Faculty of Architecture
Building Technology: Façade Design

Report for Graduation Project

P5 Final Research Result

Fire Rating Curtain Wall

Student: Yajie Wang
Student Nr: 4119045
Email: arjane.wang@gmail.com

1st Mentor: Tillmann Klein
2nd Mentor: Fred Veer

Internship: Scheldebouw
Supervisor: Karin Lamberts

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Abstract

The space that can be improved to get a better prediction bridging the gap between simulation and reality, and its reactions on design revision to increase the fire-resistance of a façade product before a formal test is the issue of this thesis. Regulations and design principles concerning a fire-resistant façade have been studies. With the technical support from Scheldebouw company, a running project was able to be taken as a case study, which is the main tool to look for the answers in this research. Calculation models with VOLTRA had been designed for this project and been compared with pre-test results to find out the link with reality and the limitation of simulation. An experiment on a simple model was made and analyzed with the help of TU Delft to get more information about a good prediction by simulation. Then via illustrating the revision steps based on the estimation of each phase, an economically and efficiently meliorated fire-resistant design procedure generated. Finally the thesis ended with evoking a space for the architects to rethink about the decisions made at an early stage.

Key words: fire-resistant façade, simulation, VOLTRA, fire test, comparison, limitation, prediction

Contents

1 Introduction

1.1 Subject & Internship

1.1.1 About fire-rated façade

In most countries, approval for a new construction or the use of an industrial product, depends on passing fire safety regulations, which have been developed around the world from the tragic experiences of real fires at the cost of losing life or property. Another fact that, a trend in pursuit of a more open space via increasing the transparency ratio of the building envelop continues in modern architecture, constantly raises new challenges on fire safety engineering. Therefore no matter from which point of view, to meet fire safety legislations, to prevent more tragedies, or to keep pace with current architectural developments, manufacturers have responsibility to investigate on design strategies and ensure the fire safety of their products.

In façade construction field nowadays, aluminium has got an increasingly higher prevalence for its light weight, great molding flexibility, high corrosion resistance and favorable price-performance ratio compared with steel. However, aluminium can be sensitive to temperature increase as it loses its rigidity and melts at around 600°C (compared with steel at 1500°C, it is relatively low). Therefore a guarantee in fire safety means a lot and determines the success of a façade system, and to pass the fire test is the decisive link for a design to step into reality.

Scheldebouw B.V., part of the Permasteelisa Group, is a company which is specialized in the field of project management, façade design, fabrication and installation on site for buildings in the top segment of the international construction market. During the past several years Scheldebouw has been requested to deliver more and more fire-resistant aluminium façades (at least 30 minutes), but they still lack the experience of doing this in an economical and efficient way. That is why they have raised this topic in collaboration with the façade research group of TU Delft as one of the possible graduation subjects and provided an intern position for it. I made this choice due to my personal preference of working with industry because I felt it necessary to acquire some knowledge about the realization of a design, no matter in future as a façade designer or an architect.

1.1.2 Why simulations?

When considering aluminium elements, it is quite difficult to estimate if a system is safe without testing. Some general design principles do exist, but they do not guarantee that everything works perfectly in reality as an integral product. To increase the probability of success of the system, tests and simulations have to be done in advance. Though tests can be more convincing, there are reasons for not only doing tests but also computer simulations.

There could be two possible situations for an inappropriate design in a fire test if without simulation beforehand. One is that the test fails and more tests are necessary, which means more money and time would be spent. Here is a rough estimation about the cost comparison considering a standard project in Scheldebouw [see Table 1.1]:

Test		Simulation	
Lab facilities:	€15,000/test	Software:	€6,000 (if new)
Mockup &Organization:	€20,000/test	Engineer:	€1,200/section
One more test if failure:	€15,000/test	Average:	≈ €4,500/project

Table 1.1 Cost comparison[1]

Another situation is that in fear of a failure test, people add more materials and constructions than necessary to make the element over fire-resistant. So though the test succeeds, it is not a good design in terms of material- and cost saving, and people gain no effective experience about where crucial parts are in making a façade fire-rated.

The both scenarios stated above are absolutely called anything but doing a fire-resistant design in a low-cost way. But if a good estimation could be made with the help of simulations, unnecessary tests and materials can be avoided. Besides, modeling in a computer is much faster than preparing a real test. There is a certain time limit for every project in reality, and working with simulations is a more efficient way for what we want.

In a word, with the help of a computer program it is possible to predict the high temperature behavior of the façade. And the design could be adjusted in time due to the quick feedbacks from the program. In this way, simulations help effectively in reducing the risk of a failure and thus save both money and time.

