Double-Skin Glass Façades and Compliance with the Fire Safety Rules in Building Code 21 (BBR 21)

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Preface

This thesis is the final part of the Master Programme in Fire Engineering (Swe: Civilingenjör Brandteknik) at Luleå University of Technology (Swe: Luleå tekniska universitet, LTU). The programme is managed by the Department of Civil, Environmental and Natural Resources Engineering (Swe: Institutionen för samhällsbyggnad och naturresurser, SBN).

I’d like to thank my internal supervisor Michael Förs for providing advice and input during the thesis, both regarding FDS and the report. In addition to this Naveed Iqbal deserves thanks for providing advice regarding Abaqus. Furthermore I want to thank my external supervisor Ulf Nygren for suggesting this subject and providing me with information for the case study.

My family and friends also deserve thanks for supporting me throughout the thesis.

*Christian Pelo*

*2015-09-06*

*Luleå*
Abstract

Double-skin glass façades has gained in popularity and is now a common feature in buildings in both Sweden and throughout the rest of the world. This gives rise to the question about the fire safety of these types of façades as the Swedish building code published by Boverket (Swe: Boverkets byggregler 21, BBR 21) currently does not provide any advice regarding how to fulfill the performance requirements.

This thesis attempted to determine how a double-skin glass façade can comply with BBR 21. To limit the extent of the thesis a case study was conducted on the building Skeppshandeln 1, Hammarby Sjöstad, Stockholm, Sweden. As a part of this a literature study of research regarding double-skin façades, and building codes were made. The building codes analyzed were the ones from Sweden, New Zealand and Hong Kong. In addition to this simulations were made on a compartment based on the case study using Fire Dynamics Simulator (FDS) and an Abaqus analysis of a window with assumed input parameters.

The information available for the case study was a floor layout and fire documentation, these were provided by Hifab AB. It was initially believed that detailed information regarding the façade could be accessed but when the information was required it was discovered that it was not available. Due to lack of time it was not possible to obtain sufficiently detailed information regarding the design of these types of façades from other sources.

The modeling of the façade in FDS was done in two different ways. The first alternative uses one single obstruction with several surface layers; the second approach uses two obstructions with the material parameters of glass and an air gap between the obstructions. It was also attempted to model the façade using Lagrangian particles but this was unsuccessful due to how these function in FDS.

The conclusions that could be drawn from the literature study is that although certain elements in the BBR 21 will also apply to double-skin glass façades there are uncertainties regarding the external glass and the air gap. Previous research and the building codes from New Zealand and Hong Kong provide some solutions to managing the air gap but these may contradict BBR 21. Specifically BBR 21 specifies that the amount of debris shall be limited whereas these façade solutions according to the building codes in New Zealand and Hong Kong require breaking the external window which will cause debris to fall down.

The temperature analysis of the results from FDS indicate that in this specific case the façade design has to take into account that temperatures ranging from 800°C to approximately 950°C may occur in a fire situation. This does not take into account that there is a sprinkler system present in the compartment. These temperatures are highly dependent on whether the fire source is designed as a burner with a peak heat release rate (HRR) or fire load density; the expected temperatures will also vary with the placement of the fuel.
The fixing points will be a weak spot in a double skin façade; the highest levels of stress will be located in proximity to these. They will also be required to maintain enough of their load bearing capacity in order to support the window. Due to the relatively high temperatures that are expected in smaller compartments aluminium is likely to be an unsuitable material; the load bearing capacity of aluminium is only 6% of its original value at 350⁰C and the fixing points are expected to be exposed to temperatures above 400 degrees.

Due to the limited amount of information available a detailed assessment of a specific façade construction could not be carried out. The thesis did however identify design choices that need to be considered in order to prevent fallout and/or cracking and fire spread inside the façade. The question of whether some of the international solutions for preventing fire spread inside the façade are applicable in Sweden is unclear and requires the attention of Boverket. This thesis should be viewed as a possible example of how a detailed analysis of a double-skin glass façade can be done and it identifies several points of interest regarding fire safety in the design of such façades.
Sammanfattning

Dubbelglasfasader har ökat i popularitet både i Sverige och övriga världen. Detta har gett upphov till frågor angående brandsäkerheten i samband med dessa fasader eftersom BBR 21 (Boverkets byggregler 21) inte innehåller några allmänna råd för hur funktionskraven kan uppfyllas.

Syftet med detta examensarbete var att undersöka hur dubbelglasfasader kan uppfylla de krav som ställs av BBR 21. För att begränsa omfattningen valdes byggnaden Skeppshandeln 1, Hammarby Sjöstad, Stockholm, Sverige som referensobjekt. En litteraturstudie genomfördes där forskning angående dubbelglasfasader och byggregler analyserades; de byggregler som undersöktes var BBR 21, Nya Zealand och Hong Kong. Utöver detta genomfördes FDS simuleringar av ett utrymme som var baserat på referensobjektet samt Abaqus simuleringar med antagna parametrar för fönster.

Den information som fanns tillgänglig om referensobjektet var planlösningen samt brandskyddsdocumentationen, denna information var tillhandahållen av Hifab AB.

Två alternativa tillvägagångssätt användes för att modellera fasaden i FDS. En av dessa använder en enda fasadskiva med flera olika lager, det andra tillvägagångssättet använder istället två fasadskivor med materialparametrarna för glas och en luftspalt mellan dessa. Försök att använda Lagrange partiklar för att modellera fasaden gjordes, detta kunde inte genomföras på grund av hur dessa hanteras i FDS.

Från litteraturstudien kunde slutsatsen dras att även om vissa delar av BBR 21 kommer att gälla även för dubbelglasfasader kvarstå fortfarande osäkerheter angående det yttra glaset och luftspalten. Forskning inom området och byggreglerna från Nya Zealand och Hong Kong har lösningar för att hantera den risk som luftspalten utgör, dock är det möjligt att dessa lösningar är i konflikt med BBR 21. BBR 21 kräver att ytterväggen ska utformas så att ”risken för personskador till följd av nedfallande delar av ytterväggen begränsas”, ett visst nedfall av glas är en förutsättning för att de lösningar som finns i byggreglerna från Nya Zealand och Hong Kong ska fungera.


Infästningarna kommer att vara en svag punkt i dubbelglasfasaden, det är i anslutning till dessa som de största spänningarna kommer att uppstå. Infästningarna kommer även att
behöva vara utformade så att deras lastbärande förmåga är tillräcklig. På grund av de höga temperaturer som förväntas i mindre utrymmen är infästningar av aluminium sannolikt ett olämplig val; vid 350°C har aluminium endast kvar 6% av sin ursprungliga bärkraft, temperaturen vid infästningarna förväntas överstiga 400 grader.

På grund av den begränsade mängden information som var tillgänglig kunde inte en fullständig analys av en dubbelglasfasad genomföras. Dock identifierades svaga punkter i dubbelglasfasader som behöver beaktas för att förhindra brandspridning i fasaden samt att fönstret spricker och/eller faller ner. Det är oklart om vissa av de internationella lösningar som finns för att förhinda brandspridning i fasaden är tillämpbara enligt BBR 21, detta behöver klargöras av Boverket. Detta examensarbete ska ses som ett möjligt exempel för hur en detaljerad analys av en dubbelglasfasad skulle kunna genomföras samt att flera viktiga punkter som är relevanta för brandäkerheten för dubbelglasfasader har identifierats.
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Nomenclature

*Latin upper case letters*

\( A \)  \quad \text{area [m}^2\text{]}

\( H \)  \quad \text{effective heat of combustion [MJ/kg]}

\( M \)  \quad \text{amount of combustible material [kg]}

*Latin lower case letters*

\( c \)  \quad \text{specific heat [J/kgK]}

\( f \)  \quad \text{fire load density [MJ/m}^2\text{]}

\( m \)  \quad \text{coefficient for combustion behavior}

*Greek letters*

\( \varepsilon \)  \quad \text{emissivity [-]}

\( \theta \)  \quad \text{temperature [°C]}

\( \lambda \)  \quad \text{conductivity [W/mK]}

\( \rho \)  \quad \text{density [kg/m}^3\text{]}

*Subscripts*

\( a \)  \quad \text{steel}

\( \text{al} \)  \quad \text{aluminium}

\( g \)  \quad \text{gas temperature [°C]}

\( i \)  \quad \text{index}
1. Introduction

Double-skin glass façades have gained in popularity both in Sweden and throughout the world in recent years. This is partially due to increased energy efficiency compared to single-skin glass façades and the appealing architecture. According to Axel Jönsson and Hans Nyman (Jönsson & Nyman, 2014) there are however concerns regarding the fire safety with double-skin glass façades in buildings since there is an increased risk for fire spread between floors compared to single skin façades. This is due to the cavity between the windows acting as a chimney and exposing windows higher up to hot gases. There is also the possibility of debris falling down on pedestrians and rescue teams; this is also a risk for single skin façades. In addition, the double-skin façade can increase the difficulty for the rescue team to estimate the magnitude of the fire (due to smoke accumulation leading to decreased visibility) and obstruct access to the building (due to high-strength window panes that could exclude the façade as a possible entry point) (Ni, Lu, & Peng, 2012). The Swedish National Board of Housing, Building and Planning (Boverket) publishes the Building Code (Swe: Boverkets bygggregler, BBR) which regulates the design of buildings, including fire safety. The most recent Building Code is BBR 21 which provides only performance requirements but no specific advice regarding how double-skin glass façades can fulfill those. Due to this, performance based design is required in order to establish that a façade complies with BBR 21. Performance based design is regulated by Boverkets general advice regarding performance based design of fire safety in buildings 3 (BBRAD 3). The lack of specific requirements in BBR 21 regarding this type of façade is not optimal since the use of performance based design might cause irregularities in the safety levels and requires attention.

Therefore this topic was determined to be an appropriate subject for a master thesis in fire protection engineering. The subject was initially suggested by Hifab AB who also provided external supervision. In addition to this internal supervision was provided by Luleå University of Technology. The thesis discusses how double-skin glass façades perform with regards to the general requirements made by Boverket on façades and windows. To limit the extent of the thesis it is focused on a case study of the building Skeppshandeln 1 which is located in Hammarby Sjöstad, Stockholm, Sweden.

The case study was only partially completed. The reason for this is that detailed information regarding the façade was unavailable and this made a detailed analysis of the façade impossible, instead a more general Finite element analysis of the stress distribution in glass depending on fixing points was made.
Purpose
The primary purpose with this thesis is to determine how a double-skin glass façade can fulfill the requirements from BBR 21. The secondary purpose is to determine if the designs for double-skin glass façades currently used in Sweden can be considered to fulfill the fire safety regulations.

1.1 Limitations
This thesis is restricted to:

- Literature study
- Case study
- Computational fluid dynamics (CFD) simulations using Fire Dynamics Simulator (FDS)
- Finite element (FEM) simulations using Abaqus CAE

To limit the number of possible scenarios involving double-skin glass façades some assumptions regarding the fire situation were required; a case study was conducted on the building Skeppshandeln 1 which is located in Hammarby Sjöstad, Stockholm, Sweden. Skeppshandeln 1 houses several types of occupancies but the only areas of interest for this thesis are the ones located in proximity to the double-skin façade; these are hotel and office areas.

The fire scenario is limited to comply with BBRAD 3 (Boverket, 2013) and the BIV document “CFD calculations with FDS” (Back, et al., 2013). Therefore the compartment was not modeled as realistically as possible but instead modeled with regard to these documents. The report “Selecting design fires” by Leif Staffansson was also used to choose a fire scenario (Staffansson, 2010).

FDS allows for the modeling of sprinkler systems (McGrattan, McDermott, Weinschenk, Overholt, Hostikka, & Floyd, 2014) but this was not done since it’s not the recommended procedure by BBRAD 3. BBRAD 3 instead supports the use of modification of the heat release rate (HRR) or fire load density (FLD) to account for the use of a sprinkler system (Boverket, 2013).
2. State of art

In this chapter previous research about double-skin glass façades and relevant regulations is presented. In the literature there are other names for double-skin glass façades, they are also called curtain walls but will be referred to as double-skin glass façades in this thesis.

2.1 Previous research

There exist large amounts of international research regarding double-skin glass façades. The majority of these papers investigate either fire spread inside the façade or the fracture mechanism of glass panes.

Apron design as a measure to limit fire spread in double-skin glass façades is discussed by (Chow, Li, & Huang, 2014). They used CFD simulations to determine the effect aprons have on fire spread inside the cavity between the windows. An apron is a horizontal projection whose purpose is to direct hot gases away from the internal windows in the double-skin façade in order to decrease the temperature of the internal window, an example of this is shown in Figure 1. They propose that the exterior pane should consist of regular glass and the interior of fire resistant glass. As a result the exterior pane would break prior to the inner and ventilate the hot gases. This combination would be essential for the aprons to efficiently limit fire spread.

