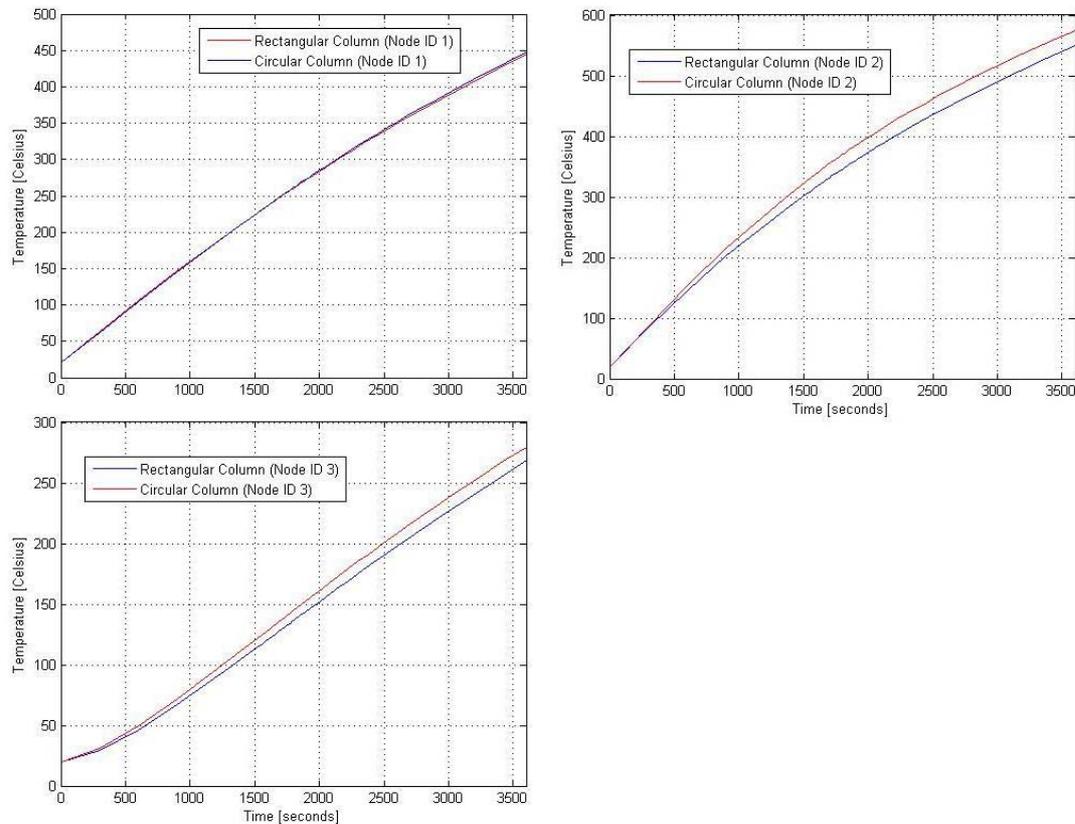
Figure 29: Temperature development in three reference points within the corbel

5.3 Mechanical Quasi-Static Analysis with Temperature Dependent Mechanical Properties

5.3.1 Deformation

A mechanical load, applied according to Figure 20, with the magnitude 300kN is present from the start of the simulation and causes an instant deformation of the corbel and column. As the temperature raises this affects the material properties and the deformation increases. However, the vertical deformations in reference Node 1 are small both before and after influence from fire, see Table 3. The differences between CFCHS and CFRHS columns are also small, even though the rectangular seems to have a slightly higher stiffness than the circular after 60 minutes of fire. Rotation was also measured, but the results are small enough that they can be negligible.

Table 3: Rotation and deflection results of the connection

	CFCHS	CFRHS
Δy(0 min)	0.16 mm	0.13 mm
Δy(60 min)	0.31 mm	0.21 mm
ω(0 min)	0.47‰	0.44‰
ω(60 min)	1.04‰	0.71‰

5.3.2 Stress Redistribution

Significant stress redistribution from the steel shell to the interior concrete core can be seen when the temperature raises, see Figure 30.

Studying the stresses in the column before fire (on the left hand side in Figure 30) shows that the highest stresses are in the steel shell both above and below the PCs corbel, compare the quasi-static load case in room temperature in Chapter 5.1. After fire exposure (on the right hand side) the stresses in the steel shell below the corbel have been considerably reduced, this since the steel properties has changed as explained in Chapter 2.2.

Stresses in the concrete under the corbel have increased and has moved towards the middle of the column because of the elevated temperatures which also affects the properties of the concrete.

Stresses in the thermally unaffected steel above the corbel have also increased.
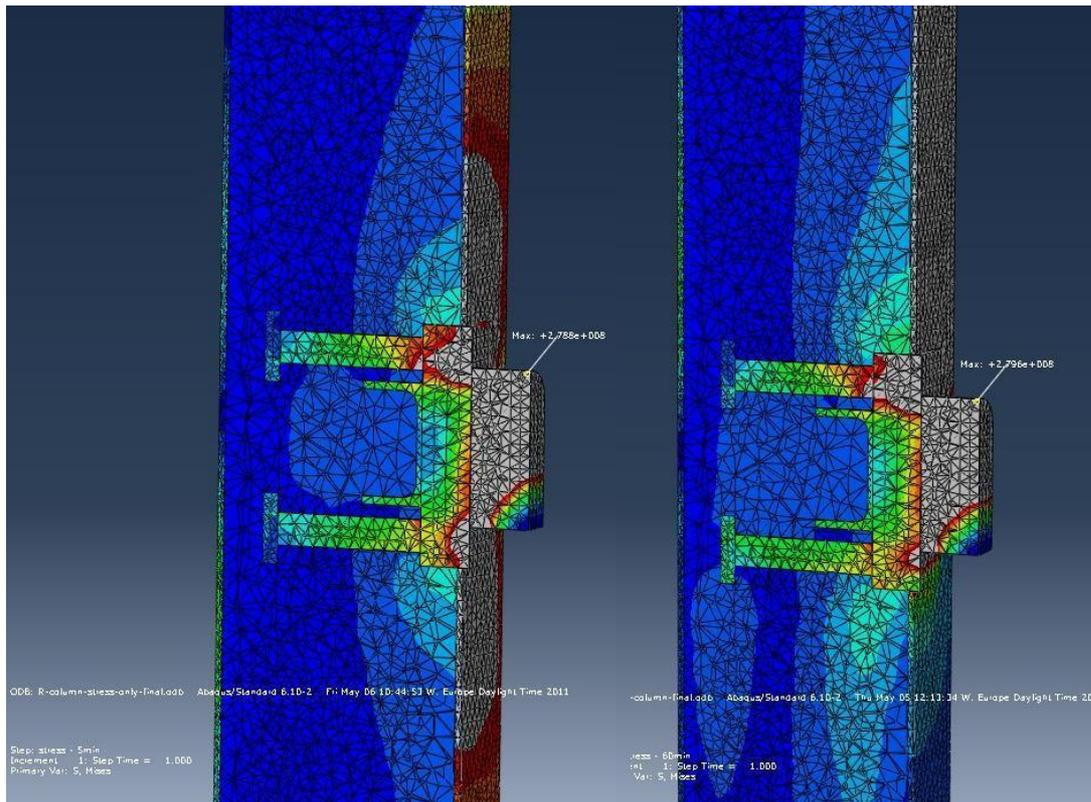
Figure 30: Stress distribution before fire initiation (left) and after 60 minutes of fire (right)

In both cases shown in Figure 30, the highest stresses are removed from the spectrum and here shown in grey, this to eliminate local peak values and to make the stress distribution more visible. Figure 30 illustrates the results from the rectangular column the results for the circular column are similar, see Appendix D.

5.3.3 Reinforcement

By conduction through the steel shell and the concrete the longitudinal reinforcement bars will also experience elevated temperatures. The highest reinforcement temperature measured was 380°C and 302°C in CFRHS and CFCHS columns respectively, see Appendix D. These temperatures do not affect the yield strength of the material, which means that the reinforcement does still have full capacity. With a highest detected stress of 40MPa the conclusion can be drawn that the reinforcement capacity is not the determining for the capacity of the whole connection.

5.3.4 Critical Regions

In Chapter 3.4 was some possible critical regions were identified. Results from both thermal and mechanical analysis in these regions are studied more detailed.