1.1.3 Scheldebouw's need & Task of the intern

With the program VOLTRA[2] being in use within Scheldebouw, it is only possible to predict temperatures in a fire calculation, but no support to link the temperature rise with structural behaviors. This is why Scheldebouw sometimes ask for external simulations using software SAFIR[3] when necessary (like when a test fails because of deformations). Even with VOLTRA, Scheldebouw has no sufficient experience doing fire calculations, considering what parameters to use for material properties, geometry simplification and cavity types in a model. Every project of Scheldebouw is a customized design, and it is not possible to establish a perfect standardized simulation model since there are no simple omnipotent modeling rules that can be applied to all different designs. Another problem of unfamiliarity with VOLTRA lies in lack of information about comparison between a simulation and a real test. Only if the relationship between a simulation and a test is known (like a simulation result is always higher or lower by how much, or what part can be overestimated, etc.), a simulation result can have practical values.

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[1] According to the internal report of Scheldebouw *DC2_Fire rating curtain walls_Technical paper*.

[2] Thermal calculation software in Physibel series, 2009.

[3] Developed by the University of Liège, Belgium, 2007.
See the homepage http://www.argenco.ulg.ac.be/logiciels/SAFIR/index.html

Scheldebouw wants to meliorate their design process into a more low-cost and efficient way, but they need to know the consequence of every change on their design. In another word, they need a good prediction about the fire-resistance of the design before it becomes a real product. This is why they are hiring trainees to extend the knowledge. Therefore within the company, my task is to explore how to give a good prediction, which includes improving modeling methodology with VOLTRA for a more correct calculation result and its interpretation in practice on design optimization. And the experience gained during this researching process will also be regarded as part of customer feedbacks for Physibel to improve their software in future.

Of course, due to the time limit and the limitation of the projects that I can reach with the company, this research is only based on two running projects of Scheldebouw. Data collected to draw a conclusion for a good simulation or rules studied to convert into a fire-rating façade may not be sufficient enough, and that is where the space for a further study lies.

1.2 Research question

Main question:
How to make a better prediction with the help of computer simulation about the fire-resistant performance of a fire-rated façade and what is its interpretation on design revision?

Sub-questions:
1. Why is there a need for simulations in the design process of a fire-resistant façade?
2. In what aspect does a simulation contribute to make estimation?
3. What are the reasons that cause the gap between a simulation and a test?
4. What are the factors influencing the accuracy of a simulation model?
5. What is the limitation of the simulation program and could it be improved?
6. What to do to get more information to make up the incapability of the simulation?
7. What are the principles of a fire-resistant design?
8. What are the relevant actions of a prediction on design adjustments?
9. What is the impact of the whole process of realization on architecture?

1.3 Methodology

During the beginning of my research, my sight was only limited in simulations and the program, no clear methodology to achieve what I want. But later on, I was able to find more sources of information and a clear way to structure my research and lead me conclusions:

Literature study:
Through literature study, it helped me build up my first knowledge about things relevant to fire-resistant façade, including fire regulations, definitions & formulas, design requirements & principles, and assessment, etc. I was able to understand the fire strategy and know rules when changing a façade into a fire-rated one.

Practical research:
This part consists of four sections, from the start of learning the program to the final result on design.

1. The first is to via studying about the existing calculation models for project “De Rotterdam” made by Scheldebouw and the University of Liège and comparing them with my rebuilt ones, playing with parameters to learn basics about VOLTRA modeling, mainly to find out influencing factors of a simulation model.

2. The second is to take a big case study about the running project “Stadskantoor Utrecht”, doing the simulations for it, comparing with pre-tests and discussing the relevant design adjustments. This section leads me a deep understanding about the program to find out limitations of a simulation and space of improvement. It also helps me with figuring ways out about how to bridge the gap between a simulation and reality, to make a better estimation.

3. A test on a simpler piece of physical model has been made and compared with its simulations by myself with a support from the university since a real façade element is too complicated to more clearly see some conclusions. This experiment provides more information on linking a simulation to reality.

4. The same case study with the one in the second item, but focusing more on the measures of design revision. Via taking a look at the problems found in simulations and pre-tests and comparing the original design and the revised version, illustrating how the design-steps are developed based on a good estimation made from all sources for a project.

Final goals of this research would be:
- Access to improve the simulation;
- Experience to bridge the gap between a simulation and reality;
- A series of efficiently and economically meliorated steps of design revision based on estimation.