![Figure 1. Example of the use of apron to divert hot gases from the wall (Chow, Li, & Huang, 2014).](image)

A report from full scale experiment that studies the performance of double-skin glass façades was published in the Journal of Fire Sciences (Ni, Lu, & Peng, 2012). These authors also arrive at the conclusion that breaking of the exterior layer decreases the temperature inside the cavity. This results in a decreased temperature of the internal windows and lowered risk that these windows will break. They also conclude that both the breakage time of the glass and the smoke movement inside the cavity is highly dependent on the Heat Release Rate (HRR). The use of aluminum frames in the façade caused considerable
deformations even before the inner glass broke, as a solution to this they proposed the use of steel frames.

The effect that the fixing of the double-skin façade has on the fracturing of the glass is also an aspect that needs to be considered. The fixing locations impact on fracture behavior was investigated by (Wang, Wang, Shao, Chen, & Su, 2014) and their conclusion was that horizontal variations of the fixing points has a greater impact than vertical ones, they also came to the conclusion that the closer to the center the fixing points are the faster the glass will fall out. The authors states that this behavior may be caused by stresses in the glass varying with the fixing points. They conclude that in order to evaluate the breaking of a window both thermal and mechanical stresses must be accounted for. Therefore they recommend that this should be investigated further. Below is an example of four point fixing, Figure 2.

![Figure 2. An example of four point fixing (Wang, Wang, Shao, Chen, & Su, 2014).](image-url)
2.2 Regulations

The purpose of this thesis is to investigate the compliance of double-skin glass façades with the Swedish regulations and therefore it relies heavily on the documents BBR 21, BBRAD 3 and BBRBE 1, thus the relevant paragraphs and details will be presented in this section. Internationally there are other national standards that provide guidelines regarding the use of double-skin glass façades, among these are the New Zealand and Hong Kong building codes, therefore these will also be briefly presented.

The Swedish regulations will be presented in English despite that BBR 21, BBRAD 3 and BBRBE 1 only exist in Swedish. This is my translation and it aims to preserve the intent of BBR 21, BBRAD 3 and BBRBE 1 but is in no way approved by Boverket. The translations and abbreviations are listed in Table 1.

Table 1. Swedish regulations cited along with abbreviations, translations and the Swedish name.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>English translation</th>
<th>Swedish</th>
</tr>
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<tbody>
<tr>
<td>BBRAD 3</td>
<td>Boverkets general advice regarding performance based design of fire safety in buildings 3</td>
<td>Boverkets allmänna råd om analytisk dimensionering av byggnaders brandskydd</td>
</tr>
<tr>
<td>BBRBE 1</td>
<td>Boverkets general advice regarding fire load density 1</td>
<td>Boverkets allmänna råd om brandbelastning 1</td>
</tr>
<tr>
<td>BFS</td>
<td>Boverkets precept and general advice regarding the application of eurocodes</td>
<td>Boverkets föreskrifter och allmänna råd om tillämpning av europeiska konstruktionsstandarder (eurokoder)</td>
</tr>
<tr>
<td>EKS</td>
<td>Eurocodes</td>
<td>Europeiska konstruktionsstandarder</td>
</tr>
</tbody>
</table>

Noteworthy is that the use of SS-EN 1991-1-2, Annex E to determine the fire load density is not permitted according to BFS 2013:10 EKS 9 (Boverket, 2013). Instead BBRBE 1 is used.
2.2.1 Boverket

The fire safety requirements of a building are determined using a classification system. Various compartments inside a building can have different occupational classes (Swe: verksamhetsklasser) that are dependent on the purpose of the compartment; every compartment inside the building must be classified. These occupational classes in combination with other variables such as the number of floors will determine the class of the entire building (Swe: byggnadsklass). The building class (Br#) determines the details regarding the required fire safety performance. The four different building classes and the safety levels are presented below (Boverket, 2014).

- Br0: the building has very large safety requirements
- Br1: the building has large safety requirements
- Br2: the building has moderate safety requirements
- Br3: the building has small safety requirements

Details regarding how the safety requirements are determined is provided by Boverket in BBR 21 section 5:22 as general advice (Swe: allmänt råd) (Boverket, 2014).

The performance requirements regarding exterior walls are presented below (Boverket, 2014). These are extracts from BBR 21 paragraphs 5:551 and 5:552.

Section 5:551 states that exterior walls in buildings of class Br1 shall be designed so that:

1. the separating function between fire compartments is maintained,
2. fire spread inside the exterior wall is limited (Swe: begränsad),
3. the risk for fire spread along the façade is limited,
4. the risk of injuries caused by falling debris from the façade is limited

Section 5:552 states that exterior walls in buildings of class Br2 and Br3 shall be designed so that fire spread along the façade is limited.

Double-skin glass façade consists of large amounts of glass, therefore section 5:553 “Windows in the exterior wall” is also relevant. The performance requirement on windows from separate fire cells that are placed vertically in relation to each other is that they shall be designed and placed so that fire spread between the fire compartments is limited. The general advice is that the distance between two windows placed horizontally in relation to each other should be greater than 1.2 m, or that one of the windows fulfills E 30, or that both fulfills E 15.
BBRAD 3 specifies guidelines regarding performance based design of the fire safety in buildings, due to compliance with the regulations being the purpose with the thesis relevant details from BBRAD 3 will be provided below. BBRAD 3 uses three different approaches depending on whether the topic is evacuation, protection against fire spread, or ventilation. Details regarding the guidelines for evacuation and protection against fire spread are presented below. The guidelines regarding ventilation are excluded since they are not used in the thesis.

2.2.1.1 Evacuation

BBRAD 3 provides design values for fire growth rate, peak HRR and heat of combustion depending on the occupation; these are presented in Table 2. The values are only applicable if the fire is not ventilation controlled.

Table 2. Design values for fire growth rate, peak HRR and heat of combustion (Boverket, 2013).

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<tr>
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<tbody>
<tr>
<td>Offices and schools</td>
<td>0.012</td>
<td>5.0</td>
<td>16</td>
</tr>
<tr>
<td>Dwellings, hotels and care facilities</td>
<td>0.047</td>
<td>5.0</td>
<td>20</td>
</tr>
<tr>
<td>Community centers</td>
<td>0.047</td>
<td>10.0</td>
<td>20</td>
</tr>
</tbody>
</table>

Section 3.3.5 in BBRAD 3 takes the existence of an automatic sprinkler system into consideration depending on the HRR at the time of sprinkler activation. If the HRR is above 5.0 MW at activation the HRR is to be kept constant. If the HRR instead is equal to or below 5.0 MW then it is kept constant for one minute and then decreased to a third of the HRR at activation (the decrease is to take place during one minute).
2.2.1.2 Protection against fire and smoke spread in the building

In section 4.1.2.1 BBRAD3 states that the separating ability of a construction element can be verified using the model of a natural fire scenario in accordance with SS-EN 1991-1-2. The fire load should be obtained using BBRBE 1.

BBRBE 1 presents two approaches; either the use of Table 3 with values for fire load density or the use of equation 1 to calculate it (Boverket, 2013).

Table 3. Fire load densities for different occupations (Boverket, 2013).

<table>
<thead>
<tr>
<th>Fire load density [MJ/m²]</th>
<th>Occupation</th>
</tr>
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<tbody>
<tr>
<td>f ≤ 250</td>
<td>Concrete products industries and breweries of occupational class 1</td>
</tr>
<tr>
<td>f ≤ 800</td>
<td>Cinema, restaurant and theater of occupational class 2</td>
</tr>
<tr>
<td></td>
<td>Offices of occupational class 1</td>
</tr>
<tr>
<td></td>
<td>Spaces of occupational class 5</td>
</tr>
<tr>
<td></td>
<td>Garage</td>
</tr>
<tr>
<td></td>
<td>Schools and grocery stores of occupational class 2A and 2B</td>
</tr>
<tr>
<td></td>
<td>Spaces of occupational class 3, 4 and 5B</td>
</tr>
<tr>
<td>f ≤ 1600</td>
<td>Mall and shopping center of occupational class 2A and 2B</td>
</tr>
<tr>
<td>f &gt; 1600</td>
<td>Archive</td>
</tr>
<tr>
<td></td>
<td>Library</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
</tr>
<tr>
<td></td>
<td>Spaces of occupational class 6</td>
</tr>
</tbody>
</table>

\[
f = \frac{1}{A} \sum M_i H_{ui}(m_i) = \sum f_i (1)
\]

Where,

- \( M_i \): Amount of combustible material [kg]
- \( H_{ui} \): Effective heat of combustion [MJ/kg]
- \( A \): Floor area of the enclosure [m²]
- \( m_i \): Coefficient for combustion behavior [-]
If the combustion behavior is unknown, $m_i$ should be assumed to be equal to one, this value is influenced by the combustion efficiency of the fuel, geometry, positioning in the compartment and ventilation (Boverket, 2013). To account for the use of an automatic extinguishing system the fire load density can be reduced to 60% of its original value.

### 2.2.2 New Zealand acceptable solutions

The New Zealand Building Code is one of the building codes that provide guidelines regarding the use of double-skin glass façades. In the C/AS5 (The Ministry of Business, Innovation & Employment, 2014) document there are acceptable solutions regarding double-skin glass façades, they are located in paragraphs 5.7.14, 4.15.3-4.15.5. The C/AS# numbering denotes which type of building the document focuses on.

Paragraph 4.15.3 which regulates cavity barriers in walls and floors states that those cavities has to be fire stopped or have cavity barriers. It also refers to paragraph 5.7.14 for details regarding double-skin glass façades. Directly quoted from C/AS5 paragraph 5.7.14: “Where there is a gap between an external wall and a fire separation which together enclose a firecell, the space between the fire separation and the external wall shall be no greater than 50 mm and shall be fire stopped.” (The Ministry of Business, Innovation & Employment, 2014). Figure 3 depicts an example of the use of fire stopping to prevent fire spread between floors.

A fire stop is “a material or method of construction used to restrict the spread of fire within or trough fire separations, and having a fire resistance rating no less than that of the fire separation”. A cavity barrier is “a construction provided to close openings within a concealed space against the passage of fire, or to restrict the spread of fire within such spaces”.

The other acceptable solution documents present exactly the same solution for double-skin façades as C/AS5; these are C/AS2, C/AS3, C/AS4 and C/AS6.
2.2.3 Hong Kong - Code of Practice for Fire Safety in Buildings 2011

The Hong Kong building code is another building code that provides guidelines regarding double-skin glass façades. It supports the same strategy for preventing fire spread as the one from New Zealand; sealing the floors off from each other.

Clause C10.2 states that any void formed by a double-skin façade should be sealed to prevent smoke and fire spread between floors, the barrier should have a fire rating equal to that of the floor. (Hong Kong Buildings Department, 2011). In clause E12.1 the code also refers to the standards that external façades should be in compliance with, the standards are BS EN 1364-3:2006 and BS EN 1364-4:2007. To prevent against external fire spread clause C11.1 recommends the use of vertical or horizontal projections (aprons) from the wall between stories. As a commentary to the clause it is noted that the projections may not prevent fire spread and instead recommends sprinkler as a more efficient system to limit fire spread (Hong Kong Buildings Department, 2011). In Figure 4 the use of horizontal and vertical projections as a protection against fire spread is illustrated.
Figure 4. Horizontal and vertical projections from the Hong Kong building code (Hong Kong Buildings Department, 2011).

(F) FRR of intervening floor

Spandrel having FRR ≥ that of (F)

a ≥ 900 mm
b ≥ 500 mm

(E) External wall (e.g. curtain wall) with no FRR or FRR < that of (F)
3. Theory
This chapter contains all the relevant theory for the thesis.

3.1 Materials
In this chapter the various material properties relevant to the thesis is presented in subchapters.

3.1.1 Glass
Glass is an amorphous material; this means that it doesn’t have a specific melting point and instead changes from a brittle to a plastic state, this occurs approximately in the interval between 520°C and 550°C (Burström, 2007). The most important components of glass are glass formers, fluxing agents and stabilizers, the most common type of glass formers are silica and boron oxide. Fluxing agents are used in glass to lower the melting point of silica. Since glass is a composite material its material properties will vary between manufacturers and the intended purpose of the glass, the material properties will be different if its fire proof glass or regular float glass.

A type of glass used in an existing façade in Sweden is Pilkington Optiwhite. This glass is a float glass and therefore it is assumed that using the material properties of float glass during this thesis is a realistic choice. The project reference is attached in appendix A. In a data sheet Pilkington refers to SS-EN 572 for the material properties of float glass (Pilkington, 2012); these are the material properties mainly used during this thesis and are presented in Table 4.

| Table 4. Material properties according to SS-EN 572 (Pilkington, 2012) . |
|---------------------------|-----------------|
| Density                  | 2 500 kg/m$^3$  |
| Modulus of elasticity    | 70 000 MPa      |
| Coefficient of linear thermal expansion | 9·10$^{-6}$/K |
| Thermal conductivity     | 1.0 W/(m·K)     |
Material data was also obtained from the book Byggmaterial (Burström, 2007); this data is presented in Table 5.