5.3.4.1 Ribbed Surface

To evaluate if the is any risk for yielding in the ribbed surface temperature and stresses along the centre line of the surface is plotted, see Figures 31 and 32. Figure 31 shows the

temperature distribution starting from the bottom side of the rounded corbel part and going upwards. It can be seen is that the surrounding concrete makes a considerable impact on the temperature in the steel, dropping from 439°C at the bottom to 206°C at the top. A temperature of 206°C does not give any lowering of the steels load bearing capacity, but at 439°C, only about 80% of the original load bearing capacity remains.
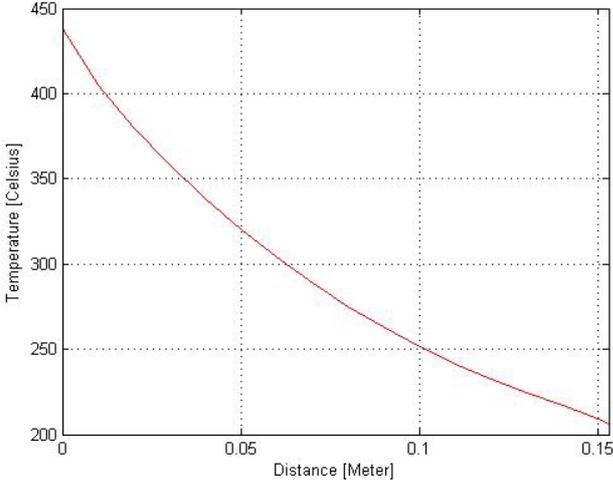
Figure 31: Temperature distribution along the ribbed surface starting from the bottom of the rounded corbel part after 60 minutes of fire

Stresses along the ribbed surface are shown in Figure 32. The risk for yielding in the ribs is largest at the bottom of the corbel since a stress peak coincides with the highest temperature, 439°C. At this temperature, 91% of the yield strength is left. The used steel quality, S355, has original yield strength of 355 MPa which gives:

$$\sigma_{Rd} = 0.91 * \frac{355}{\gamma} = 0.91 * \frac{355}{1.0} = 323 \; MPa \qquad (7)$$

The peak at the top of the corbel is due to its rounded shape which decreases the contact area. However, the temperature there is not high enough to affect the yield strength of the steel, and the peak only leads to a utilization ratio of about 34% at this point of the corbel.
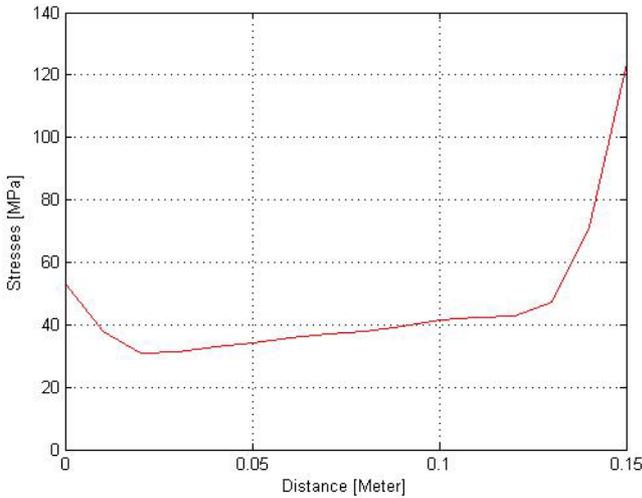
*Figure 32: Stresses along the ribbed surface, starting from the bottom of the rounded corbel part after 60 minutes of fire*

5.3.4.2 U-plate to Concrete Connection

At the interface between U-plate and concrete, the maximum compressive stress was measured to be 7.6 MPa. The temperature in the same point was 477°C. By using the graph in Figure 11 showing how the characteristic strength of concrete changes with temperature, it can be stated that about 70% of the characteristic concrete strength remains.

Since fire is considered an accidental load in Eurocode the partial factor is $\gamma_c = 1.2$ for concrete, compared to $\gamma_c = 1.5$ which is the normal case.

$$\sigma_{Rd} = 0.70 * \frac{25}{\gamma_c} = 0.70 * \frac{25}{1.2} = 14.6 \; MPa \qquad (8)$$

This calculation shows that the compression capacity is not exceeded.

5.3.4.3 Studs to Concrete Connection

From the thermal analysis it can be seen that the temperatures in the two studs are elevated, and especially the lower stud has such high temperature that it will affect the capacity of the steel, see Chapter 5.2.

Comparing stresses in the lower stud soon after fire initiation and after 60 minutes of fire shows that the stress are increased along the entire stud after 60 minutes, see Figure 33. This can be an effect of the reduced steel properties, which results in a longer effective anchorage length of the studs.
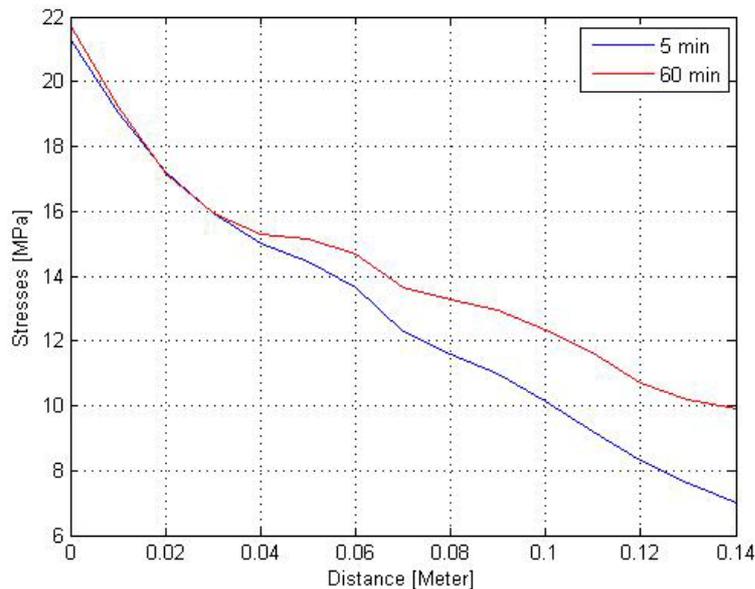
Figure 33: Stresses in the steel along the lower stud for times 5 min and 60 min after initiated fire

It is also of interest to study the concrete in the region close to the studs. Since the applied load will create a rotation of the corbel the concrete must have the capacity to withstand shear forces along both upper and lower stud.

Shear stresses in the concrete are presented in Figure 34. It shows that the shear stresses are higher near the base plate in the CFCHS column. It is true in both upper and lower stud, but is more significant in the upper.