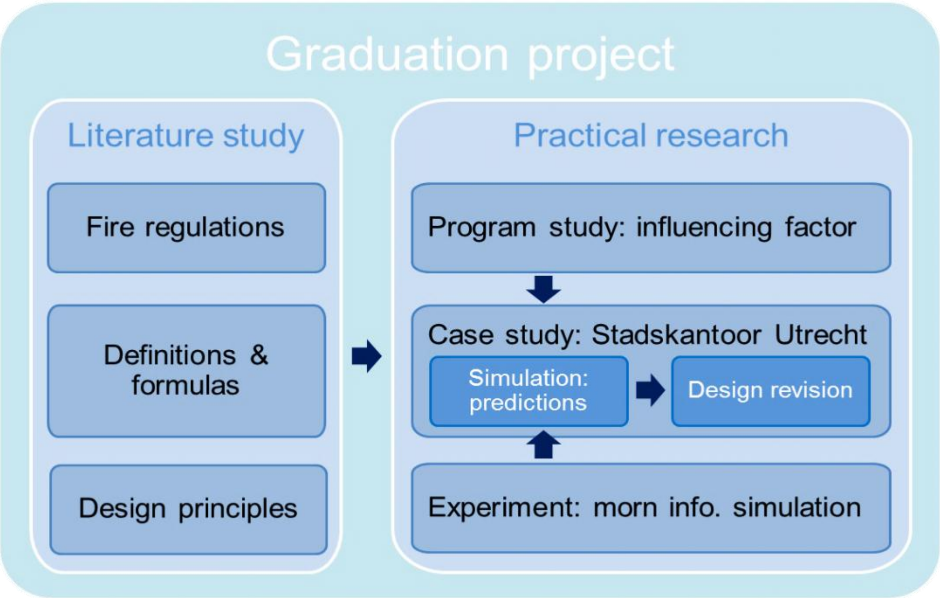

Table 1.2 Methodology

1.4 Projects & computer program involved in the research

Related drawings and statistics of simulations/tests in this research are based on the running projects of Scheldebouw – “De Rotterdam” and “Stadskantoor Utrecht” [Figure 1.1 and Figure 1.2]. “De Rotterdam” is studied as a sample project to learn the computer program, and then refined simulations will be done and revising strategies will be studied for “Stadskantoor Utrecht”.
The computer program studied in the research is VOLTRA from Physibel. Sometimes because Scheldebouw has little experience yet, external calculations with SAFIR are asked, but it is only for extra advices and, Scheldebouw does not work with SAFIR at all but only VOLTRA.

Figure 1.1 De Rotterdam

Figure 1.2 Stadskantoor Utrecht

2 Literature Study: Background knowledge

2.1 General about fire resistance in façades

2.1.1 Fire safety strategy

A fire safety strategy of a building is made firstly and fire resistant regions of the façade will be defined after that. Risk of fire spreading must be minimized from one floor to another one above or from one room to the next one horizontally. Typically there are three categories of places [see Figure 2.1] of the façade need to be fire resistant:

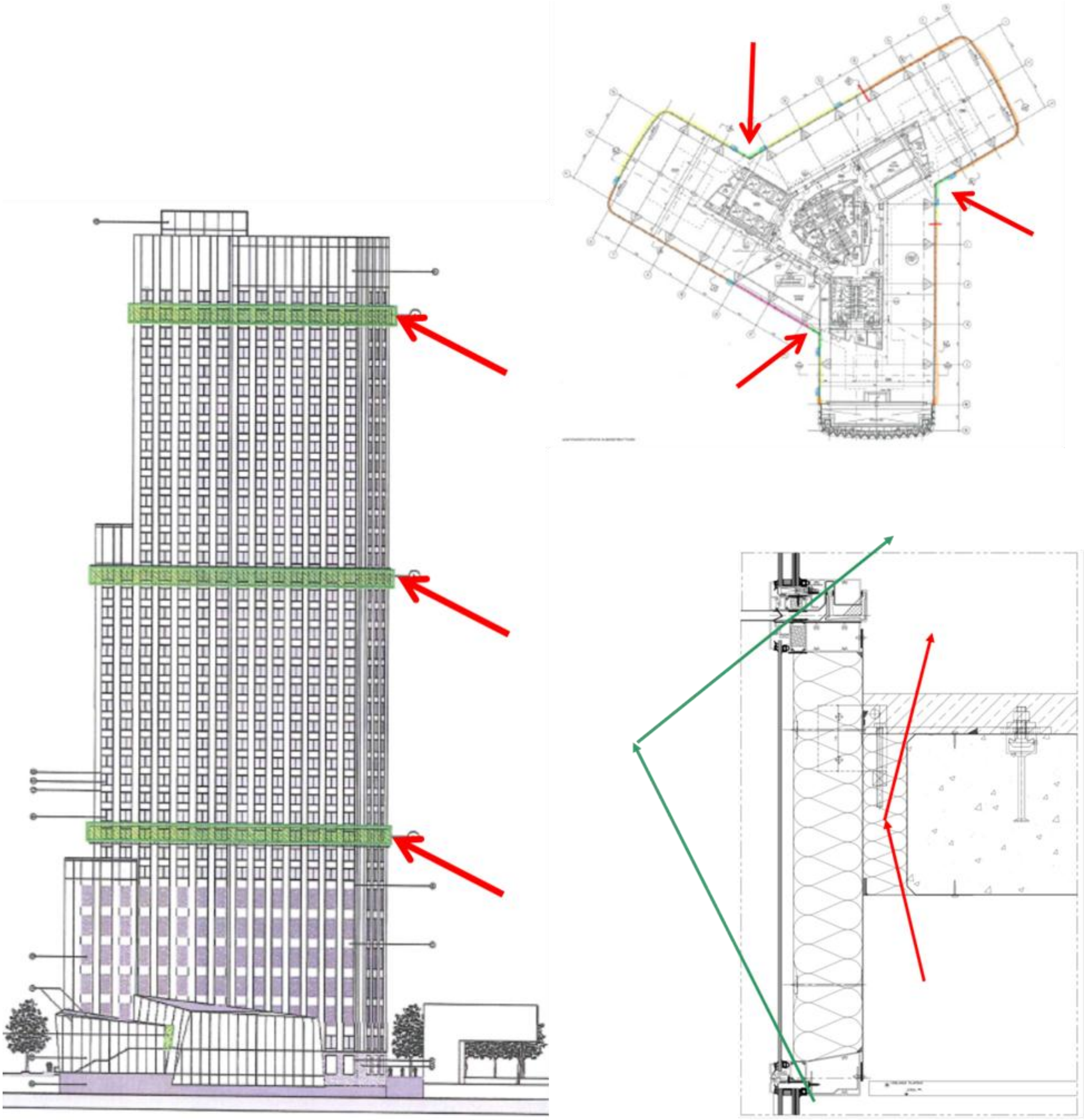

Figure 2.1 Positions that need to be fire resistant on façade

2.1.2 Classification & Assessment

There are three performance criteria concerning curtain walling fire-resistance[4]:

E – Integrity

The integrity E is the ability of a test specimen of a separating element of building construction, when exposed to fire on one side, to prevent the passage through it of flames and hot gases and to prevent the occurrence of flames on the unexposed side. The assessment of integrity shall be made on the basis of the following three aspects:

- Cracks or opening in excess of given dimensions;
- Ignition of a cotton pad;
- Sustained flaming on the unexposed side.

Note: Failure of the loadbearing capacity criterion shall also be considered as failure of integrity.

I – Thermal insulation

The insulation is the ability of a test specimen of a separating element of building construction when exposed to fire on one side, to restrict the temperature rise of the unexposed face to below specified levels. The performance level, used to define thermal insulation, shall be the mean temperature rise on the unexposed face, limited to 140 °C above the initial mean temperature, with the maximum temperature rise at any point limited to 180 C° above the initial mean temperature.

Note: Failure of any loadbearing or integrity criterion shall also mean failure of thermal insulation, whether or not the specific thermal insulation temperature limits have been exceeded.

W – Radiation

The radiation W is the ability of the element of construction to withstand fire exposure on one side only, so as to reduce the probability of the transmission of fire as a result of significant radiated heat either through the element or from its unexposed surface to adjacent materials. The element may also need to protect people in the vicinity. The radiation classification shall be given by the time for which the value of radiation, measured as specified in the test standard, does not exceed 15 kW/m^2.

Note: Failure of integrity under the “cracks or openings in excess of given dimensions” or the “sustained flaming at unexposed side” criteria means automatically failure of the radiation criterion.

The fire-resistance of a building element is always declared in a combination of a specification of any of the above and a time period[5] in minutes [Table 2.1].

[4] See EN 13501-2:2007, Chapter 5.2 & Chapter 7.5.3.

[5] The chosen time often depends on conditions of occupancy of building or fire compartment, possible installation and maintenance of sprinkler systems, and the use of approved insulation and coating materials, including their maintenance.

Criteria	Time [min]					
E	15		30	60	90	120
EI	15		30	60	90	120
EW		20	30	60		

Table 2.1 Classes

For example:

Figure 2.2 shows a façade with an E-performance which can be passed by a running person within 30 minutes.

Figure 2.3 shows a façade with an EW-performance which can be passed by a walking person within 60 minutes. The radiation is restricted to a maximum of 15 kW/m^2.

Figure 2.4 shows a façade with an EI-performance behind which a person can stay within 90 minutes. The mean temperature rise should not exceed 140 °C and with any local temperature rise limited to 180 °C.

Figure 2.2 E30

Figure 2.3 EW60

Figure 2.4 EI90

Test and classification may be performed from one side only or from both sides. The classes are identified by:

"i→o" when classification is envisaged from inside to outside;
"o→i" when classification is envisaged from outside to inside;
"o↔i" when classification is envisaged from inside to outside and from outside to inside.

For example, EI 60 (i→o) indicates an element which is capable of providing 60min integrity and thermal insulation performance from the inside only, whereas a classification EI 60 (o↔i) indicates the ability to provide the same level of performance from both inside and outside.