Table 5. Material properties of glass (Burström, 2007).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of linear thermal expansion</td>
<td>$9 \times 10^{-6}$/K</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>720 J/(kg·K)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.0 W/(m·K)</td>
</tr>
<tr>
<td>Density</td>
<td>2500 kg/m³</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>880-930 MPa</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>30-90 MPa</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>30-100 MPa</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>70 000-75 000 MPa</td>
</tr>
</tbody>
</table>

To allow radiation to penetrate through a material in FDS an absorption coefficient has to be defined, without this the solid would be assumed to be completely opaque. A previous study implementing SDOM (Spectral radiation heat transfer model based on the Discrete Ordinates Method) into FDS 5.0 used absorption coefficients ranging from 0.1 to 100 m⁻¹ (Dembele, Rosario, Wen, Paul, & Stuart, 2008). The coefficient determines the amount of heat that is absorbed per unit length. Details regarding the mathematical model used by FDS can be found in the FDS technical reference guide, mathematical model. The value used during the thesis was 20 m⁻¹. The default value in FDS is 50 000 m⁻¹, which is realistic for opaque materials.

3.1.2 Steel
Steel is a composite material which consists mainly of iron, other possible components are coal, silicon, chrome and manganese (Burström, 2007) (there are other materials that are also used but not included). It is a common material in constructions and a few of the uses are as beams, pillars and concrete reinforcement.

The material properties used for steel are based on SS-EN 1993-1-1 (European Committee for Standardization, 2008) and SS-EN 1993-1-2 (European Committee for Standardization, 2010).


<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7850 kg/m³</td>
</tr>
<tr>
<td>Coefficient of linear thermal expansion</td>
<td>$12 \times 10^{-6}$/K</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Temperature dependent values for the modulus of elasticity for steel are presented in Table 7.

Table 7. Temperature dependent values for the modulus of elasticity for steel from SS-EN 1993-1-2 (European Committee for Standardization, 2010).

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Modulus of elasticity [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>210 000</td>
</tr>
<tr>
<td>100</td>
<td>210 000</td>
</tr>
<tr>
<td>200</td>
<td>189 000</td>
</tr>
<tr>
<td>300</td>
<td>168 000</td>
</tr>
<tr>
<td>400</td>
<td>147 000</td>
</tr>
<tr>
<td>500</td>
<td>126 000</td>
</tr>
<tr>
<td>600</td>
<td>65 100</td>
</tr>
<tr>
<td>700</td>
<td>27 300</td>
</tr>
<tr>
<td>800</td>
<td>18 900</td>
</tr>
<tr>
<td>900</td>
<td>14 175</td>
</tr>
<tr>
<td>1000</td>
<td>9 450</td>
</tr>
<tr>
<td>1100</td>
<td>4 725</td>
</tr>
<tr>
<td>1200</td>
<td>0</td>
</tr>
</tbody>
</table>

The specific heat of carbon steel (steel grades according to EN 1993-1-1 except stainless steels) is calculated according to the equations presented below, these are from SS-EN 1993-1-2 (European Committee for Standardization, 2010). The specific heat is dependent on the temperature; the temperature is denoted by $\theta_a$.

Range: $20^\circ\text{C} \leq \theta_a < 600^\circ\text{C}$

$$c_a = 425 + 7.73 \cdot 10^{-1} \theta_a - 1.69 \cdot 10^{-3} \theta_a^2 + 2.22 \cdot 10^{-6} \theta_a^3 [\text{J/kgK}]$$

Range: $600^\circ\text{C} \leq \theta_a < 735^\circ\text{C}$

$$c_a = 666 + \frac{13002}{738-\theta_a} [\text{J/kgK}]$$

Range: $735^\circ\text{C} \leq \theta_a < 900^\circ\text{C}$

$$c_a = 545 + \frac{17820}{\theta_a-731} [\text{J/kgK}]$$

Range: $900^\circ\text{C} \leq \theta_a < 1200^\circ\text{C}$

$$c_a = 650 [\text{J/kgK}]$$
The thermal conductivity of steel is calculated using the following equations from SS-EN 1993-1-2 (European Committe for Standardization, 2010).

Range: $20^\circ \leq \theta_a < 800^\circ C$

$$\lambda_a = 54 - 3.33 \cdot 10^{-2} \theta_a$$ [W/mK]

Range: $800^\circ C \leq \theta_a \leq 1200^\circ C$

$$\lambda_a = 27.3$$ [W/mK]

The stress-strain relationship in SS-EN 1993-1-2 was used during the Abaqus analysis, this relationship is presented in Figure 5 (European Committe for Standardization, 2010) and the specific data used in Abaqus is located in appendix B. The stress-strain data is valid for steel quality S235.

![Stress-strain relationship for carbon steel at elevated temperature according to SS-EN 1993-1-2](image-url)

**Figure 5.** Stress-strain relationship for carbon steel at elevated temperature according to SS-EN 1993-1-2 (European Commitee for Standardization, 2010).
The reduction factors for the yield strength of steel were obtained from SS-EN 1993-1-2; these values are presented in Table 8.

Table 8. Reduction factors for effective yield strength at elevated temperatures.

<table>
<thead>
<tr>
<th>Steel temperature</th>
<th>20</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction factor for effective yield strength</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.78</td>
<td>0.47</td>
<td>0.23</td>
<td>0.11</td>
<td>0.06</td>
<td>0.04</td>
<td>0.02</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

3.1.3 Aluminium

Aluminium is often used as an alternative to steel due to it having greater corrosive resistance and is relatively lightweight compared to steel (Burström, 2007); the density of aluminium is roughly a third of the density of steel.

The material properties used for aluminium are based on SS-EN 1999-1-1 (European Committe for Standardization, 2009) and SS-EN 1999-1-2 (European Committe for Standardization, 2009), the data used is presented in Table 9, Table 10 and calculated using the equations presented in this chapter.

Table 9. Non temperature-dependent material properties of aluminum according to SS-EN 1999-1-2.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2,700 kg/m³</td>
</tr>
<tr>
<td>Coefficient of linear thermal expansion</td>
<td>$23 \times 10^{-6}$/K</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Temperature dependent data for the modulus of elasticity for aluminium is presented in Table 10.

Table 10. Temperature dependent values for the modulus of elasticity of aluminium according to SS-EN 1999-1-2.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Modulus of elasticity [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>70 000</td>
</tr>
<tr>
<td>50</td>
<td>69 300</td>
</tr>
<tr>
<td>100</td>
<td>67 900</td>
</tr>
<tr>
<td>150</td>
<td>65 100</td>
</tr>
<tr>
<td>200</td>
<td>60 200</td>
</tr>
<tr>
<td>250</td>
<td>54 600</td>
</tr>
<tr>
<td>300</td>
<td>47 600</td>
</tr>
<tr>
<td>350</td>
<td>37 800</td>
</tr>
<tr>
<td>400</td>
<td>28 000</td>
</tr>
<tr>
<td>550</td>
<td>0</td>
</tr>
</tbody>
</table>

The specific heat is calculated according to the following equation which is valid in the range 0°C ≤ θ_{al} ≤ 500°C.

\[ c_{al} = 0.41 θ_{al} + 903 \]  

[J/kg°C]

The thermal conductivity is determined through the following equations which are valid in the range 0°C ≤ θ_{al} ≤ 500°C. For the 3xxx and 6xxx series:

\[ λ_{al} = 0.07 \cdot θ_{al} + 190 \]  

[W/m°C]

For the 5xxx and 7xxx series:

\[ λ_{al} = 0.1 \cdot θ_{al} + 140 \]  

[W/m°C]

The yield strength reduction factors of aluminium is assumed to correspond to the lower limits of the 0.2% proof strength ratios from SS-EN 1999-1-2, these values are presented in Table 11.

Table 11. Lower limits of the 0.2% proof strength ratios for aluminium alloys at elevated temperatures (European Committe for Standardization, 2009). This is directly from SS-EN 1999-1-2.

<table>
<thead>
<tr>
<th>Aluminium alloy temperature [°C]</th>
<th>Lower limit values</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.00</td>
</tr>
<tr>
<td>100</td>
<td>0.90</td>
</tr>
<tr>
<td>150</td>
<td>0.75</td>
</tr>
<tr>
<td>200</td>
<td>0.50</td>
</tr>
<tr>
<td>250</td>
<td>0.23</td>
</tr>
<tr>
<td>300</td>
<td>0.11</td>
</tr>
<tr>
<td>350</td>
<td>0.06</td>
</tr>
<tr>
<td>550</td>
<td>0</td>
</tr>
</tbody>
</table>
4. Method
The method used in this thesis relies upon a literature study of the subject and a case study of a building with a double skin glass façade. The software used in the thesis are also presented.

To determine what temperatures the double skin façade might be exposed to during a fire scenario CFD simulations were performed using the software Fire Dynamics Simulator (FDS). To a large extent the FDS models were created using the software Pyrosim which is a graphical user interface for FDS. The FDS models are based on the guidelines provided by Boverket (Boverket, 2013).

To analyze the stresses in a window pane caused by elevated temperatures the FEM software Abaqus was used. The modeling is lacking when it comes to detail due to insufficient information regarding the design of the façade being available during the thesis.

4.1 Software
In this chapter the software used during this thesis is presented.

4.1.1 Fire Dynamics Simulator (FDS)
FDS is a Computational Fluid Dynamics (CFD) program originally developed by NIST (National Institute of Standards and Technology) and is used to simulate smoke and heat transport from fires (McGrattan, McDermott, Weinschenk, Overholt, Hostikka, & Floyd, 2014). CFD is used to simulate the interactions between fluids and gases with surfaces; this is accomplished by numerical calculations. FDS solves Navier-Stokes equations numerically in the simulations and turbulence is managed using large-eddy simulations (LES). Detailed information regarding the mathematical model FDS uses can be found in the FDS technical reference guide (McGrattan, McDermott, Weinschenk, Overholt, Hostikka, & Floyd, 2013). The program has been used in this thesis to simulate a room fire and predict the temperature development at the double-skin façade.

During this thesis FDS 6.0.1 was used. The simulations were performed on a server which is owned and maintained by Luleå University of Technology.

4.2.2 Smokeview
Smokeview is developed by NIST and is used to visualize results from FDS.

During this thesis Smokeview 6.1.11 was used.

4.2.3 Pyrosim
Pyrosim is a graphical user interface (GUI) for FDS which is developed by Thunderhead Engineering Consultants Inc. Pyrosim has been used during this thesis as a pre-processor for FDS.

The trial version used during this thesis was 2014.2.0807.
4.2.4 Abaqus CAE
Abaqus CAE (Complete Abaqus Enviroment) is a Finite Element Method (FEM) program developed by Dassault Systemes. In Abaqus CAE it’s possible to create, edit, monitor, diagnose, and visualize advanced Abaqus analyses (Dassault Systemes). The program has been used to model and analyze a glass screen and the fixing points. FEM divides a complex model into smaller parts that are interconnected; the differential equations for these parts and interactions are then solved numerically.

The Abaqus version used during the thesis was 6.13.2.

4.2.5 Matlab
Matlab is a high-level programming language and interactive environment for numerical computation, visualization and programming (MathWorks). Matlab was used for the majority of the post-processing of the output data from FDS and Abaqus.

The Matlab version used during this thesis was R2013a 8.1.0.604.

4.2 Case study
The building Skeppshandeln 1 is an eight story building (this includes two levels located underground); it is located in Hammarby Sjöstad, Stockholm, Sweden. The entrance is located on floor three; there is no fourth floor in the floor layout and fire documentation. Several different types of occupations (Swe: verksamhetsklasser) are present in this building; these are hotel, garage, office spaces and a grocery store. The double-skin façade is facing Hammarby Allé; this corresponds to the south-east façade in the floor layout, the façade is visible in Figure 6. The double-skin façade spans floor five to eight using the same numbering of floors that the fire documentation and floor layout have.

Figure 6. Picture of the double-skin façade from Google maps.
To reduce the number of fire scenarios only compartments adjacent to the double-skin façade were considered, other compartments are assumed to be irrelevant for the performance of the double-skin façade during a fire. Compartments located underground and at ground level are also not considered since the double-skin façade only spans floor five to eight and such fires are deemed not to be worst case scenarios for the performance of the double-skin façade in a fire situation.

The majority of the spaces on floors five to eight consists of hotel areas and parts of floors seven to eight houses both hotel and office areas, floor nine consists of only offices. BBRAD 3 prescribes a faster growth rate for hotel than office compartments (see Table 2); therefore the worst case scenario is assumed to be if a fire develops inside one of the hotel compartments adjacent to the façade. These compartments range in size from 22.5 m$^2$ and 36 m$^2$. These two sizes of hotel compartments can be seen in Figure 7 and Figure 8. There is also a fitness room that is a part of the hotel and is adjacent to the façade; the fitness room is presented in Figure 9. This compartment does not have a separate classification in the fire documentation. It also has a relatively small size (43.5 m$^2$) and is therefore assumed to not be classified as a community center, according to BBR 215:21 compartments designed for a larger number of persons are to be classified as community centers.