The stresses are high enough to cause cracking of the concrete, but due to known limitations in the model it is not possible to conclude if the stress peaks occur neither in the correct position nor with the correct magnitude. What can be concluded is that this is a critical region and that the situation gets worse after exposure to fire. Cracking of concrete will cause redistribution of stresses and introducing stirrups in the model could also influence the stress pattern. Exactly how this will affect the system must be further investigated.
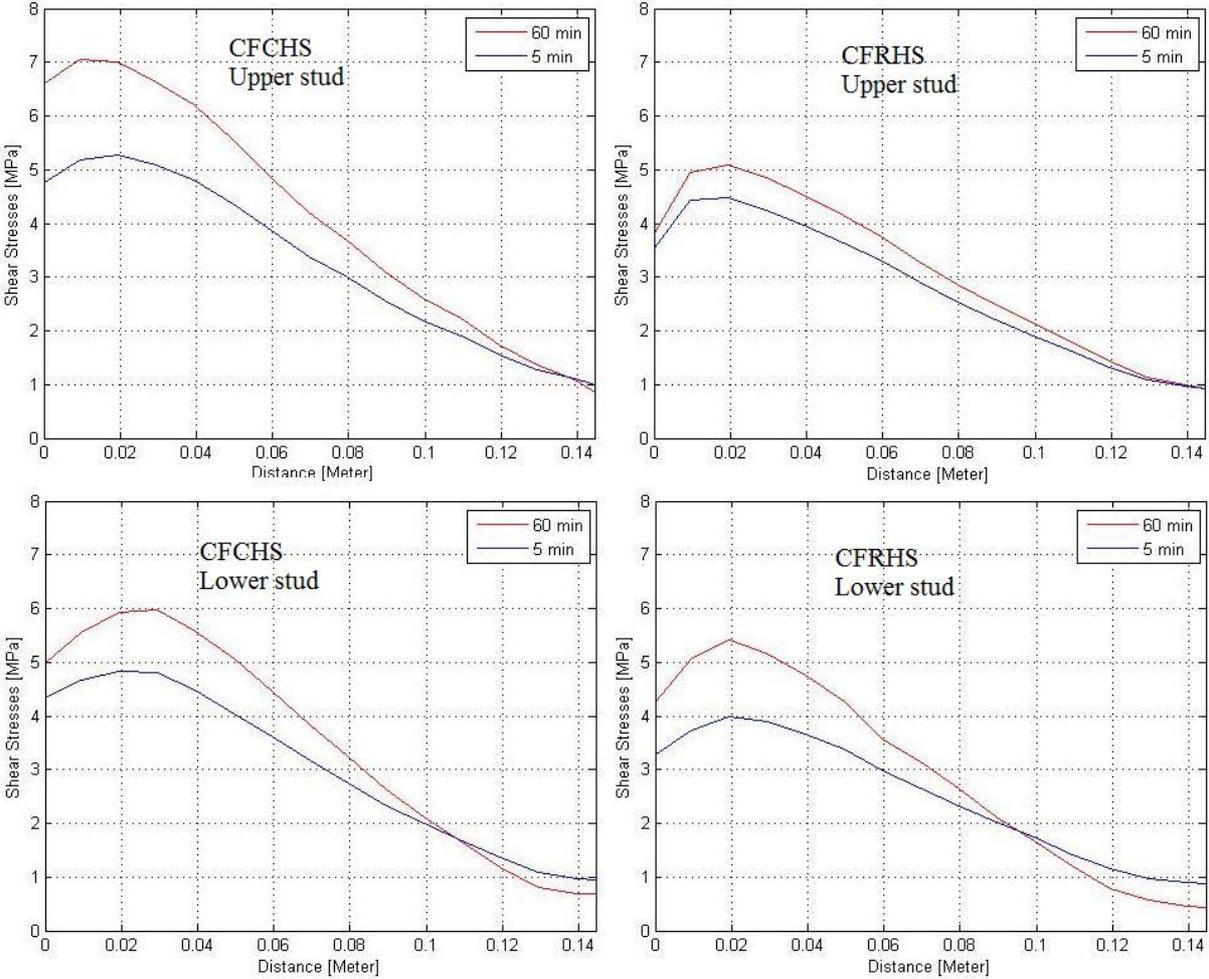
Figure 34: Shear stresses in the concrete along the studs

6 Conclusions and Discussion

The main interest in this report was to study if the PCs corbel is an efficient solution in case of fire. That it has several benefits in the building phase and in serviceability limit state has already been established, but considering fire was not enough investigated earlier. Also should the PCs corbels influence on heat distribution be studied and two column shapes be compared and evaluated.

There is a need for further investigations before concluding that the PCs corbel is an suitable solution to use in a composite column like the case investigated in this master thesis, but the results given from Abaqus simulations presented in this report is cautiously optimistic and can be used as a base for further investigations.

As expected does the corbel act as a heat bridge, but the temperatures in the connection are still kept on a lower level than could be foreseen. One explanation to this can be the large heat buffering effect from the concrete slab used to screen the fire, in combination with the design where only a small part of the PCs corbel is exposed to direct fire.

Studying the PCs corbel exclusively shows that the temperature distribution is similar for CFCHS and CFRHS columns, see figures in Appendix D. Even if the temperature differences within the connection are small between the two column types, the difference has to be considered in other parts of the system. For example in the longitudinal reinforcement bars is maximal temperature difference about 80°C, highest in the CFRHS column. However the reinforcement temperature after 60 minutes of fire is still below the limit where steel's yield strength is affected. It is therefore not possible to say that one column is preferable before the other considering fire design.

Presented results show that the column shape to a small extent affect the temperature distribution, the difference is not enough to be able to recommend which one to use from a fire design point of view. Other aspects have to be considered as well, for example behaviour in serviceability limit state and aesthetics. The fact that fire design does not limit the selection considering cross section type must be seen as a benefit for the PCs corbel. It gives a freedom for the designer to choose circular or rectangular columns depending on what is best suited for the context, not only which withstands fire best.

One effect of the fire is that stresses in the steel shell are redistributed to the concrete and longitudinal reinforcement bars, this since steels stiffness is considerably reduced, see Figure 30. At room temperature the steel shell also holds the cross section together, when it loses stiffness the role is taken over by stirrups.

As far as this study goes one cannot see any risk for total failure of the connection when exposed to 60 minutes of fire. Temperatures are elevated, but in general not high enough to cause severe degradation of the material properties, which is a condition needed to be present. This since the applied load (300kN) is not high enough to cause any failure at room temperature.

Concerning the quasi-static analysis the generated results show almost no plastic behaviour in the steel. This could be prevented by adding a higher shear force to the system. Although this would be to exceed the design load used by Peikko it might be of interest since the load of 300kN gave small deformations and a not very defined stress pattern for the connection.

In this model are stresses created along the studs not high enough to cause neither yield failure in steel nor anchorage failure in the nearby region, but due to limitations in the model this possible failure mode most be investigated further.

As mentioned in the introduction is standard solutions like the PCs corbel preferable both from a reliability and economical point of view. Prefabrication and standard solutions is a growing branch within the building industry today. Therefore development of an already existing standard solution for use in new contexts is encouraged. From the results presented in this report there cannot be seen any reason why this development should not continue.

6.1 Recommendations for Future Studies

In this master thesis is some simplifications made and decisions about limitations are taken. This affects the results and therefore is further research needed to fully investigate the connection and its suitability for this kind of structure.

The most important limitation made is the assumption of linear concrete behavior, which in practice means that an assumption of no cracks in the concrete is made. To be able to perform a complete analysis of the system must the non-linearity of concrete be built-in to the model. For example since cracks will for example lead to redistribution of stresses.

The connection is modeled with an assumption of full interaction between all parts of the system. Any change in bond properties between concrete and steel due to temperature changes must also be included in a future model.

Modelling of the ribbed surface can be done in a more advanced way by including the real geometry of the surface and the prestressing force in the bolts. When the temperature raise in the interface, the prestressing force will decrease and there will most likely be a redistribution of stresses to the upper bolt, which has as a lower temperature and thereby higher stiffness. If this will have a significant impact on the load bearing capacity is still to be investigated.

In this master thesis it was agreed with Peikko to simplify the system of joists separating the fire on the lower floor from the upper floor with an equivalent concrete screen. Since the PCs corbel is designed to support a Deltabeam (composite beam, see Chapter 3.2) it would be more correct to include this one in the model. The difference will probably be very small compared to the results in this report.

When the PCs corbel is used in a building it is likely to believe that there are several floors. Therefore it could be of interest to put a normal force on the column illustrating load coming from floors above, this load case was never discussed in this thesis.

An alternative method to analyse this connection could have been by performing a coupled analysis. Coupled analysis means that temperature will be distributed in the same time as a mechanical load is applied. The difference between coupled analysis and the method used in this thesis is that the temperature distribution is loaded gradually with five minutes intervals.

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EC3. Eurocode 3: Design of Steel Structures Part 1-2: *General rules and fire design.* (Swedish version) Swedish Standard Institution SS EN 1993-1-2; 2005

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Appendix A – Problem description (in Swedish)

These drawings were provided by Peikko Sverige AB and show the connection and the original framing of the question.

PELARDEL SVETSAS TILL RÖR

PEIKKO PCs3 KONSOLDEL
VERTIKAL KRAFT 300 kN
I BROTTSTADIET

30

4 ST Ø25 B500BT
TB 30mm TILL HUVUDAARMERINGEN

BYGLAR Ø6 B500BT

PELARRÖR CFRHS 250x250x6 S355

BTG C25/30

VERTIKAL LAST 300kN
I BROTTSTADIET

KVADRATISK SAMVERKANSPELARE
CFRHS 250x250x6 GJUTEN MED BTG C25/30

PEIKKO DELTABALK
(SAMVERKANSBALK)

PEIKKO PCs 3 KONSOL
SVETSAS TILL STÅLEPLARE
OCH GJUTS FAST I SAMVERKANSPELARE

VILKEN LAST KLARAR KONSOLEN AV I BRANDKLASS R60?
HUR SKALL BYGLARNA VARA PLACERADE KRING KONSOLEN?