2.1.3 Fire curves[6]

There are three types of temperature-time relationships [Chart 2.1] that can be applied when testing. The choice of curve depends on the type of fire to be expected.

[6] See EN 1991-1-2:2002, Chapter 3.2.

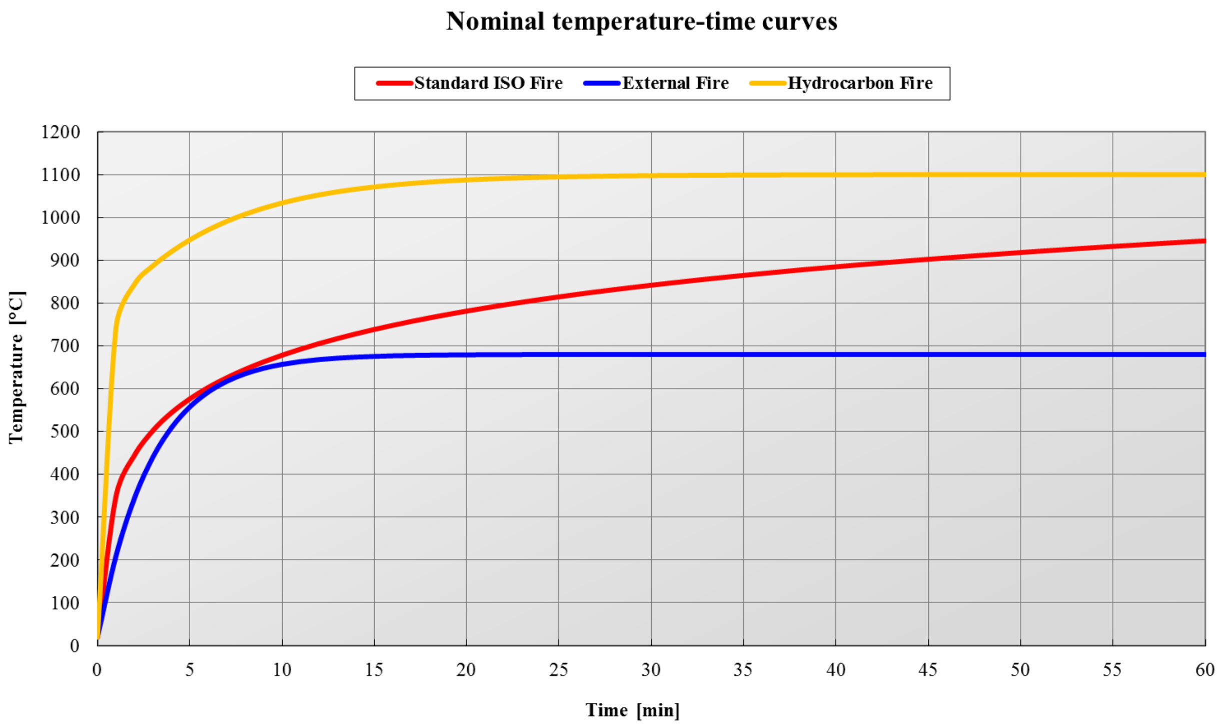

Chart 2.1 Fire curves

a. Standard temperature-time curve

The standard ISO fire curve is based on the burning of cellulose containing materials such as wood, and thus is also known as cellulosic curve. The relationship is defined by:

$$Q_g = 345 \log_{10} (8\,t + 1) + 20$$ [7]

Q_g: the gas temperature in the fire compartment [°C]

t: the time [min]

The coefficient of heat transfer by convection α_c = 25 W/ (m^2K)

b. External fire curve

For a fire happens outside of a building, it is considered that a lot of cold external air is mixed in and thus consumes a lot of heat, so that the temperature would rise less higher. There are two different expressions for the temperature-time relationship of the curve in European standard and Dutch norm:

According to Eurocode, the curve is defined by the formula below, and it will reach its maximum temperature of 680 °C after 22 minutes.

$$Q_g = 660\,(1 – 0.687\, e^{-0.32\,t} – 0.313\, e^{-3.8\,t}) + 20$$ [8]

Q_g: the gas temperature near the member [°C]

t: the time [min]

The coefficient of heat transfer by convection α_c = 25 W/ (m^2K)

[7] EN 1991-1-2:2002, Chapter 3.2.1, Formula 3.4

[8] EN 1991-1-2:2002, Chapter 3.2.1, Formula 3.5

According to the Dutch norm, the curve of temperature rise is the same as the ISO type for the first 10 minutes, and stays 659 °C after that. The temperature will no longer rise after 10 minutes and stabilizes at 659 °C [Chart 2.2][9]. This is a critical temperature for aluminium since the melting point of it is around 660 °C. The test EI 60 (o→i) for "Stadskantoor Utrecht" used the Dutch method.