![Figure 7. Hotel compartment with an area of 22.5 m$^2$. This is a snapshot from the floor layout, the complete layout can be found in appendix C.1.](image)
Figure 8. Hotel compartment with an area of 36 m². This is a snapshot from the floor layout, the complete layout can be found in appendix C.2.

Figure 9. Fitness room located in the building with an area of 43.5. This is a snapshot from the floor layout, the complete layout can be found in appendix C.3.
The fire cell separations are visible in figures 11 to 13 and the fire cell separation markers can be seen in Figure 10. E denotes the integrity of the fire cell separation and I denotes the insulating capabilities, the numbering is the time requirement. This means that each hotel compartment wall is required to maintain its integrity and insulating capabilities for 60 minutes and thus prevent fire spread to other compartments during this time. The requirements on the floor structure are that it must maintain its load bearing capacity for 60 minutes (R60); this requirement is made in the fire documentation. Therefore the fire is assumed to be limited to one compartment for at least 60 minutes.

---

Brandcellsgräns El60, Se även brandklass för specifik bygdel enligt littera.

Brandcellsgräns El30, Se även brandklass för specifik bygdel enligt littera.

Brandcellsgräns E30, Se även brandklass för specifik bygdel enligt littera.

---

Figure 10. Fire cell separation markers used in the floor layouts. This is a snapshot from appendix C.4.

In this specific building Hifab AB has defined fire safety requirements on the façade in the fire documentation. The lower part of the inner glass must fulfill the classification requirements of E 30 and the upper part must consist of tempered glass. The external window shall consist of unclassified glass. This is illustrated in Figure 11. The tempered glass shall have been subjected to a Heat Soak Test (HST) where the quality has been evaluated at 290°C.
Figure 11. Requirements on the façade made by Hifab AB in the fire documentation. The upper part (green) of the inner glass must consist of tempered glass; the lower part (blue) must fulfill the requirements of E30. The external window (purple) shall consist of unclassified glass.

### 4.3 FDS modeling

The FDS model is an approximation of the room seen in Figure 7; certain simplifications were made so that it could be modeled in FDS. Here details regarding the model are presented; the complete FDS file can be found in appendix D. The FDS model was to a large extent created using Pyrosim, a 3D-view of the model in Smokeview can be seen in Figure 12.

Figure 12. Figure depicting the 3D FDS model in Smokeview, details such as openings and holes are included. This compartment is 22 m².
4.3.1 Geometry

The hotel compartment is represented as a square room of approximately 22 m$^2$ excluding the walls, this is slightly larger than the real compartment which is 20.5$^2$ (this excludes the internal bathroom walls). Outside of the compartment a hallway is located, 2.3x5.5 m$^2$. The burner has a height of 0.5 m and is located 0.75m from the façade wall, the walls enclosing the hotel compartment and the corridor has a thickness of 0.2 m and the wall separating the bathroom has a thickness of 0.1 m. Details regarding the dimensions of the compartment can be found in Figure 13.

Information regarding the ceiling height was not included in the documentation that was available, therefore it is assumed to comply with BBR 21, in section 1:6 of BBR 21 it is apparent that the compartment is classified as a “compartment to stay in longer than temporarily”. The section that regulates ceiling height in BBR 21 is 3:3 and due to the compartment type section 3:311 specifies the details. According to 3:311 the ceiling height must be at least 2.4 m, therefore it’s assumed that the ceiling height is 2.4 m (Boverket, 2014). Limited areas of a room may have a ceiling height of less than 2.4 m but it’s assumed that this is not the case.
Due to severe issues with the oxygen levels in the compartment certain modifications to the walls were required to ensure that combustion could occur. The walls were modified so that there was a gap of 0.1 m at both the floor and roof. In the mesh sensitivity analysis using a mesh of 0.2m x 0.2m x 0.2m this gap was adjusted to 0.2m, this in order to ensure that the geometry is in compliance with the mesh. Without this adjustment the gap might be ignored in the simulation and in turn limit the oxygen supply.

4.3.2 Fire scenario
When choosing a fire scenario there is a need to determine whether the fire will be ventilation or fuel controlled, this is due to FDS having issues with handling ventilation controlled fires. In the report “Risks in using CFD-codes for analytical fire-based design in buildings with a focus on FDS:s handling of under-ventilated fires” (Björklund, 2009) FDS:s capabilities of handling under-ventilated fires is analyzed and one of the conclusions is that simulating an under-ventilated fire in FDS may result in temperature differences of up to 10-50% (both upwards and downwards) compared to reality. Therefore it’s of significant importance to ensure that the enclosure is not ventilation controlled to obtain conservative values.

Using the design fire suggested by BBRAD 3 which is a prescribed fire load density makes it difficult to determine whether the fire is ventilation or fuel controlled; there are no equations readily available that can be used to estimate the oxygen consumption while using fire load density. Due to this the approach of using a burner surface with a ramped HRR is also included. BBRAD 3 uses this approach to assess evacuation (Table 2), although this is not the recommended approach in BBRAD 3 it’s supported by the report “Selecting design fires” (Staffansson, 2010). The values for peak HRR for hotel compartments in BBRAD 3 (Table 2) is the same that is recommended for small hotel compartments in “Selecting design fires”, therefore it’s assumed that the approach of using peak HRR as design fire is valid.

4.3.2.1 Peak heat release rate
In this chapter the approach of peak HRR is detailed.

To estimate the peak HRR that the hotel compartment can sustain with its opening dimensions equation 2 was used (Staffansson, 2010). In Figure 7 where the hotel compartment is depicted information regarding the width of the door is also available (0.91m). In the fire documentation it is stated that doors leading to an evacuation route must have a height of minimum 2 m, this is used as the height of the door.

\[ \dot{Q}_v = 1500A_o \sqrt{H_o} \]  

(2)
Where

\[
\dot{Q}_v \quad \text{maximum heat release rate} \quad [\text{kW}]
\]

\[
A_o \quad \text{area of opening} \quad [\text{m}^2]
\]

\[
H_o \quad \text{height of opening} \quad [\text{m}]
\]

This results in a peak HRR that the compartment can support of approximately 3.9 MW. According to “Selecting design fires” (Staffansson, 2010) the peak HRR that the compartment can sustain based on oxygen supply should be compared to the peak HRR based on occupancy. The lower of these two values should be chosen as the peak HRR since this procedure will determine whether it’s the oxygen or fuel supply that is the limiting factor. The result from this was that the oxygen was the limiting factor in these simulations. Despite this the peak HRR based on oxygen supply was not chosen as the limiting factor since as mentioned in chapter 4.3.1 there were issues with the oxygen supply to the compartment and to solve this additional openings were required to be added, this causes the oxygen supply to exceed the expected consumption.

The growth rate was assumed to be equal to 0.047 kW/s², Table 2. The fire is assumed to be of the type t-squared, FDS requires a ramp up time which was calculated using the following equation (Karlsson & Quintiere, 2000):

\[
\dot{Q} = \alpha \cdot t^2
\]

The resulting ramp up time for a peak HRR of 5 MW is 327 seconds which was used for the burner in the FDS model.

The organization Föreningen för brandteknisk ingenjörsvetenskap, BIV publishes a document that contains advice on how to use FDS in a way that complies with BBRAD (Back, et al., 2013). The document contains advice regarding the size of the fire source in FDS; the recommended HRRPUA (Heat Release Rate Per Unit Area) for a hotel/office fire is 0.8 MW/m² which results in a fire area of 6.25 m² (2.5 x 2.5 m²) to achieve the desired peak HRR of 5 MW. This is therefore used as fire source in the FDS input file.
BIV also provide advice regarding the growth rate, the recommended approach is to use the function SPREAD_RATE to imitate a radially spreading fire (Back, et al., 2013). To calculate the spread rate the following equation was used:

\[
SPREAD_RATE = \sqrt{\frac{\alpha}{\pi \cdot HRRPUA}}
\]

Where

- \(SPREAD_RATE\) Rate of fire spread [m/s]
- \(\alpha\) Growth rate [kW/s\(^2\)]
- \(HRRPUA\) Heat release rate per unit area [kW/m\(^2\)]

With a growth rate of 0.047 kW/s\(^2\) and HRRPUA equal to 0.8 MW/m\(^2\) the spread rate is approximately 0.0043 m/s.

The fuel was specified according to the advice provided by (Back, et al., 2013) using the code:

&REAC ID='BBRAD_20',
  FYI='BBRAD1 20MJ/kg',
  C=4.56,
  H=6.56,
  O=2.34,
  N=0.4,
  HEAT_OF_COMBUSTION=2.0E4,
  CO_YIELD=0.1,
  SOOT_YIELD=0.1/

4.2.5.2 Fire load density

To analyze the fire cell separating capabilities of construction parts BBRAD 3 advices that the fire scenario should be based on fire load density, in this section details regarding this is presented.

In BBRAD 3 Boverket (Boverket, 2013) clearly states that the fire load density should be determined using BBRBE and that to account for an automatic sprinkler system the fire load density can be reduced to 60% of its original value.
According to BBRBE 1 the fire load density can either be determined using tabulated data or calculated (performance based design). The tabulated value for the fire load density of a hotel (occupational class 4) is 800 MJ/m$^2$ (Boverket, 2013). Using the alternative approach the permanent fire load density is 200 MJ/m$^2$ and the variable fire load density 400 MJ/m$^2$, these values are from BBRBE 1. This yields a fire load density of 600 MJ/m$^2$ for a hotel room using the procedure prescribed in BBRBE 1. The fire load densities are per floor area (Boverket, 2013). In the FDS simulations 800 MJ/m$^2$ is used as design value to represent a fire without an automatic sprinkler system, to simulate the presence of an automatic sprinkler system this is reduced to 480 MJ/m$^2$. This yields a total fire load of 16 400 MJ and 9840 MJ, respectively.

The fire load is represented in FDS using the fuel specified in Table 12. This fuel is based on the properties of wood and was used in a previous master thesis to represent flammable groceries (Björkstad, 2012). Due to the lack of guidelines regarding material properties of the fuel it is assumed to fulfill the purpose despite not being designed with regards to a hotel fire.

| Emissivity | 0.9 | [-]        |
| Density    | 120 [kg/m$^3$] |
| Heat of combustion | 20 [MJ/kg] |
| Conductivity | 0.2 [W/mK] |
| Thickness  | 0.05 [m] |
| HRRPUA     | 120 [kW/m$^2$] |
| Ignition temperature | 300 [°C] |
| Specific heat | 1.3 [kJ/kgK] |

The fuel is represented in FDS by boxes with a size of 1.2m x 1.2m x 0.4m.

**4.3.3 Sprinkler system**

To simulate the presence of a sprinkler system inside the building the fire load density is reduced to 60% of the original value. For the specific value read the chapter about fire load density.

**4.3.4 Walls**

Due to a lack of specific information regarding the walls they are represented as adiabatic surfaces, this to ensure that the results are conservative. This procedure is supported in BIV:s tillämpningsdokument 2/2013 – Utgåva 1 CFD-beräkningar med FDS (Back, et al., 2013).
4.3.5 Façade
To represent a double-skin façade in FDS three alternative solutions were tried. These three alternatives are: using Lagrangian particles, a single obstruction consisting of several layers and several obstructions with one layer each. These are described more in-depth below.

4.3.5.1 Lagrange particles
To represent the glass used in the façade Lagrangian particles were investigated as a possible solution; a significant amount of time was spent on trying to achieve this. In the FDS user guide it’s stated that Lagrangian particles can be used to represent subgrid-scale objects (McGrattan, McDermott, Weinschenk, Overholt, Hostikka, & Floyd, 2014). In the FDS technical reference guide it’s suggested that Lagrangian particles arranged in a plane can be used to model a window screen (McGrattan, McDermott, Weinschenk, Overholt, Hostikka, & Floyd, 2013). Specifically chapter 8.6 and 8.6.1 in the technical reference guide can lead one to believe that Lagrangian particles can be used to model a window.

This solution is however not possible due to Lagrangian particles not having a volume in the Eulerian space which makes them incapable of preventing flow through them. This would result in a façade which allows a flow through it and therefore using Lagrangian particles to model a façade in FDS not a viable solution.

No code regarding the attempts of using Lagrangian particles to represent a face is presented in this thesis since it’s not possible regardless of the code.