PELARDEL SVETSAS TILL RÖR

PEIKKO PCs3 KONSOLDEL
VERTIKAL KRAFT 300 kN
I BROTTSTADIET

4 ST Ø25 B500BT
TB 30mm TILL HUVUDAARMERINGEN

BYGLAR Ø6 B500BT

PELARRÖR CFCHS Ø273x6 S355

BTG C25/30

VERTIKAL LAST 300kN
I BROTTSTADIET

RUND SAMVERKANSPELARE
Ø273x6mm. IGJUTEN MED BTG C25/30

PEIKKO DELTABALK
(SAMVERKANSBALK)

PEIKKO PCs 3 KONSOL
SVETSAS TILL STÅLEPLARE
OCH GJUTS FAST I SAMVERKANSPELARE

VILKEN LAST KLARAR KONSOLEN AV I BRANDKLASS R60?
HUR SKALL BYGLARNA VARA PLACERADE KRING KONSOLEN?

Appendix B – PCs3 corbel dimensions
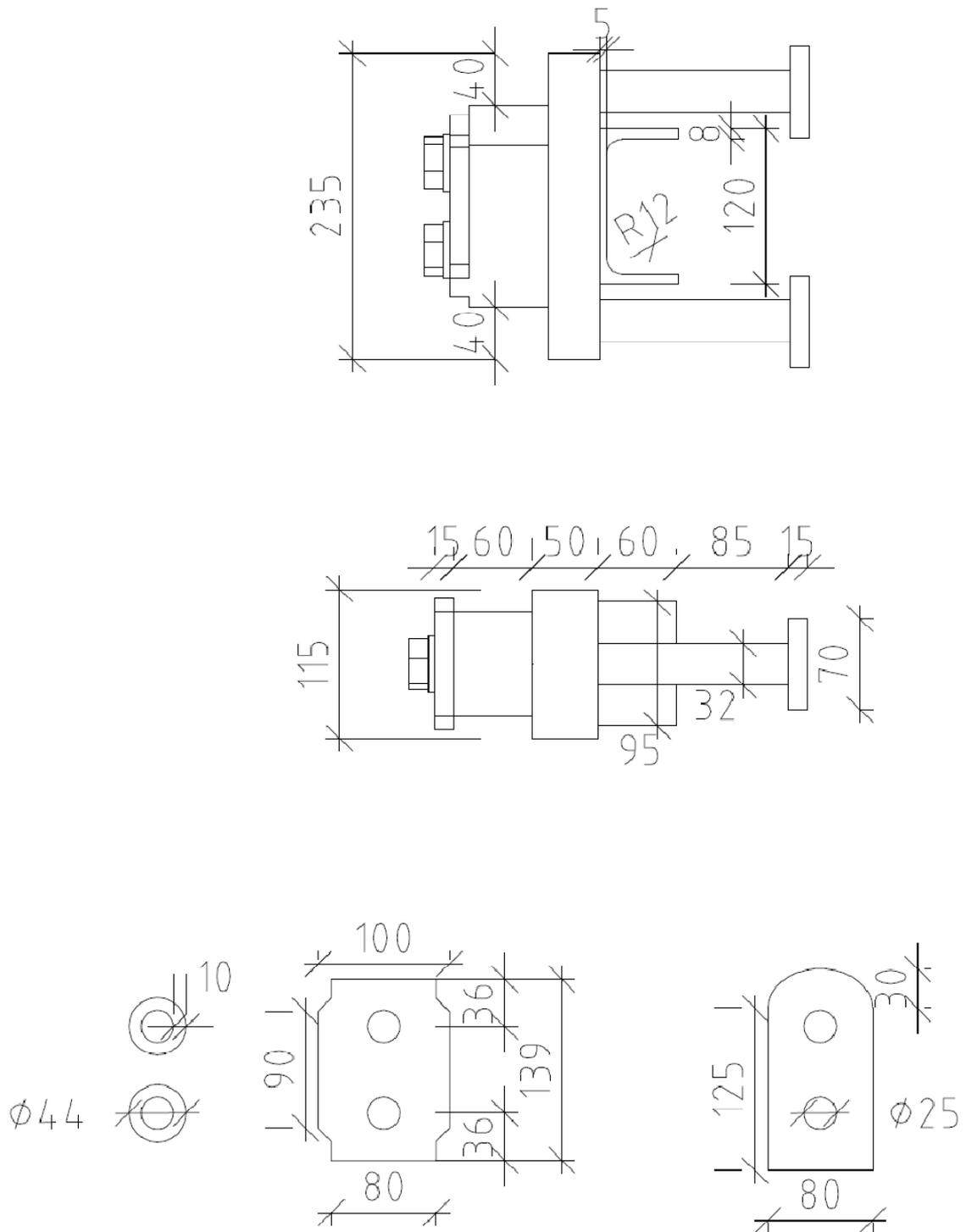
Appendix C – Pictures of the PCs3 corbel
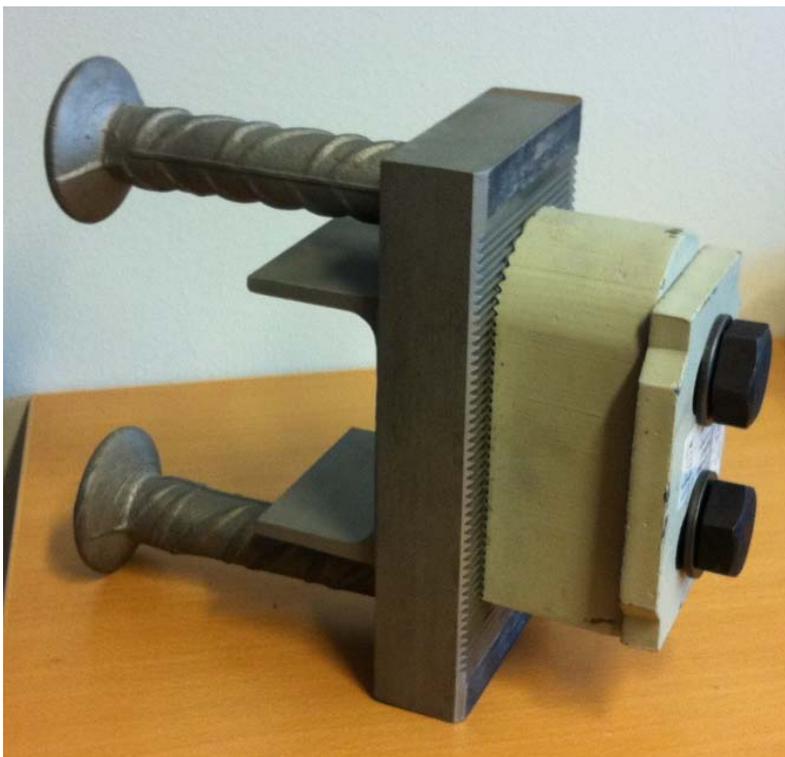
Appendix D – More Simulation Results

A selection of the most important results are presented in the report, more figures and details about the simulation results are collected in this appendix.

Thermal Simulation Results

One of the main objectives in this thesis was to study what a 60 minutes long fire will lead to when it comes to temperature distribution in to the connection. Based on these results also determine if the PCs corbel is a trustworthy connection detail. In this chapter additional results to those shown in Chapter 5.2 are presented.