θ is de getalwaarde van de gemiddelde temperatuur in °C;

θ_0 is de getalwaarde van de aanvangstemperatuur in °C;

t is de getalwaarde van de tijd in min.

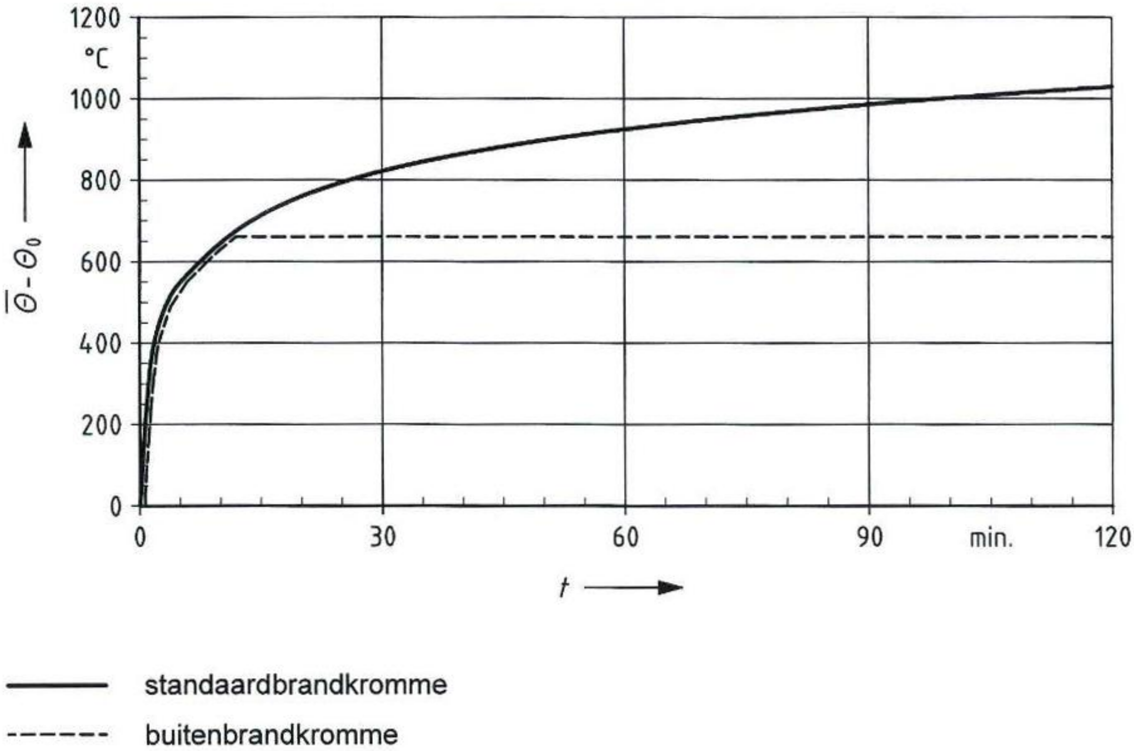

Chart 2.2 De standardbrandkromme en de buitenbrandkromme[10]

c. Hydrocarbon curve

The Hydrocarbon curve is much more intense than the standard ISO fire curve and reaches 1000 °C in around 7 minutes and stabilizes at 1100 °C. It represents combustion of hydrocarbons for applications such as aviation and vehicle fuel fires and fires in the offshore industry.

$\mathbf{Q_g = 1080\,(1 - 0.325\,e^{-0.167\,t} - 0.675\,e^{-2.5\,t}) + 20}$ [11]

Q_g: the gas temperature in the fire compartment [°C]

t: the time [min]

The coefficient of heat transfer by convection α_c = 50 W/ (m^2K)

[9] NEN 6069:2011, Chapter A.2.3

[10] NEN 6069:2011, Chapter A.2, Figuur A.1

[11] EN 1991-1-2:2002, Chapter 3.2.1, Formula 3.6

2.1.4 Applicable norms

EN 1363-1 Fire resistance tests / Part 1: General requirements
EN 1363-2 Fire resistance tests / Part 2: Alternative and additional procedures
EN 1364-3 Fire resistance tests for non-loadbearing elements / Part 3: Curtain walling
EN 13501-2 Fire classification of construction products and building elements / Part 2: using data from fire resistance tests, excluding ventilation services
EN 1991-1-2 Eurocode 1: Actions on structures / Part 1-2: General actions

2.2 Basic design principles

Figure 2.5 Combustion conditions

There are three key factors for combustion: heat, fuel and oxygen. Fire growth is a function of the fuel itself, with little or no influence from the configuration of a building. But with sufficient fuel and oxygen, fire will continue to grow resulting in an increase in compartment temperature. When heat accumulated to 500 °C – 600 °C, flashover occurs and the fire becomes fully developed, engulfing the whole compartment until the fuel or oxygen within the compartment is totally consumed. [12] What these facts tell us is that to contain the fire to its place of origin and prevent it from spreading, it is crucial to reduce the amount of gas/smoke leakage and thermal propagation below a certain level for a safe construction [Figure 2.5]. This is the theoretical base of all the measures we could take to make a façade fire-rated.