4.3.5.2 Single obstruction façade
The second approach used to model a double-skin façade was to prescribe the obstruction at the façade location with a surface that consisted of three layers. Two of these layers were prescribed with the material properties of glass and a third layer was prescribed with the properties of air. The code used to achieve this is presented below. Both the thickness of the air gap and windows panes can be adjusted by changing the thickness parameter. An absorption coefficient was defined so that radiation could be allowed to penetrate the material.

```
&SURF ID='window',
  MATL_ID='Glas', 'Luft', 'Glas',
  COLOR='GREEN',
  BACKING='EXPOSED',
  THICKNESS=0.005,0.015,0.005/
```
4.3.5.3 Multiple obstruction façade

The third approach used is utilizing two obstructions with an air gap between them, the obstacles has the material and surface properties of glass prescribed to them. Two obstructions with an thickness equal to one grid cell were placed at the location of the façade, between these two there is the air gap which also has a size equal to the grid cell size. This approach requires a separate mesh do be specified for the façade in order to create an air gap between the windows. The double-skin façade is visualized in Figure 14.

![Figure 14. Visualization of the double-skin façade in Smokeview.](image)

Modeling the complete enclosure with this cell size would result in a massive increase of the computational time required for the simulation, therefore two meshes are used. Note that the region of mesh 2 in Figure 14 is unnecessarily large and it’s possible to decrease it in order to decrease the time required to complete the simulations. An absorption coefficient was defined so that radiation could be allowed to penetrate the material. The specific code used to achieve this is specified below.
&MESH ID='MESH2', IJK=70,24,48, XB=0.0,3.5,-0.2,1.0,0.0,2.4/
&MESH ID='MESH1', IJK=55,100,28, XB=-1.0,4.5,1.0,11.0,-0.2,2.6/

&SURF ID='window',
   MATL_ID='Glas',
   COLOR='GREEN',
   BACKING='EXPOSED',
   THICKNESS=0.005/

&MATL ID='Glas',
   EMISSIVITY=0.92,
   SPECIFIC_HEAT=0.72,
   CONDUCTIVITY=1.,
   DENSITY=2500.,
   ABSORPTION_COEFFICIENT=20./

&OBST XB=0.0,3.5,0.0,0.05,0.0,2.4,
SURF_ID6='ADIABATIC','ADIABATIC','ADIABATIC','window','ADIABATIC','ADIABATIC'/ Inner_window
&OBST XB=0.0,3.5,-0.1,-0.05,0.0,2.4,
SURF_ID6='ADIABATIC','ADIABATIC','ADIABATIC','window','ADIABATIC','ADIABATIC'/ Outer_window

The thickness of the window is unrelated to the thickness of the obstruction; this is instead specified on the surf line. When changing the thickness of the air gap the complete mesh in the vicinity of the façade required adjustment.

4.3.6 Output
To estimate the temperature on the façade devices were placed on the windows, the devices used were QUANTITY='ADIABATIC SURFACE TEMPERATURE’, as a complement to these devices statistic output devices are also located at the façade which measures the mean temperature.

The placement and numbering of the QUANTITY='ADIABATIC SURFACE TEMPERATURE’ devices can be seen in Figure 15; the exact location of each device is included in the complete FDS file, appendix D. An example of the code used for one device is:

&DEVC ID='INNER_THCP-01', QUANTITY='ADIABATIC SURFACE TEMPERATURE',
XYZ=0.25,0.05,0.55, IOR=2/
Figure 15. Here the numbering and placement of each temperature device is shown, the view in this figure is from the façade into the compartment.

The mean temperatures in proximity of the façade was measured using devices with QUANTITY='TEMPERATURE' and STATISTICS='MEAN'. The placement of these devices in relation to each other is shown below, specific details regarding placement is located in the FDS input file.

VH  MH  HH
VM  MM  HM
VL  ML  HL

To be able to quickly review the temperature distribution in Smokeview several slices that measures temperature were placed in the compartment, these are shown in Figure 16; more detailed information regarding their placement is located in the FDS input file.
4.3.7 Sensitivity analysis
A sensitivity analysis was conducted to identify parameters that may have a significant impact on the temperature close to the façade; the parameters that the sensitivity analysis was conducted on are presented in Table 13.

Table 13. Table presenting the variables included in the FDS sensitivity analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit (Mesh size or Radiation angles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh size</td>
<td>Smaller mesh 0.05m x 0.05m x 0.05m</td>
</tr>
<tr>
<td></td>
<td>Larger mesh 0.2m x 0.2m x 0.2m</td>
</tr>
<tr>
<td>Façade mesh size</td>
<td>Smaller mesh 0.025m x 0.025m x 0.025m</td>
</tr>
<tr>
<td>Radiation angles</td>
<td>1000</td>
</tr>
<tr>
<td>Attempt at limiting the maximum velocity error</td>
<td>&amp;PRES VELOCITY_TOLERANCE=0.001, MAX_PRESSURE_ITERATIONS=100/</td>
</tr>
</tbody>
</table>

The grid sensitivity analysis of the façade mesh size only covers a smaller mesh size. This is due to that an increased mesh size would also require altering the size of the air gap and thus require modifying several parameters.

4.4 Parametric temperature-time curve
In section 4.1.3.1 in BBRAD 3 the use of a parametric temperature-time curve is suggested as a method to evaluate the fire separating capabilities of a construction element (Boverket, 2013). The procedure that is to be followed when calculating this temperature-time curve is the one in SS-EN 1991-1-2 Annex A. All equations and information presented below are from SS-EN 1991-1-2 Annex A (European Committee for Standardisation, 2009).
\[ \theta_g = 20 + 1325 \left( 1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*} \right) \]

\[ t^* = t \cdot \Gamma \quad \text{[h]} \]

\[ \Gamma = \frac{\left( \frac{d}{h} \right)^2}{\left( \frac{0.04}{1160} \right)^2} \quad \text{[-]} \]

\[ b = \sqrt{\rho c \lambda} \quad \text{[J/m}^2\text{s}^{1/2}\text{K]} \quad (100 \leq b \leq 2200) \]

\[ O = \frac{A_v}{A_t} \quad \text{[m}^{1/2}\text{]} \quad (0.02 \leq O \leq 0.20) \]

Where:

- \( \theta_g \): is the gas temperature in the fire compartment \[^{\circ}\text{C}\]
- \( t \): time \[\text{[h]}\]
- \( \rho \): density of boundary of enclosure \[\text{[kg/m}^3\text{]}\]
- \( c \): specific heat capacity of boundary of enclosure \[\text{[J/kgK]}\]
- \( \lambda \): thermal conductivity of boundary of enclosure \[\text{[W/mK]}\]
- \( A_v \): total area of vertical openings on all walls \[\text{[m}^2\text{]}\]
- \( h_{eq} \): weighted average of window heights on all walls \[\text{[m]}\]
- \( A_t \): total area of enclosure (including openings) \[\text{[m}^2\text{]}\]

Due to lack of information the compartment walls are assumed to consist entirely of gypsum. The input geometry is based on Figure 7 with the door being a 0.91 m x 2 m opening and a ceiling height of 2.4 m. The resulting temperature development for the hotel compartment is shown in Figure 57.

To determine the maximum temperature inside the compartment Annex A in SS-EN 1991-1-2 is used. The procedure is presented below:

\[ t^*_{\text{max}} = t_{\text{max}} \cdot \Gamma \quad \text{[h]} \]

\[ t_{\text{max}} = \max \left( \left( 0.2 \cdot q_{t,d}/O \right) ; t_{\text{lim}} \right) \quad \text{[h]} \]

\[ q_{t,d} = q_{f,d} \cdot \frac{A_f}{A_t} \quad \text{[MJ/m}^2\text{]} \]
Where:

- $A_f$  
  floor area of enclosure  
  \[ \text{[m}^2\text{]} \]

- $A_t$  
  total surface area of enclosure  
  \[ \text{[m}^2\text{]} \]

- $q_{f,d}$  
  design value of the fire load density related to the floor area  
  \[ \text{[MJ/m}^2\text{]} \]

$t_{\text{lim}}$ is equal to 15 minutes in the case of fast fire growth rate.

### 4.5 Abaqus modeling
Details regarding the Abaqus models are presented in this chapter.

#### 4.5.1 Materials
Details regarding the material parameters used as input are described in this chapter.

The input data for glass and aluminium consisted of five parameters for each material. These were thermal conductivity, density, modulus of elasticity, specific heat capacity and the thermal expansion coefficient, this data is found in chapter 3.1.1 for glass and in 3.1.3 for aluminium. All the input data for glass were independent of the temperature. The material properties of aluminium were a mix of temperature dependent and independent data, the thermal conductivity, specific heat capacity and modulus of elasticity of aluminium were assigned temperature dependent values.

The number of input parameters for steel was mainly the same as for glass and aluminium except that it also includes a stress-strain relationship. All of these parameters were assigned temperature dependent values except the density and thermal expansion coefficient. The majority of this data is located in chapter 0; the stress-strain relationship is located in appendix B.

The input values were modified to correspond to the units’ millimeters, gram and Newton before being implemented into Abaqus.

#### 4.5.2 Sections and section manager
To prescribe a material to the parts used in Abaqus sections are used, the different sections used are presented in Figure 17 and an example of a section is visible in Figure 18. The “Solid, Homogenous” sections were used for solid parts and the “Shell, Homogenous” sections were used for parts modeled as shells.
Figure 17. The section manager in Abaqus with all the different sections used to assign material properties to the different parts. The name and type is included.

Figure 18. The section used to prescribe the material glass to the part window pane.

4.5.3 Geometry and mesh
In this chapter the geometry and mesh of all the parts created and used in the Abaqus models are described. Each part is assigned a separate subsection.

4.5.3.1 Window pane
The window pane was assumed to have a thickness of 5 mm and the sides to have a length of 2 m. The reasoning for this is based on information available in the document “Grundläggande glasfakta” from Pilkington’s website (Pilkington, 2012); in this document Pilkington lists the recommended dimensions of insulating window panes. From this information a 2m x 2m window pane with a thickness of 5 mm was deemed to be reasonable. This information is available in Figure 19. The window pane was created as a 3D deformable solid.
Figure 19. Figure from the document “Grundläggande glasfakta” that is available on Pilkington’s website (Pilkington, 2012). The figure contains the recommended dimensions for insulating window panes.

A view of the window pane as an Abaqus part is shown in Figure 20; this includes the datum planes used to partition the part. The partitioning of the part varied depending on the fixing points used in the assembly; it was adjusted in order to achieve the desired positioning of the fixing points and establish the interactions between the parts.

Figure 20. A view of the 2m x 2m window pane in Abaqus. The window pane has a thickness of 5mm. The figure includes the datum planes used to partition the part.
This part was meshed using 3D stress with the standard element library and linear geometric order (Element type: C3D8R); this specific tab is visible in Figure 21.

![Element Type](image)

Figure 21. The element type used to mesh the part window pane.

The standard mesh size used to mesh the part was 5 mm; the resulting mesh is visible in Figure 22, the mesh size of this part was varied in the sensitivity analysis.
4.5.3.2 Circular fixing point – radius 30 mm

The reasoning for this fixing point is that in the research paper “Fracture behavior of a four-point fixed glass curtain wall under fire conditions” (Wang, Wang, Shao, Chen, & Su, 2014) circular fixing points are used and is therefore deemed to be realistic. The part was created as a 3D deformable solid.

There was no information available regarding the dimensions of the fixing points and therefore the dimensions used are arbitrary, the used dimensions are a radius of 30 mm and a thickness of 10 mm. In Figure 23 this part along with the mesh is presented, it also includes the datum planes used to partition this part. The part was partitioned to maximize the number of cubic elements which was the desired element shape.

This part was meshed using 3D stress with the standard element library and linear geometric order (Element type: C3D8R); this is similar to the mesh used for the window pane and is presented in Figure 21. The standard mesh size used for this part was 5 mm and this mesh is presented in Figure 23; the mesh size of this part was varied in the sensitivity analysis.
4.5.3.3 Circular fixing point – radius 40 mm
This part has identical properties and meshing with respect to the part described in 4.5.3.2 except that the radius is 40 mm instead of 30 mm.

4.5.3.4 Square fixing point – length 60 mm
The reasoning for this fixing point is to determine how a square fixing point instead of a circular will impact the stress distribution in the window pane. The elements size was the same as for the circular fixing points but the number of elements was not the same. The part was created as a 3D deformable solid.

This part has a side length of 60 mm and a thickness of 10 mm; this along with the mesh is visualized in Figure 24.

This part was meshed using 3D stress with the standard element library and linear geometric order (Element type: C3D8R); this is similar to the mesh used for the window pane. The standard mesh size used for this part was 5 mm.
4.5.3.5 Square fixation point – length 80 mm
This part has identical properties and meshing with respect to the part described in 4.5.3.4 except that the length is 80 mm instead of 60 mm.