Connection in 'Concrete Filled Rectangular Hollow Section'

Temperature distribution after 60 minutes of fire for the column with rectangular cross section is presented in Figures 35 and 36. They show a very similar behavior to the rectangular column seen in Figures 24 and 25.
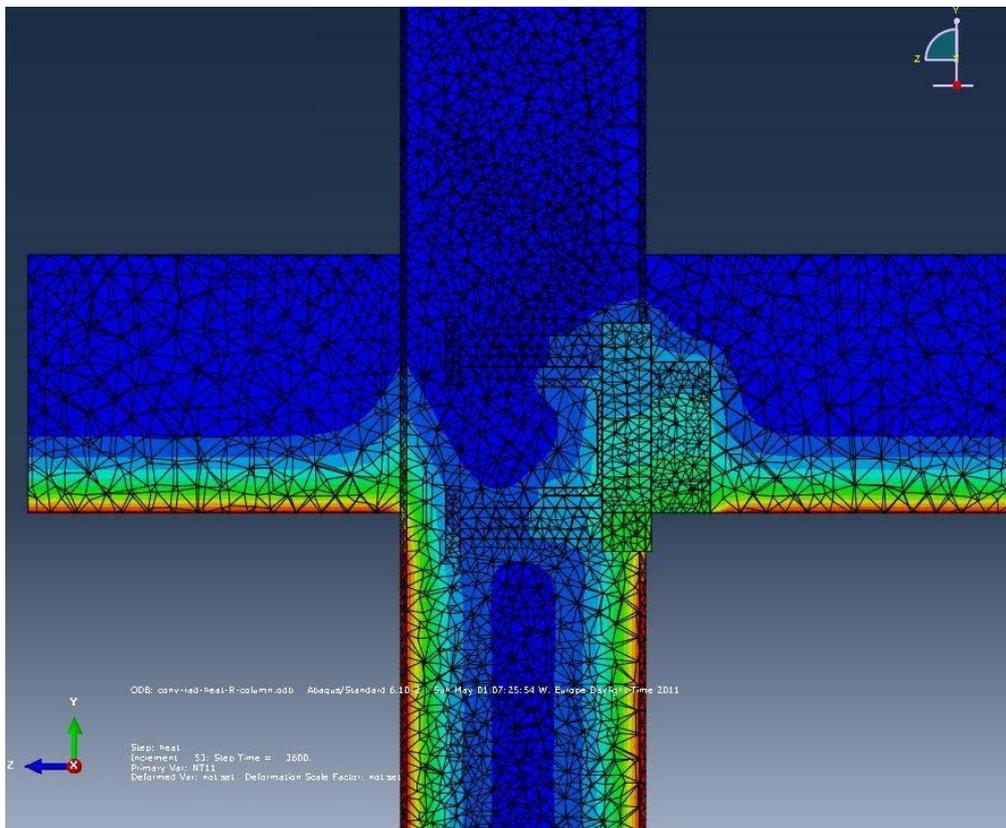

Figure 35: Temperature distribution in CFRHS connection after 60 minutes of fire. Blue=20°C Red=922°C
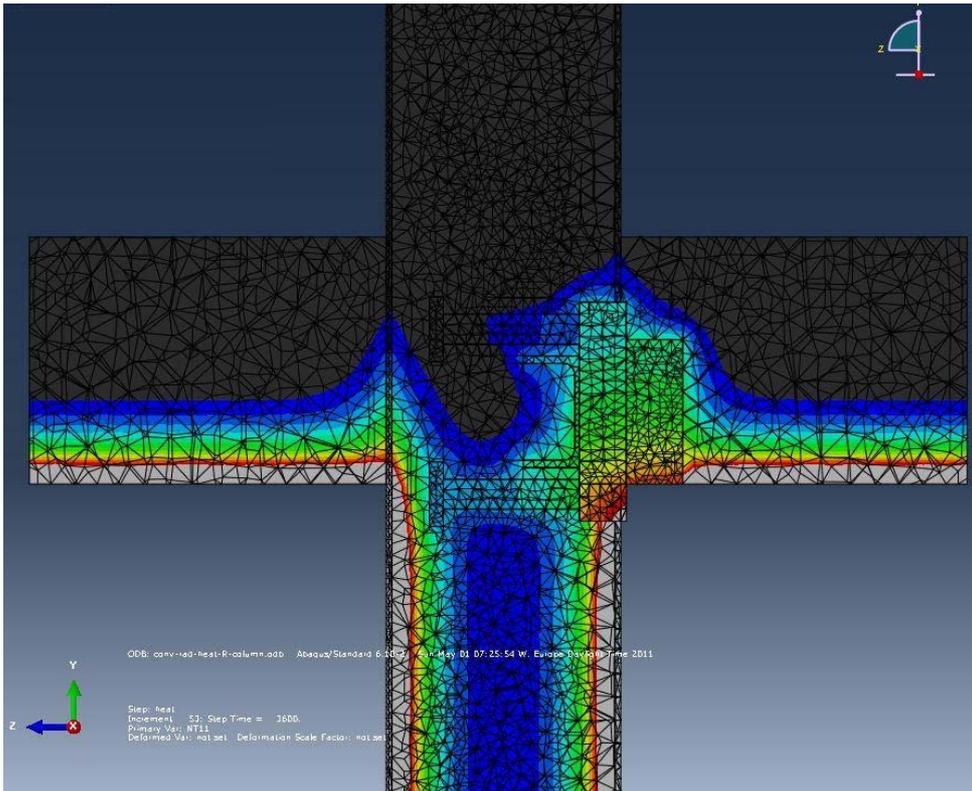
Figure 36: Blue =50°C Red=500°C

Thermal Distribution in Corbel

The most important part in the studied connection is the PCs corbel, in addition is steel much more sensitive to temperature changes than concrete. Therefore an extended analysis of temperatures in the corbel has been performed.

Note that the simulation is performed with the corbel placed within the connection, but for studying the corbel exclusively all other parts are hidden.

Corbel in 'Concrete Filled Circular Hollow Section'

Figures 38-40 show the temperature distribution for the PCs corbel when placed in a CFCHS column, ϕ273mm.

For current temperature scale and spectrum see Figure 37. Note that the unit is Kelvin, to get the results in Celsius subtract 273 from the Kelvin temperature.
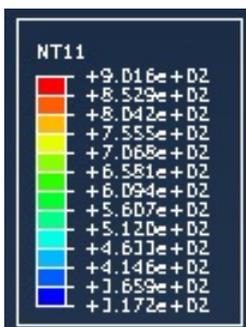
Figure 37: Temperature scale in Kelvin

Temperatures are from 628.6°C (red region) down to 44.2°C (darkest blue regions) are found in the PCs corbel in the circular column.

At temperatures over 400°C is the steels yield strength starting to decrease. Looking at the corbel from the side it can be seen that such high temperatures are found at the parts directly exposed to fire and the nearby region, see Figure 38. The lower stud is more critical than the upper since its temperature is considerably higher in the lower stud.
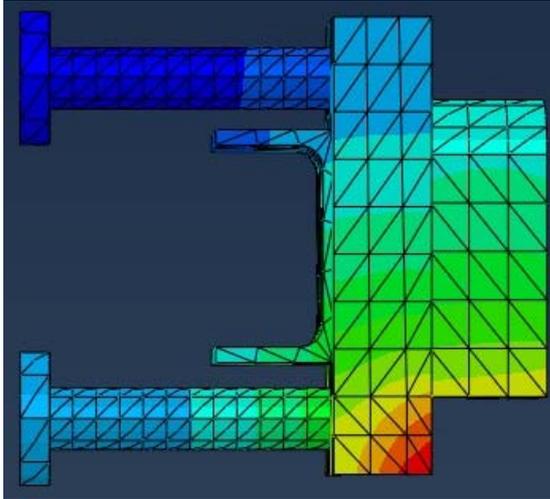
Figure 38: Corbel in CFCHS from side