2.2.1 Architectural design

Normally to make a fire-rating façade means based on the standard module of a design, doing minimal adjustments to convert this façade module into a fire-rated one for the fire-resistant regions. And such adjustment should make no difference to the outside appearance of the building and will not affect the performance concerning water impermeability and insulation, so that the façade system stays fundamentally the same and there is no visual difference between fire-resistant and non-fire-resistant windows and walls. However, if the consideration of fire-resistance issue could be taken into account at an earlier phase together with architectural design, or when it refers to a façade refurbishment project, the fire-resistance could be improved significantly via some adjustments to façade configuration.

From an architectural level, shape of openings and prominences on the external walls will have a lot of influence on controlling of the fire spreading. Experience shows that tall narrow windows present a lesser hazard than short wide ones [see Figure 2.6]. Tall windows tend to project the flame away from the façade, decreasing the thermal coupling of the flames and keeping the thermal exposure

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[12] CSR Bradford Insulation Group, *Design guide: fire protection*, P9
http://www.bradfordinsulation.com.au/Bradford/UploadedFiles/54/54bcbafc-e9f3-44ca-9b2b-b6bb999700c7.PDF

relatively low.

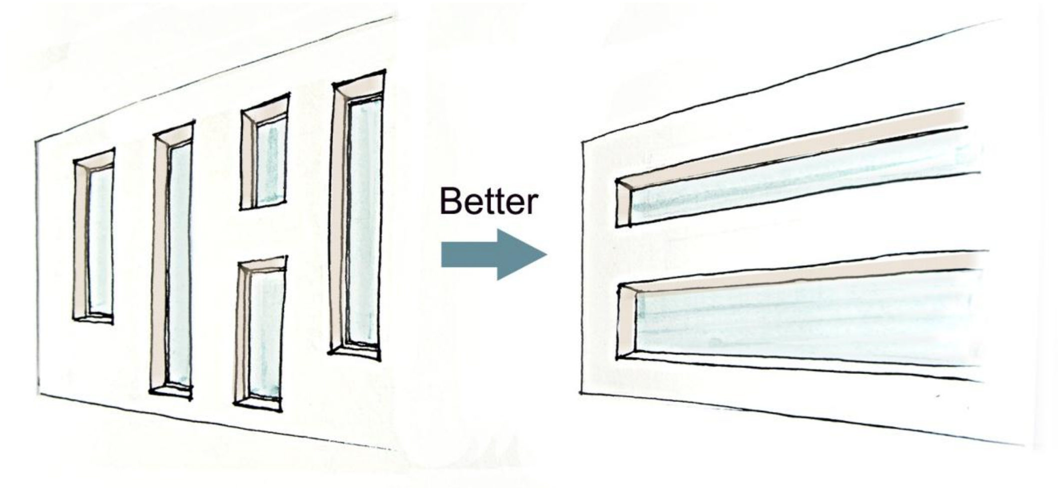

Figure 2.6 Tall narrow windows are better than short wide ones

Prominences on the façade like vertical spandrels or horizontal ledges also help to reduce the risk of fire spreading a lot. For vertical separation [Figure 2.7], any external opening must be separated by a spandrel which is not less than 900mm in height, and extends not less than 600mm above the upper surface of the intervening floor; for horizontal separation [Figure 2.9], the external projections must not be less than 1100mm and extend along the wall not less than 450mm beyond the openings.[13] Both should be constructed from a non-combustible material having a suitable fire resistant level which complies with the relevant country's requirements.

Figure 2.7 Concrete spandrels

Figure 2.8 Façade with horizontal ledges[14]

[13] CSR Bradford Insulation Group, *Design guide: fire protection*, P10

[14] Sugamo Shinkin Bank, Tokyo.

Figure 2.9 External projections as horizontal separation

Figure 2.10 Useful for both shading & fire safety[15]

2.2.2 Materialization

Materials selected for such use must have at least one of the properties: heat-reflecting, adiabatic, or heat-absorbing, and at the same time they should have low toxicity as well. There are several vital components that must be considered in aluminium fire-resistant façades.

2.2.2.1 Glazing

Currently there are two types of glazing to be used based on different principles concerning fire resistance:

a. Intumescent glazing

This laminated glass uses a special transparent intumescent interlayer made of fire resistive gels and resins to reach its fire resistance. Infilling materials are chosen depending on required time and fire-resistance class. Possibilities in combination with different visual effects (light transparency, haze, streak look, etc.), acoustic insulation and UV resistance are available. Normally this interlayer is 3mm in thickness.