4.5.3.6 Framework
The reasoning for this fixing method is to determine how using a frame to fixate the window instead of fixing points will impact the stress distribution in the window pane. The part was created as a 3D deformable shell and meshed using shell with the standard element library and linear geometric order (Element type: S4R, The element type tab for S4R is presented in Figure 25). The element size was 5 mm; the framework with this element size is presented in Figure 26.
4.5.4 Steps

Two different steps were used in the Abaqus simulations, Initial and Temperature; these steps along with the step manager are presented in Figure 27. The temperature step has a length of 1.

Figure 25. Element type tab for S4R.

Figure 26. Framework fixing as a shell with 5 mm S4R elements.
The settings used for the Temperature step was the default ones, the incrementation of the Temperature step is visible below in Figure 28.

4.5.5 Interactions and boundary conditions

The interactions between the fixing points and window screen were created using ties, the surface of the fixing point was set to be the master surface while the surface of the window screen was set as slave surface. In Figure 29 the slave surface is visible as a pink area while the master surface has red contours. It may be noted that the circular fixing point in Figure 29 is tied to a square surface; this is not an issue since the position tolerance will cause nodes outside of the circular zone which is in direct contact with the master surface not to
be tied. Thus the tied nodes used during the simulations will be inside the intended circular zone.

Figure 29. The interaction between the fixing points and the window screen.

The fixing point is in turn coupled to a control point using the constraint tab, the surface of the fixing point is coupled with a reference point; this is presented in Figure 30.

Figure 30. Constraint between control point and the circular fixing point.

The reference points have prescribed boundary conditions in order to limit the displacement and rotations allowed in the simulations, the prescribed boundary conditions are shown in Figure 31. The boundary conditions are established in the Initial step and are kept during the
Temperature step. Displacements in the x-, y- and z-plane are prevented while rotation is allowed.

![Figure 31. Boundary conditions prescribed to the reference points.](image)

### 4.5.6 Predefined fields and amplitudes

To subject the window screen and the fixing points to elevated temperatures predefined fields were used. In the Initial step a predefined field was used to define an initial temperature for the model, this predefined field is visible in Figure 32.
In the Temperature step a second predefined field is established to account for the elevated temperatures. This is true for all the simulations except three where there are several different fields, this will be discussed below. This field is visible in Figure 33, it should be noted that the field does not cover the whole surface and that there are areas in proximity to the circular fixing point that are not subjected to elevated temperatures.

Figure 32. The predefined field used to define the initial temperature.

Figure 33. Predefined field established in the Temperature step to account for the elevated temperature.
The amplitude in Figure 33 was designed so that it would reflect the parametric temperature curve in Figure 57; the amplitude was defined as a table.

There are exceptions to the use of a single predefined field in the Temperature step; information regarding the use of multiple temperature fields is located in chapter 4.5.8.

### 4.5.7 Output

The output requested from Abaqus was information regarding stress, strain and nodal temperatures. The output requests were made for the entire model with a frequency of one every increment.

### 4.5.8 Sensitivity analysis

Several different models were created to examine the impact of the design of the fixing points, materials, temperature distributions and element sizes has had on the simulations. Directly below Table 14 contains the models concerned with fixing points and the specific details regarding these.

**Table 14. Models used for determining the impact of the fixing points.**

<table>
<thead>
<tr>
<th>Name</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>R30-d5050-steel-primary</td>
<td>This is the primary model which all the other models are a variant of. The fixing points were circular with a radius of 30 mm and located 50 mm from the window pane edges. The fixing points were prescribed the material properties of steel. A single temperature field based on the parametric temperature curve was used.</td>
</tr>
<tr>
<td>R30-d5050-aluminium</td>
<td>The fixing points are prescribed the material properties of aluminium instead of steel.</td>
</tr>
<tr>
<td>R30-d40050-steel</td>
<td>The fixing points are located 400 mm from the window edge in y-direction and 50 mm from the window edge in x-direction. This is visualized in Figure 34.</td>
</tr>
<tr>
<td>R30-d400400-steel</td>
<td>The fixing points are located 400 mm from the edges instead of 50 mm. This distance is from the edge of the window pane to the closest edge of the fixing point, Figure 35.</td>
</tr>
<tr>
<td>R30-assymmetric-steel</td>
<td>Two of the fixing points are locate 50 mm from the window edge and two are located 400 mm from the edge, this is shown in Figure 36.</td>
</tr>
<tr>
<td>R40-d3838-steel</td>
<td>Circular fixing points with a radius of 40 mm instead of 30 mm, the center of this fixing point is located at the exact same location as the ones with a radius of 30 mm. The center is located 80 mm from the window edge. To account for the larger fixing points the ties were adjusted, the ties are shown in Figure 37.</td>
</tr>
<tr>
<td>Material</td>
<td>Description</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>B60-d5050-steel</td>
<td>Square fixing points with a length of 60 mm instead of circular ones.</td>
</tr>
<tr>
<td>B80-d4040-steel</td>
<td>Square fixing points with a length of 80 mm instead of circular ones.</td>
</tr>
<tr>
<td>Framework steel</td>
<td>Framework of steel instead of circular fixing points.</td>
</tr>
<tr>
<td>Framework aluminium</td>
<td>Framework of aluminium instead of circular fixing points.</td>
</tr>
</tbody>
</table>

Figure 34. Model R30-d40050-steel with the fixing point distances marked.
Figure 35. Model R30-d400400-steel with the fixing point distances marked.
Figure 36. Model R30-assymmetric-steel with the fixing point locations shown. The upper fixing points distances in x-direction to the window edge are 50 mm while the lower fixing points distances is 400 mm.

Figure 37. Model R40-d3838-steel, in this figure the additional ties created to account for the larger size are visible.

The models used to determine the impact of temperature differences on the model are presented in Table 15.
Table 15. Models designed to determine the impact of using multiple temperature fields.

<table>
<thead>
<tr>
<th>Name</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>R30-d505-temperaturediff10-steel</td>
<td>Two different temperature fields, one has a temperature 10°C lower than the parametric temperature curve. An example of a model with two different temperature fields is shown in Figure 38.</td>
</tr>
<tr>
<td>R30-d505-temperaturediff50-steel</td>
<td>Two different temperature fields, one has a temperature 50°C lower than the parametric temperature curve.</td>
</tr>
</tbody>
</table>

Figure 38. Model with two temperature fields.
In addition to the various fixing points, temperatures and materials used the mesh sensitivity was examined by using different element sizes. The different element sizes used are presented in Table 16.

**Table 16. The various element sizes used to analyze the impact element size has on the simulations.**

<table>
<thead>
<tr>
<th>Part</th>
<th>Element size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window pane</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Circular fixing point, radius 30 mm</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Square fixing point, length 60 mm</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Framework</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

There were also a variant of the R30-d400400-steel model where the window was assigned an element size of 2.5 mm.
5. Results
In this chapter the results obtained during the thesis are presented.

5.1 FDS
The results from the FDS simulations are presented here. To limit the size of this chapter not all the results are shown here. Some results not provided here can be found in appendix E. Several abbreviations are used in the results in order to describe the position of temperature devices, these are shown directly below. This shows the placement of these devices in relation to each other, this view is from the inside of the room with “VH” being the upper left corner of the window.

VH  MH  HH
VM  MM  HM
VL  ML  HL

5.1.1 Dual obstruction facade
In this chapter the results from the dual obstruction facade model is presented. The HRR is in Figure 39, adiabatic surface temperatures of the inner window (INNER_THCP16 to INNER_THCP20) in Figure 40, adiabatic surface temperatures of the external window OUTER_THCP16 to OUTER_THCP20) in Figure 41 and mean temperatures in Figure 42. These results are from a model with a minor error in the geometry and are a part of the sensitivity analysis, the results from the model with corrected geometry is in chapter 5.1.10 Corrected geometry.

![Heat Release Rate - Primary model](image)

Figure 39. HRR of the primary FDS model.
Figure 40. Adiabatic surface temperatures of the devices INNER_THCP16 to INNER_THCP20 for the dual obstruction facade FDS model. These devices are located on the surface at the center of the inner window with 16 being closest to the floor and 20 closest to the roof.

Figure 41. Adiabatic surface temperatures of the devices OUTER_THCP16 to OUTER_THCP20 for the dual obstruction facade FDS model. These devices are located on the surface at the center of the outer window with 16 being closest to the floor and 20 closest to the roof.
5.1.2 Peak heat release rate

The results from the simulation based on a peak HRR of 5 MW instead of fire load density are presented in this chapter. The HRR of the simulation is in Figure 43 and the adiabatic surface temperatures of INNER_THCP16 to INNER_THCP20 in Figure 44.

Figure 42. Mean temperatures in the proximity of the façade for dual obstruction facade FDS model.

Figure 43. HRR of the simulation based on a peak HRR of 5 MW. This can be compared to the use of fire load density as fire scenario in Figure 39.
Figure 44. Adiabatic surface temperatures of the devices INNER_THCP16 to INNER_THCP20 from the simulation based on peak HRR. These devices are located on the surface at the center of the inner window with 16 being closest to the floor and 20 closest to the roof. This can be compared to the use of fire load density as fire scenario in Figure 40.

5.1.3 Sprinkler – fire load density 600 MJ/m²
This chapter contains the results from the simulation with a lowered fire load density to account for an automatic sprinkler system. The HRR is presented in Figure 45 and the adiabatic surface temperatures of INNER_THCP16 to INNER_THCP20 are in Figure 46.

Figure 45. HRR of the model using a fire load density of 600 MJ/m². This can be compared to the resulting HRR while using a higher fire load density in Figure 39.
Figure 46. Adiabatic surface temperatures of the devices INNER_THCP16 to INNER_THCP20, this is results from the sprinkler simulation where the FLD was reduced to 600 MJ/m². These devices are located on the surface at the center of the inner window with 16 being closest to the floor and 20 closest to the roof. This can be compared to the resulting adiabatic surface temperatures from using a higher fire load density in Figure 40.

5.1.4 Single obstruction façade
The results from the simulation using a single obstruction to represent the façade are presented in this chapter. The adiabatic surface temperatures of INNER_THCP16 to INNER_THCP20 are in Figure 47.
Figure 47. Adiabatic surface temperatures of the devices INNER_THCP16 to INNER_THCP20, this is results from the simulation using a single obstruction to model the façade. These devices are located on the surface at the center of the inner window with 16 being closest to the floor and 20 closest to the roof. This can be compared to the results from the model using a dual obstruction façade in Figure 40.

5.1.5 Mesh 1 0.05m x 0.05m x 0.05m
The results from the mesh sensitivity analysis of mesh 1 are partially presented in this chapter, the mesh size was 0.05m x 0.05m x 0.05m. The HRR is in Figure 48 and the adiabatic surface temperatures of INNER_THCP16 to INNER_THCP20 are in Figure 49.
Figure 48. HRR of the simulation with mesh 1 having a mesh size of 0.05m x 0.05m x 0.05m. This HRR can be compared to the one that occurs while mesh 1 has a size of 0.1m x 0.1m x 0.1m in Figure 40.

Figure 49. Adiabatic surface temperatures of the devices INNER_THCP16 to INNER_THCP20, these results are from the simulation with mesh 1 having a mesh size of 0.05m x 0.05m x 0.05m. These devices are located on the surface at the center of the inner window with 16 being closest to the floor and 20 closest to the roof.

5.1.6 Mesh 1 0.2m x 0.2m x 0.2m
The results from the mesh sensitivity analysis of mesh 1 are partially presented in this chapter, the mesh size was 0.2m x 0.2m x 0.2m. The HRR is in Figure 50 and the adiabatic surface temperatures of INNER_THCP16 to INNER_THCP20 are in Figure 51.
Figure 50. HRR of the simulation with mesh 1 having a mesh size of 0.2m x 0.2m x 0.2m. This HRR can be compared to the one that occurs while mesh 1 has a size of 0.1m x 0.1m x 0.1m in Figure 40.

Figure 51. Adiabatic surface temperatures of the devices INNER_THCP16 to INNER_THCP20, these results are from the simulation with mesh 1 having a mesh size of 0.02m x 0.02m x 0.02m. These devices are located on the surface at the center of the inner window with 16 being closer to the floor and 20 closest to the roof. These results can be compared to the results in Figure 40 where mesh 1 instead has the size 0.1m x 0.1m x 0.1m.
5.1.7 Façade – mesh 2 0.025m x 0.025m 0.025m
The results from the mesh sensitivity analysis of mesh 2 are presented in this chapter, the mesh size was 0.025m x 0.025m x 0.025m. The HRR is in Figure 52 and the adiabatic surface temperatures of INNER_THCP16 to INNER_THCP20 are in Figure 53.

Figure 52. HRR of the simulation with mesh 2 having mesh size of 0.025m x 0.205m x 0.025m. This HRR can be compared to the one that occurs while mesh 2 has a size of 0.05m x 0.05m x 0.05m in Figure 40.