In Figure 39 the backside of the corbel can be seen showing the U-shaped plate has an elevated temperature close to the lower corner (green region).
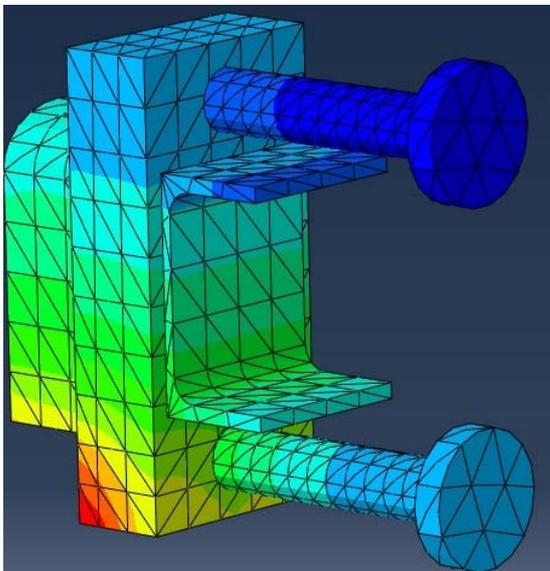
Figure 39: Corbel in CFCHS from back
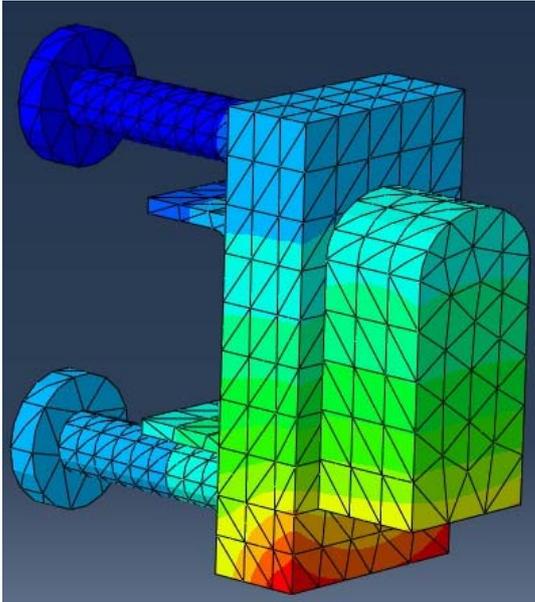
Figure 40: Corbel in CFCHS from front

Corbel in 'Concrete Filled Rectangular Hollow Section'

Figure 41-44 show the temperature distribution for the PCs corbel when placed in a composite column with rectangular cross section, 250x250mm^2.


Figure 41: Temperature scale in Kelvin

Temperatures from 596°C (red region) down to 48°C (darkest blue regions) are found in the PCs corbel in CFRHS column.

Compared to the CFCHS column, the temperature span from highest to lowest temperature is smaller for the CFRHS column, ΔT_R=547.2°C compared to ΔT_C=584.4°C.

Maximum temperature within the corbel is 33°C higher for a CFCHS column.

Minimum temperature within the corbel is 4°C lower for a CFRHS column.
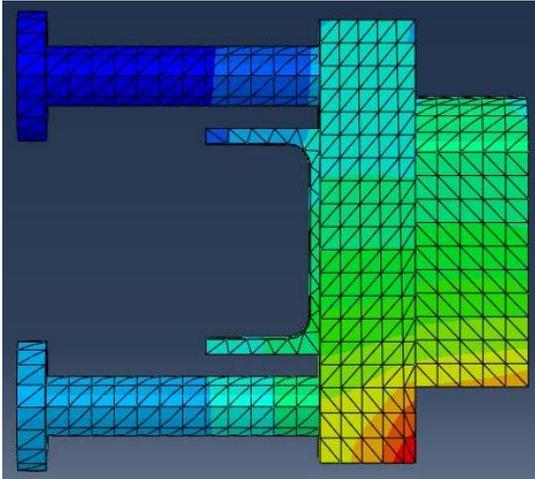
Figure 42: Corbel in CFRHS from side

By studying Figures 42-44, showing temperature distribution in the corbel when placed in a rectangular column, it can be seen that it is very similar to the case with circular column.
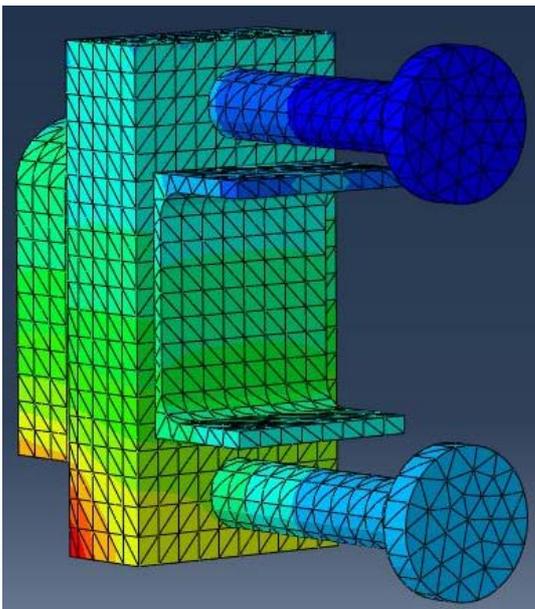
Figure 43: Corbel in CFRHS from back
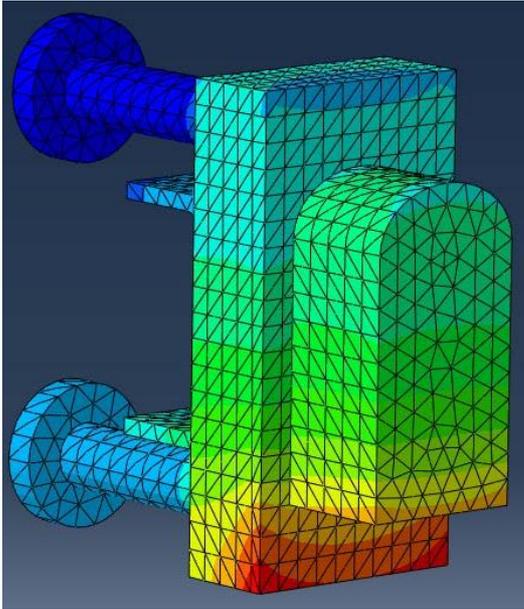
Figure 44: Corbel in CFRHS from front

Undisturbed Column Section

Here is a comparison between CFCHS and CFRHS-columns presented. The comparison regards temperature distribution in a cutting plane where the section is not affected by the corbel connection, see Figures 45 and 46.
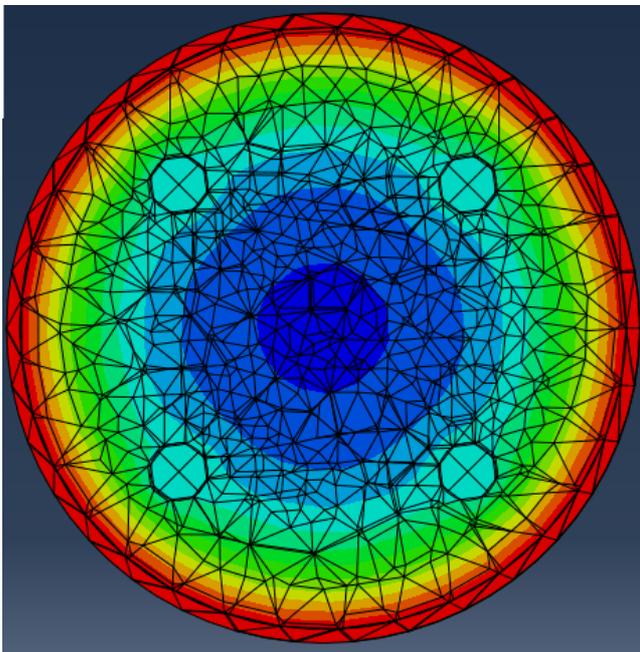
Figure 45: Temperature distribution in CFCHS-column
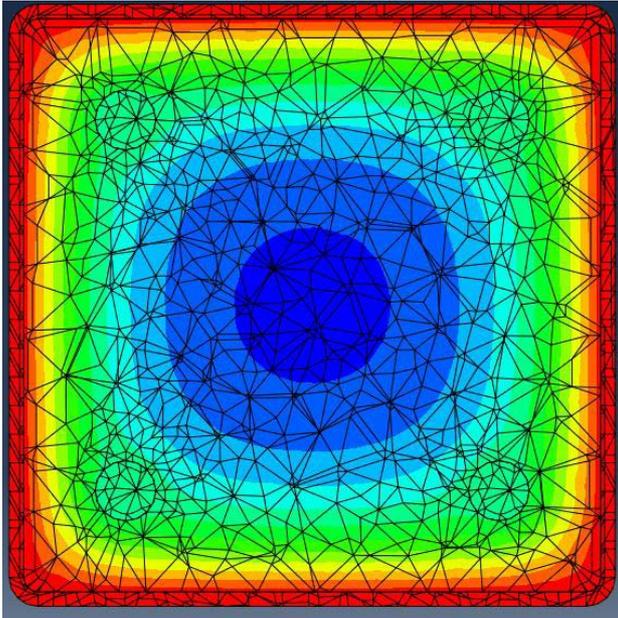
Figure 46: Temperature distribution in CFRHS-column

Reinforcement temperature is $302°C$ for the circular column and $380°C$ for the rectangular.