Figure 53. Adiabatic surface temperatures of the devices INNER_THCP16 to INNER_THCP20, these results are from the simulation with mesh 2 having a mesh size of 0.025m x 0.025m x 0.025m. These devices are located on the surface at the center of the inner window with 16 being closes to the floor and 20 closest to the roof. These results can be compared to the results in Figure 40 where mesh 2 instead has the size 0.05m x 0.05m x 0.05m.

5.1.8 Radiation angles
The results from the simulation using 1000 radiation angles instead of the default number of 100 are presented in this chapter. The adiabatic surface temperatures of INNER_THCP16 to INNER_THCP20 are in Figure 54.
Figure 54. Adiabatic surface temperatures of the devices INNER_THCP16 to INNER_THCP20, these are results from the simulation where the number of radiation angles was increased to 1000. These devices are located on the surface at the center of the inner window with 16 being closest to the floor and 20 closest to the roof. These results can be compared to the ones in Figure 40 where the number or radiation angles are 100 (the default in FDS). The span of this simulation is only 10 minutes; this is due to stability issues with the server causing simulation to abort.

5.1.9 Maximum velocity error
The results from the simulation where restrictions on the number of pressure iterations and velocity tolerance were implemented are presented in this chapter. The adiabatic surface temperatures of INNER_THCP16 to INNER_THCP20 are in Figure 55.

Figure 55. Adiabatic surface temperatures of the devices INNER_THCP16 to INNER_THCP20, these are results from the simulation with restrictions imposed upon the number of pressure iterations and velocity tolerance. These devices are located on the surface at the center of the inner window with 16 being closest to the floor and 20 closest to the roof. These results can be compared to the ones in Figure 40 where there are no restrictions on the pressure iterations and velocity tolerance.
5.1.10 Corrected geometry
The results in 5.1.1 are from a model with a minor error in the geometry, here the results from the corrected model is presented. The adiabatic surface temperatures of INNER_THCP16 to INNER_THCP20 are in Figure 56.

![adiabatic surface temperatures - inner window](image)

Figure 56. Adiabatic surface temperatures of the devices INNER_THCP16 to INNER_THCP20, these are results from the simulation with adjusted geometry. These devices are located on the surface at the center of the inner window with 16 being closes to the floor and 20 closest to the roof. These results can be compared to the ones in Figure 40 which is from a model with a minor fault in the geometry.
5.2 Parametric temperature-time curve
The resulting temperature-time curve obtained using SS-EN 1991-1-2 Appendix A is presented in Figure 57.

Figure 57. Parametric temperature-time curve calculated according to SS-EN 1991-1-2 Annex A.

The maximum temperature occurs after approximately five hours in the case without sprinkler, with sprinkler this instead occurs after approximately three hours.
5.3 Abaqus
The results from the Abaqus simulations are presented below in different subchapters.

5.3.1 R30-d5050-steel-primary
The results from the R30-d5050-steel-primary simulation are presented below. The stress curve for a node in the center of the glass is in Figure 58 and the stress curve for a node in close proximity to a fixing point is in Figure 59. The stress distribution is in Figure 60.

Figure 58. Stress curve for the R30-d5050-steel-primary simulation. The output is from the center of the window pane and of the type max principal, mises and pressure.

Figure 59. Stress curve for the R30-d5050-steel-primary model. The output is from a node in close proximity to a fixing point and of the type max principal, mises and pressure.
5.3.2 R30-d5050-aluminium

The results from the R30-d5050-aluminium are presented below. The stress curve is in Figure 61 and the stress distribution in Figure 62.

Figure 60. Stress distribution of the R30-d5050-steel-primary model.

Figure 61. Stress curve for the R30-d5050-aluminium model. The output is from the center of the window pane and of the type max principal, mises and pressure.
5.3.3 R30-d40050-steel
In this chapter the result for the R30-d40050-steel model are presented, the stress distribution is in Figure 63.
5.3.4 R30-d400400-steel

In this chapter the results from the R30-d400400-steel simulation is presented. The result when using a window element size of 5 mm is in Figure 64 and when using an element size of 2.5 mm is in Figure 65.

Figure 64. Stress distribution of the R30-d400400-steel model. The window element size was 5 mm.

Figure 65. Stress distribution of the R30-d400400-steel model. The window element size was 2.5 mm.
5.3.5  R30-assymmetric-steel
In this chapter the result from the R30-assymmetric-steel is presented in Figure 66.

Figure 66. Stress distribution of the R30-assymmetric-steel model.

5.3.6  R40-d3838-steel
The results from the R40-d3838-steel simulation is located in this chapter, the stress curve is in Figure 67 and the stress distribution is in Figure 68.

Figure 67. Stress curve for the R30-d3838-steel model. The output is from the center of the window pane and of the type max principal, mises and pressure.
5.3.7 B60-d5050-steel

The stress curve and stress distribution for the B60-d5050-steel simulation is located in this chapter. Figure 69 depicts the stress curve and the stress distribution is shown in Figure 70.

Figure 68. Stress distribution of the R40-d3838-steel model.

Figure 69. Stress curve for the B60-d5050-steel model. The output is from the center of the window pane and of the type max principal, mises and pressure.
5.3.8 B80-d4040-steel

The results from the B80-d4040-steel simulation are provided in this chapter, in Figure 71 the stress curve is in Figure 71 and the stress distribution is in Figure 72.

![Stress curve for the B80-d4040-steel model. The output is from the center of the window pane and of the type max principal, mises and pressure.](image)

Figure 71. Stress curve for the B80-d4040-steel model. The output is from the center of the window pane and of the type max principal, mises and pressure.
5.3.9 Framework steel

The stress curve and stress distribution for the framework with material properties of steel is presented in this chapter. The stress curve is in Figure 73 and stress distribution in Figure 74.

![Figure 72. Stress distribution of the B80-d4040-steel model.](image)

![Figure 73. Stress curve for the framework steel model. The output is from the center of the window pane and of the type max principal, mises and pressure.](image)
5.3.10 Framework aluminium

The results from the simulation using framework fixing points of aluminium are provided in this chapter. The stress curve is in Figure 75 and the stress distribution in Figure 76.

Figure 75. Stress curve for the framework aluminium model. The output is from the center of the window pane and of the type max principal, mises and pressure.
5.3.11 R30-d5050-temepreaturediff10-steel
The resulting stress distribution from introducing a second temperature field with a temperature of 10°C lower is in Figure 77.

5.3.12 R30-d5050-temepaturediff50-steel
The resulting stress distribution from introducing a second temperature field with a temperature of 50°C lower is in Figure 78.
5.3.13 Window pane element size sensitivity analysis

The result of reducing the element size to 2.5 mm is presented in this chapter, the stress curve is in Figure 79 and the stress distribution is shown in Figure 80.
5.3.14 Circular fixing point element size sensitivity analysis

The results from the circular fixing point element size sensitivity analysis are presented in this chapter. The stress curve for element size of 2.5 mm is in Figure 81 and the stress distribution is in Figure 82.

Figure 81. Stress curve for the circular fixing point 2.5 mm element size sensitivity analysis. The output is from the center of the window pane and of the type max principal, mises and pressure.
Figure 82. Stress distribution for the 2.5 mm circular fixing point element size sensitivity analysis.

The stress curve from using an element size of 10 mm for the circular fixing points is in Figure 83 and the stress distribution is in Figure 84.

Figure 83. Stress curve for the 10 mm circular fixing point element size sensitivity analysis. The output is from the center of the window pane and of the type max principal, mises and pressure.
5.3.15 Square fixing point element size sensitivity analysis

The results from the square fixing point element size sensitivity analysis are provided in this chapter. The stress curve from using an element size of 2.5 mm is in Figure 85 and the stress curve is in Figure 86.
Figure 86. Stress distribution for the 2.5 mm square fixing point sensitivity analysis.

The resulting stress curve from using an element size of 10 mm is in Figure 87 and the stress distribution is in Figure 88.

Figure 87. Stress curve for the 10 mm square fixing point element size sensitivity analysis. The output is from the center of the window pane and of the type max principal, mises and pressure.
Figure 88. Stress distribution for the 10 mm square fixing point sensitivity analysis.

6. Analysis
In this chapter is the analysis of the regulations and simulations presented.

6.1 Regulations and research
In the research it’s suggested that the external glass could consist of glass with lower fire rating than the inner in order to accelerate breaking of the external glass and thereby ventilate the hot gases. This approach could be viable in Sweden depending on how the phrase “the risk of injuries caused by falling debris from the façade is limited” from BBR 21 is interpreted, it implies that some debris may be allowed without violating the building code. This is however unclear and the extent of acceptable debris from a double-skin glass façade would have to be clarified by Boverket. Specifically the issue of the external glass in the façade used in the case study where the external glass is unclassified, breaking of the external glass may pose a risk for injuries due to the sharp debris.

The general advice (“Windows in exterior wall”, see 2.2.1) provided in section 5:553 in BBR 21 must be assumed to also apply to double-skin glass façades. The general advice is that distance should be greater than 1.2 m, or that one of the windows fulfills E 30, or that both fulfills E 15. While the distance between the windows in the case study is less than the advised 1.2 m there is 1.75 meters between the tempered glass and where the E 30 glass section ends on the upper floor. This combines the two general advices and should be sufficient in order to fulfill the safety requirements made by section 5:553, especially when also considering that there is a sprinkler system inside the compartment.

Nothing is said in the fire documentation of fire stopping or aprons as is suggested as a solution by both the New Zealand and Hong Kong building codes to limit the fire spread inside the façade. The only measure against fire spread inside the façade is the use of sprinkler inside the compartment and that the external glass is unclassified, this will both
limit the fire and ventilate some of the hot gases after both layers of windows have been broken.

The use of aprons/fire stopping that is proposed by some of the research is in line with what the New Zealand and Hong Kong building codes uses as solution to prevent fire spread inside the façade. There is however no requirements made regarding the classification of the glass, this gives rise to the possibility that the external glass is of the same type as the inner. This has the potential to be problematic since the research quoted in chapter 2.1 reaches the conclusion that breaking of the external glass is essential to the ventilation of hot gases.

6.2 FDS
In this chapter the results from FDS are analyzed.

6.2.1 Parametric vs. Heat release Rate vs. Fire Load Density
In this chapter the output temperatures from FDS are compared to the parametric temperature curve. The parametric temperature curve is plotted along with the adiabatic surface temperature of INNER_THCP20 and the mean gas temperature of MH in Figure 89.

![Figure 89. Temperature comparison of the parametric temperature curve and FDS simulations based on HRR and FLD.](image)

The parametric temperature curve results in a significantly higher temperature than both the gas and adiabatic surface temperatures in the proximity of the ceiling when basing the simulation on the use of FLD. While basing the simulation on HRR with a peak HRR of 5 MW the temperature from FDS is still lower but the difference is smaller. This is an expected result since the parametric temperature curve is an analytical solution which is supposed to be conservative in comparison to numerical simulations. Worth to consider is that the
The geometry of the compartment was adjusted in order to ensure that the oxygen supply was sufficient.

The large difference in temperature between the simulation based on peak HRR and the one based on FLD is caused by the significant difference in heat released during the simulations; this is visible in Figure 90 where the HRR of each is presented. The peak HRR simulation has a maximum of 5 MW while the FLD (this is the primary simulation used) simulation hasn’t yet reached maximum at the end of the simulation.

![Graph comparing HRR between FDS simulations based on peak HRR and FLD.](image)

Figure 90. Comparison of the HRR between the FDS simulations based on peak HRR and FLD.

### 6.2.2 Sprinkler

In this chapter the impact of lowering the fire load density due to the presence of a sprinkler system is analyzed. The adiabatic surface temperatures of the device INNER_THCP20 is presented in Figure 91, this is from the two simulations dual obstruction facade which had a FLD of 800 MJ/m² and sprinkler which had a FLD of 480 MJ/m².
Figure 91. The adiabatic surface temperatures of the device INNER_THCP20 for the two fire load densities 800 MJ/m$^2$ and 480 MJ/m$^2$.

There is a significant difference in the temperatures between the two simulations and a notable drop in temperature for the sprinkler simulation, the cause of this is the corresponding drop of HRR that is present in the sprinkler simulation. This drop is also present in the with higher fire load density simulation but it’s much smaller. This is visible in Figure 92. The higher temperature that the sprinkler simulation has early on is discussed later in this section.
Figure 92. The HRR in the simulations primary and sprinkler.

This drop is in turn probably caused by the placement of the fuel inside the compartment. The placement of the fuel and HRRPUV (Heat Release Rate Per Unit Volume) is visualized in Figure 93. The upper views are at 60 seconds and the lower at 400. The primary simulation is shown to the right and the sprinkler to the left.
Figure 93. The HRRPUV visualized in Smokeview for the two different simulations primary and sprinkler at approximately the times 60 and 400 seconds. The upper views are at 60 seconds and the lower at 400 seconds. The primary simulation is shown to the right and the sprinkler to the left.