A comparison between the two cross sections are made in Figure 47, here can it be seen that the temperature distribution is very similar in the two cases. Some small differences are expected since the circular has an outer diameter of 273mm compared to the quadratic with outer measurement $250\text{x}250\text{mm}^2$. Zero at the x-axis is placed centric of respectively column.
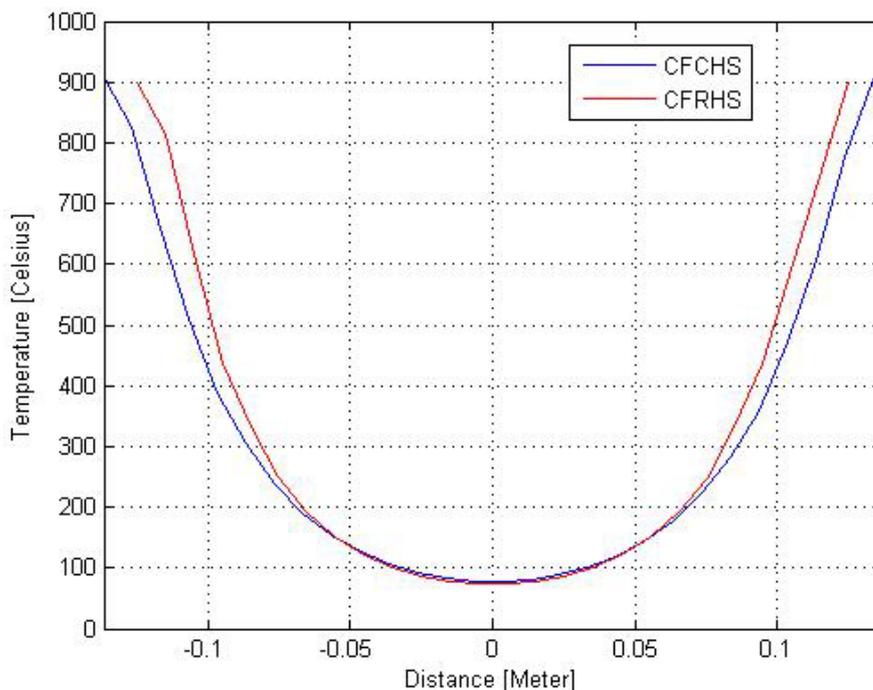
Figure 47: Temperature in a cut through the middle of both CFCHS and CFCHS

Temperature distribution simulations has been made by Peikko, see Figure 48. This simulation is anyhow not based on Eurocode, but is still accurate enough to be used as a reference.
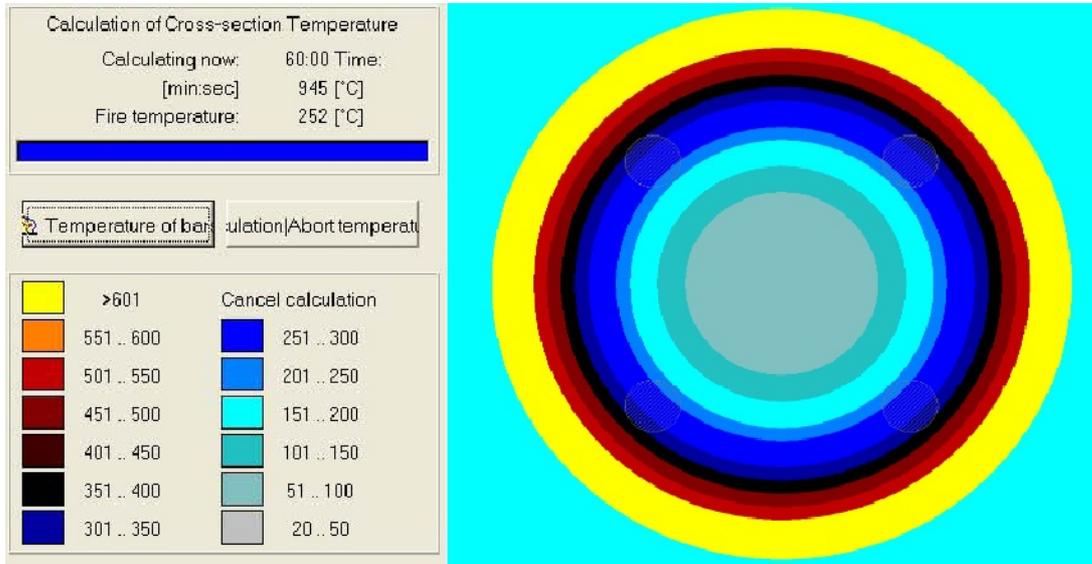
Figure 48: Reference simulation provided by Peikko

Stress Simulation

As the temperature raises does stresses redistribute from the steel shell to the inner concrete core. In Figure 49 are the stresses in a CFCHS column presented before fire initiation and after 60 minutes of fire. Similar illustration from CFRHS column was presented in Chapter 5.3.2.
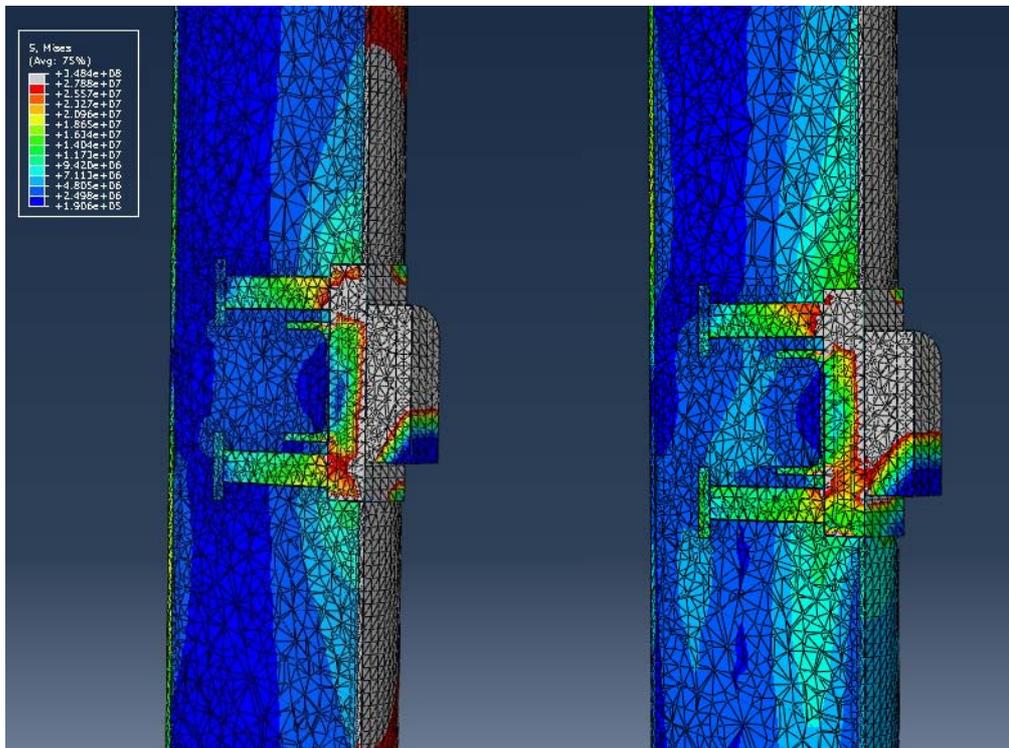
Figure 49: Stress redistribution before fire initiation and after 60 minutes of fire