In the primary simulation the ignition burner is mostly covered by fuel during the time it is active while in the sprinkler simulation approximately half of the burner is not covered. This has probably had an impact on the combustion in the proximity of the burner and affected the HRR. The higher temperature that is present early on in the sprinkler simulation (Figure 91) is also probably caused by the placement of the fuel, both by the higher HRR and that there are no fuel between the window and burner.

Therefore the placement of the fuel has probably had a significant impact on both HRR and the temperature in all the simulations.
6.2.2 Multiple obstruction façade vs single obstruction façade

In the simulations two different ways to model the double-skin façade were used, in this chapter the effect those had on the temperature is determined. The temperature developments of the façade types are shown in Figure 94.

![Graph showing temperature developments](image)

**Figure 94.** Comparison between the different alternatives used to model a double-skin façade in FDS.

The use of a single obstruction to model the double-skin façade causes the temperature to deviate and rise more rapidly after approximately 500°C. The cause of this may be that when using a single obstruction the air gap will be static both regarding the material properties of air and that it'll be regarded as a solid material.
6.2.3 Mesh size
In this chapter the mesh sizes used are evaluated. The temperature plots for the different mesh sizes are located in Figure 95.

Figure 95. Plot over the adiabatic surface temperatures of the device INNER_THCP20, the primary simulations is presented along with two different mesh sizes for mesh 1 and one different mesh size for mesh 2.

The impact of using a smaller mesh size for mesh 2 is minor while the mesh size of mesh 1 is significant during parts of the simulation, at the end the temperature development appears to be converging. Using a smaller mesh for mesh 1 results in a higher temperature, this element size does however require longer time to simulate. Unfortunately this simulation was not allowed to complete due to stability issues with the server causing simulations to not complete, due to insufficient time it was not restarted. The larger mesh in mesh 1 resulted in a temperature several hundred degrees lower and must be regarded as too coarse. Using a finer mesh for mesh 2 did not have a significant impact on the temperature development in the simulation.
These temperature differences can be explained by the fact that the mesh sizes have had an impact on the HRR, this is visible in Figure 96.

Figure 96. Heat release rates for the different mesh sizes used in the sensitivity analysis.
6.2.4 Radiation angles

In this chapter the results from the primary simulation (see Figure 54) using 100 radiation angles (the default value in FDS) is compared to a simulation using 1000 radiation angles. These two temperature plots are presented in Figure 97.

![Temperature plot comparison](image)

**Figure 97.** A temperature plot of the primary simulation which is using the default number of radiation angles and an alternative which was using 1000 radiation angles. The simulation using 1000 radiation angles was exited after 10 minutes due to stability issues with the server causing all simulations running at that time to exit. The default number of radiation angles used by FDS is 100.

An increase of the radiation angles used in FDS resulted in a slightly higher temperature, unfortunately the simulations using 1000 radiation angles only simulated approximately 10 minutes until stability issues with the server caused any simulations run at that time to exit. It’s possible that the temperature difference would have increased at a later stage of the simulation. From the data available it appears that the number of radiation angles did not have a significant impact on the results but since only 10 minutes were simulated this is not certain.
6.2.5 Maximum velocity error
An attempt to eliminate the maximum velocity error was made by introducing code which limited the velocity tolerance and number of pressure iterations, the results from these two simulations are presented below in Figure 98. The maximum velocity error is a diagnostic function introduced in FDS 6; it’s used to indicate whether there is a possibility of numerical instabilities in the simulations.

![Graph showing temperature over time for two simulations](image)

Figure 98. The primary simulation and the simulation where the code limiting velocity tolerance and pressure iterations were implemented.

This appears to have had no impact on the temperature results and didn’t eliminate the maximum velocity error.
6.2.6 Geometry
In this chapter the impact of the defect geometry present in the majority of the simulations is analyzed. The temperatures of INNER_THCP20 and INNER_THCP19 are plotted in Figure 99.

![Temperature plots](image)

Figure 99. The temperature plots of the correct geometry simulation and the faulty geometry simulation.

The temperature difference of the INNER_THCP20 devices is minor until the temperature starts to stabilize. When this happens the simulation with correct geometry stabilizes at a higher temperature, this is due to the adjusted geometry which prevents hot gases from exiting the compartment.

When instead comparing the temperatures of INNER_THCP19 from the simulation with correct geometry to the temperatures of INNER_THCP19 from the simulation with faulty geometry the temperature difference is negligible.
6.2.7 Inner window vs external window

During the thesis it was attempted to model a double-skin glass façade in FDS by using multiple obstructions in combination with adjusting the absorption coefficient. The adiabatic surface temperatures of the inner window are shown in Figure 100 and the temperatures of the external window are shown in Figure 101.

![Adiabatic surface temperatures - inner window](image)

Figure 100. Adiabatic surface temperatures of the inner window.
As seen in Figure 101 the temperature rise of the external window is less than 5°C which is unrealistically low in comparison to the inner window which has a temperature rise of several hundred degrees. Therefore it must be assumed that the amount of heat allowed to pass through the window were unrealistically low and that the attempt to model a double-skin façade using multiple obstructions in combination with an absorption coefficient was unsuccessful. It’s therefore impossible to make any predictions of the temperatures of the external window from these simulations.

6.3 Façade
In the case study it’s stated that the lower part of the window consists of E30 and the upper part of tempered glass. The tempered glass quality is required to have been evaluated at 290°C. INNER_THCP20 will reach this temperature in less than 10 minutes when using a peak HRR of 5 MW and also when using a fire load density of 800 MJ/m². Therefore it must be assumed that this glass will break, this can also be assumed for the external window with unclassified glass.

The lower glass is required to be of class E30, while this is expected to be fulfilled there were no details available regarding the fixing points. This makes it difficult to determine the viability of these. It’s however possible to analyze the temperature in combination with the reduction factors of aluminium and steel. Since in this case only the lower part of the window is of E30 class it’ll be INNER_THCP16 and INNER_THCP17 that is of most interest to predict the possible temperatures the fixing points might be exposed to. In the adjusted
geometry simulation INNER_THCP16 stabilizes at approximately 400°C after 20 minutes while INNER_THCP17 does not stabilize completely but is not expected to exceed 600°C.

If the fixing point material is assumed to be steel and located at a height similar to INNER_THCP16 the steel will be at almost full strength when the temperature stabilizes. If the fixing points instead are located at approximately the height of INNER_THCP17 they’ll be only at half strength which will then have to be taken into account.

If the fixing point material is instead assumed to be aluminium the strength will be severely reduced at significantly lower temperatures; the material will only have 6% strength left at 350°C. This temperature is expected to be exceeded regardless of fixing point location. This would make aluminium a rather undesirable material for fixing points.

### 6.4 Abaqus

The results from an Abaqus analysis of a double-skin glass façade will be highly dependent on the specifications of that particular façade. Therefore it’s not possible to establish what amount of stresses the glass in a double-skin glass façade should be required to withstand without analyzing a relatively large number of façades. Without a detailed analysis focus should instead be on how long the fixing points can be expected to support the façade.

#### 6.4.1 Distance from edge

All simulations that were designed to estimate the impact from varying the distance between the fixing point and edge of the window suffered from unrealistic anomalies. This concerns the following simulations:

- R30-d40050-steel
- R30-d400400-steel
- R30-assymetric-steel

The results from these simulations indicate that relatively large stresses will occur where there is no interaction between the fixing point and window screen. This is an unexpected result and must be assumed to not reflect the reality; therefore these simulations are deemed to be unreliable. When adjusting the element size of the window to 2.5 mm in the R30-d400400-steel simulation the anomaly was eliminated; using an element size of 5 mm appears to be insufficient in some simulations.

#### 6.4.2 Fixing points

The impact of the type of fixing point is not possible to determine due to unrealistic variation in the results. Using a finer mesh caused these anomalies to disappear.

#### 6.4.3 Material

Using aluminium instead of steel in the analysis causes the stress increase to be linear; this is probably caused by steel being prescribed a stress-strain relationship while aluminium was not.
6.4.4 Temperature
Introducing another temperature field with lower temperature did not have a significant impact on the overall stress distribution. There was no significant increase of stress in the intersection of these two fields and the areas with highest stress were still at the fixing points.

6.4.5 Mesh sizes
Element sensitivity analysis of the models with a framework failed to complete due to simulations with element sizes of 5 mm and 2.5 mm being aborted by Abaqus, the issue seemed to be that the solution was diverging and causing the simulations to abort.

A comparison between the stress curves of the R30-d5050-steel-primary simulation and the window pane element sensitivity analysis model shows that a decreased element size caused the stress to increase linearly. This also eliminated the stress difference that previously was apparent in the simulation at the partition intersections.

Decreasing the element size of the circular fixing points to 2.5 mm does not have a significant impact on the results while an increase to 10 mm causes the stress curve to become linear.

The stress curve of the square fixing point model with an element size of 10 mm is completely linear while the 2.5 mm model is a smooth curve. The 5 mm model is somewhere in between which indicates that the square model requires smaller elements than the circular fixing points.
7. Conclusions and Recommendations

This thesis identified several points of interest regarding double-skin glass facades. Both the New Zealand and Hong Kong building codes have acceptable solutions to manage the fire safety; it’s however unclear whether these solutions can be applied in Sweden. The fixing points were identified to be a weak point regarding the fire safety. It’s in the immediate proximity to these that the highest levels of stress will occur, the fixing points must also be able to maintain the load bearing capacity which causes aluminium to be an unsuitable material. Due to difficulties in obtaining detailed information regarding the façade it was not possible to complete the case study. This in turn made it impossible to analyze an actual façade in Abaqus and determine whether the double-skin façade complies with BBR 21. Therefore it’s recommended that a complete analysis of a double-skin glass façade is conducted to determine whether it can be considered to fulfill the requirements made by BBR 21. This requires details regarding the façade and these should be obtained beforehand to ensure that the information is available.

BBR 21 provides some advice regarding the inner glass of the façade in section 5:553 but questions regarding fire spread inside the façade and the risk of debris are still unsolved. The building codes from Hong Kong and New Zealand provides acceptable solutions for double-skin façades and it is proposed that Boverket works towards being able to provide acceptable solutions in a future version of BBR. It is also proposed that Boverket clarifies to which extent debris is acceptable since some of the research indicates that breaking the external window is essential for some fire safety solutions in order to prevent fire spread inside the façade. This is an area in which the New Zealand and Hong Kong building codes also lacks guidelines, the building codes would allow a higher fire rating of the external window than in the inner which could elevate the risk of fire spread inside the façade. Until it’s known to which extent debris is acceptable it’s possible to interpret BBR 21 to allow for a certain amount of glass to fall down in order to prevent fire spread inside the façade.

Using FDS for a small compartment where the oxygen supply is limited will require a significant amount of time regarding pre-processing and simulation time while yielding uncertain results. An FDS simulation would instead be more useful in a larger compartment where the geometry doesn’t require modifications to ensure sufficient oxygen levels.

When modeling the compartment the choice of using either a burner with HRR or using fire load density will have a substantial impact on the resulting temperatures. If the approach of using fire load density is chosen the placement of the fuel will have to be carefully considered, this in order to ensure that the fuel ignites as intended and that the fire spreads properly. In this specific case the placement of the HRRPUA burner was not adjusted since it was placed close to the façade to begin with, in a larger compartment this will be of more interest.

The fixing points are a weak spot due to the higher levels of stress these cause in the glass when heated. Therefore the interaction between the fixing point and glass must be
considered when evaluating the durability of the façade, not only the E classification of the glass. The material of the fixing points is an important factor since if the fixing points can’t support the façade this will cause window panes to fall out; aluminium will therefore be an unsuitable material choice in many cases due to the low load bearing capacity at elevated temperature. Instead fixing points of steel should be considered.

The attempts to use Lagrangian particles to model a double-skin glass façade in FDS were unsuccessful since the particles are not capable of preventing flow through them. Therefore this requires no further investigation since it’s not possible due to how the particles function in FDS.

The “maximal velocity error” present in the FDS simulations is used to indicate if there may be numerical instabilities in the simulation. It’s unknown if this had a significant impact on the FDS simulations but it should be stated that the simulations in this thesis probably suffer from some degree of numerical instability. The attempt to eliminate this error was unsuccessful and limiting the pressure iterations and velocity tolerance had no impact on the results.

A gap between the roof and the façade was present in the FDS models, this error had a minor impact depending on which device that is being analyzed. It caused the uppermost temperature device to have a slightly lower temperature.

When creating an Abaqus model of a double-skin glass façade it may not be necessary to take temperature differences along the surface into account since using multiple temperature fields did not impact the overall stress distribution. The maximum stresses will be located at the fixing points regardless of temperature variations on the surface of the window.

With the limited information available regarding the design of the façade along with fixing points there’s little point in correcting and refining the faulty Abaqus models due to difficulties in assuming realistic input parameters. The results will also vary greatly depending on the design of the façade and will yield different levels of stress, therefore several façades should be analyzed in order to determine which levels of stresses that can be expected.
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