Appendix E – Extract from Abaqus Job Input Data

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[CFCHS corbel - Thermal analysis]
** Job name: convect-temp2 Model name: Corbel-heat
** Generated by: Abaqus/CAE 6.10-2
*Preprint, echo=NO, model=NO, history=NO, contact=NO
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.
.
** INTERACTION PROPERTIES
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*Surface Interaction, name=IntProp-1
1.,
*Gap Conductance
1000.,   0.
   0.,1000.
*Film Property, name=IntProp-2
25.
**
** PHYSICAL CONSTANTS
**
*Physical Constants, absolute zero=0., stefan boltzmann=5.67e-08
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** PREDEFINED FIELDS
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** Name: Predefined Field-1   Type: Temperature
*Initial Conditions, type=TEMPERATURE
_PickedSet639, 293.
**
** INTERACTIONS
**
** Interaction: corbel-shield
*Contact Pair, interaction=IntProp-1, type=SURFACE TO SURFACE
_PickedSurf486, _PickedSurf485
.
.
.
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**
** STEP: heat
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*Step, name=heat, inc=150
*Heat Transfer, end=PERIOD, deltmx=1500.
300., 3600., 10., 3600.,
**
** INTERACTIONS
**
** Interaction: CONVECTION
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_PickedSurf641, F, 1., IntProp-2
** Interaction: RADIATION CONCRETE
*Sradiate, amplitude="ISO834 kelvin"
_PickedSurf634, R, 1., 0.8
** Interaction: RADIATION STEEL
*Sradiate, amplitude="ISO834 kelvin"
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_PickedSurf633, R, 1., 0.8
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*Restart, write, frequency=0
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*Output, field
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NT,
*Output, history, frequency=0
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*
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[CFRHS corbel – Thermal analysis]

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rectangular-column
** Generated by: Abaqus/CAE 6.10-2
*Preprint, echo=NO, model=NO, history=NO, contact=NO
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**
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1.,
*Gap Conductance
1000.,   0.
   0.,1000.
*Film Property, name=IntProp-2
25.
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** PHYSICAL CONSTANTS
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*Physical Constants, absolute zero=0., stefan boltzmann=5.67e-08
**
** PREDEFINED FIELDS
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** Name: Predefined Field-1   Type: Temperature
*Initial Conditions, type=TEMPERATURE
_PickedSet687, 293.
**
** INTERACTIONS
**
** Interaction: corbel-2-concrete
*Contact Pair, interaction=IntProp-1, type=SURFACE TO SURFACE

*Contact Pair, interaction=IntProp-1, type=SURFACE TO SURFACE
_PickedSurf668, _PickedSurf671
** ----------------------------------------------------------
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```
*Heat Transfer, end=PERIOD, deltmx=1500.
300., 3600., 10., 3600.,
**
** INTERACTIONS
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** Interaction: CONVECTION
*Sfilm, amplitude="ISO834 kelvin"
_PickedSurf663, F, 1., IntProp-2
** Interaction: RADIATION CONCRETE
*Sradiate, amplitude="ISO834 kelvin"
_PickedSurf660, R, 1., 0.8
** Interaction: RADIATION STEEL
*Sradiate, amplitude="ISO834 kelvin"
_PickedSurf662, R, 1., 0.8
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NT,
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*End Step
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[CFRHS corbel – Quasi-static analysis (temperature dependent input data]
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*Preprint, echo=NO, model=NO, history=NO, contact=NO
** ----------------------------------------------------------------
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*Gap Conductance
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   0.,1000.
*Film Property, name=IntProp-2
25.
**
** PHYSICAL CONSTANTS
**
*Physical Constants, absolute zero=0., stefan boltzmann=5.67e-08
**
** BOUNDARY CONDITIONS
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** Name: BC-1 Type: Displacement/Rotation
*Boundary
_PickedSet723, 1, 1
_PickedSet723, 2, 2
_PickedSet723, 3, 3
```

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** Name: BC-2 Type: Displacement/Rotation
*Boundary
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_PickedSet724, 2, 2
_PickedSet724, 3, 3
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*Step, name="stress - 5min"
*Static
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**
** LOADS
**
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*Dsload
_PickedSurf736, P, 3.21964e+08
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
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**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step
** ----------------------------------------------------------------
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*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
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binc=2, einc=2, interpolate
```

```
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step
** ----------------------------------------------------------------
**
** STEP: stress - 15min
**
*Step, name="stress - 15min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
binc=3, einc=3, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step
** ----------------------------------------------------------------
**
** STEP: stress - 20min
**
*Step, name="stress - 20min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
binc=4, einc=4, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
```

```
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step
** ----------------------------------------------------------------
**
** STEP: stress - 25min
**
*Step, name="stress - 25min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
binc=5, einc=5, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step
** ----------------------------------------------------------------
**
** STEP: stress - 30min
**
*Step, name="stress - 30min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
binc=29, einc=29, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
```

```
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step
** ----------------------------------------------------------------
**
** STEP: stress - 35min
**
*Step, name="stress - 35min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
binc=44, einc=44, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step
** ----------------------------------------------------------------
**
** STEP: stress - 40min
**
*Step, name="stress - 40min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
binc=49, einc=49, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
```

```
*Output, history, frequency=0
*End Step
** ----------------------------------------------------------------
**
** STEP: stress - 45min
**
*Step, name="stress - 45min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
binc=50, einc=50, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step
** ----------------------------------------------------------------
**
** STEP: stress - 50min
**
*Step, name="stress - 50min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
binc=51, einc=51, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step
** ----------------------------------------------------------------
**
```

```
** STEP: stress - 55min
**
*Step, name="stress - 55min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
binc=52, einc=52, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step
** ------------------------------------------------------------------
**
** STEP: stress - 60min
**
*Step, name="stress - 60min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/conv-rad-heat-R-column.odb,
binc=53, einc=53, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
NT, U, UR, UT
*Element Output, directions=YES
E, EE, PE, PEMAG, S, PEEQ
*Output, history, frequency=0
*End Step

-------------------------------------------------------------------------

[CFCHS corbel – Quasi-static analysis (temperature dependent input
data]
** Job name: C-column-final Model name: Corbel-CFCHS-final
** Generated by: Abaqus/CAE 6.10-2
```

```
*Preprint, echo=NO, model=NO, history=NO, contact=NO
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Initial Conditions, type=TEMPERATURE,
file=/beda/users/home/jkvist/convect-temp2.odb, step=2, inc=0,
interpolate
** ----------------------------------------------------------------
**
** STEP: Stress -5min
**
*Step, name="Stress -5min"
*Static
1., 1., 1e-05, 1.
**
** BOUNDARY CONDITIONS
**
** Name: BC-1 Type: Displacement/Rotation
*Boundary
_PickedSet597, 1, 1
_PickedSet597, 2, 2
_PickedSet597, 3, 3
** Name: BC-2 Type: Displacement/Rotation
*Boundary
_PickedSet598, 1, 1
_PickedSet598, 2, 2
_PickedSet598, 3, 3
**
** LOADS
**
** Name: Load-1   Type: Pressure
*Dsload
_PickedSurf476, P, 3.21964e+08
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=1,
einc=1, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
*Contact Output
CDISP, CSTRESS
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
```

```
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress - 10min
**
*Step, name="Stress - 10min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=2,
einc=2, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
*Contact Output
CDISP, CSTRESS
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress - 15min
**
*Step, name="Stress - 15min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=3,
einc=3, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
```

```
*Contact Output
CDISP, CSTRESS
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress - 20min
**
*Step, name="Stress - 20min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=4,
einc=4, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
*Contact Output
CDISP, CSTRESS
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress -25min
**
*Step, name="Stress -25min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=5,
einc=5, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
```

```
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
*Contact Output
CDISP, CSTRESS
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress - 30min
**
*Step, name="Stress - 30min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1    Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=17,
einc=17, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
*Contact Output
CDISP, CSTRESS
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress - 35min
**
*Step, name="Stress - 35min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1    Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=31,
einc=31, interpolate
```

```
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
*Contact Output
CDISP, CSTRESS
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress - 40min
**
*Step, name="Stress - 40min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=36,
einc=36, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress - 45min
**
*Step, name="Stress - 45min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
```

```
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=39,
einc=39, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress - 50min
**
*Step, name="Stress - 50min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=42,
einc=42, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress - 55min
**
*Step, name="Stress - 55min"
*Static
1., 1., 1e-05, 1.
```

```
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=45,
einc=45, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** ----------------------------------------------------------------
**
** STEP: Stress - 60min
**
*Step, name="Stress - 60min"
*Static
1., 1., 1e-05, 1.
**
** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Temperature, file=/beda/users/home/jkvist/convect-temp2.odb, binc=46,
einc=46, interpolate
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, U
*Element Output, directions=YES
LE, PE, PEEQ, PEMAG, S, TEMP
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
```