The tempered glass of the fire side fractures under fire, but the interlayer will hold the shatters in place. As temperature rises, the interlayer becomes opaque and intumesces with heat insulated and radiation proof to shield flame and smoke [Figure 2.11]. It prevents radiant heat which may cause flashover on the non-fire side, and it also provides good thermal insulation to keep the temperature of the non-fire side as low as possible [Figure 2.12], which enables a safe evacuation on fire occasion.

If higher levels of fire resistance are required, the glazing can be built with triple glass panes and two gel-layers or other stronger combinations.

[15] North West Vista College, San Antonio, Texas

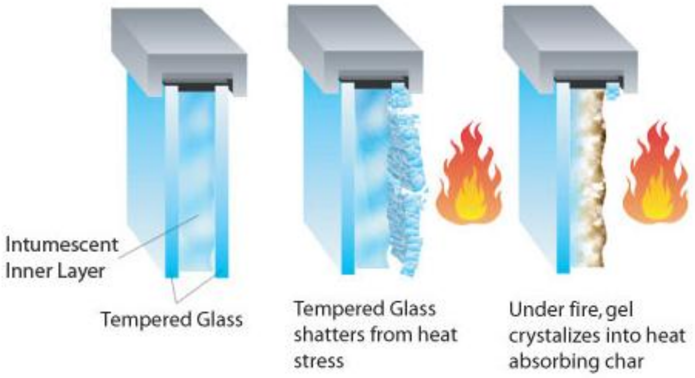

Figure 2.11 Working principle of intumescent glazing

Figure 2.12 The surface remains cool to touch

Points of attention:

- A combined use with additional solar-control coatings will negatively influence the capacity of fire-resistance of the entire glazing. It would be necessary to thicken up the interlayer and the new composition needs to be tested.
- The intumescing layer becomes yellowish and therefore affects the optical effect of the glazing in long-term non-fire situation of high temperatures. When it exceeds 65 °C, this type of glass should be avoided.
- Keeping an eye on the stocking period would be necessary because the gel-layer itself cannot stand exposure to water.
- With an annealed glass pane laminated to the package, rigidity will be improved a lot.
- The maximum dimension of fire-resistant glazing is smaller than normal glazing. So this maximum should always be checked whether it fits with architectural picture.

b. Monolithic fire resistant glass[16]

Monolithic glass is single pane. This fire protective glass blocks flames, fumes and smoke but not heat radiation, but this can be improved by application of heat-reflecting coatings and multi-layer glazing. Its advantages are:

- As it is not wired or laminated, it stays clear at all times during fire accident so that evacuation and putting out fire could be carried out properly.
- It is thermal shock proof and resists to cold, heat, solar irradiation and humidity.
- This high strengthened fire resistant glass is 3 to 5 times stronger than thermal temper glass.
- Various glass thickness of monolithic fire resistant glass is available.
- Monolithic fire resistant glass is light. Framework is cheaper. Mounting and installation is easier.
- It is easily upgraded to several types of fire resistant glass such as reflective coated fire resistance glass, insulated fire resistant glass, laminated fire resistant glass and energy save fire resistant glass, etc.

There are several types of monolithic fire rated glazing reaching different classes and grades of fire resistance:

[16] See http://xinology.com:888/Glass-Mirrors-Products/fire-resistant-glass/overview/glass-configuration.html

Chemically Strengthened Glass

Soda lime glass is always chemically strengthened to improve its thermal stability and internal strength. Then glass is thermally tempered by conventional tempering furnace by air quenching to it turn into Class C monolithic fire resistant glass. This glass can be used in E- and EW- category façades. Example: Pyroswiss by Saint-Gobain.[17]

Metallic Coated Glass

Glass could be metallic coated on both sides to reflect away heat and minimize the possibility of thermal shock. Monolithic fire resistant glass performs consistent regardless of fire attack direction. It is used in E- and EW- category façades. Example: Vetroflam by Vetrotech.[17]

Borosilicate Glass

Borosilicate glass is excellent in heat proof. It has also very low coefficient of thermal expansion to resist thermal shock. Borosilicate glass is generally fully thermal tempered upgraded to fire resistant glass. This glass is mostly known as it used in ceramic furnaces, coffee-pots and tea-glasses. It can also be used in E- and EW- category façades. Example: Pyran by Schott.[17]

Glass Ceramic

It is a special composition of glass and ceramic with excellent thermal shock and heat insulation. This glass is not suitable for façades.

With intumescent glazing category E, EW and EI can be fulfilled; glass with heat-reflecting coatings can maximally reach category E and EW due to its transparency. For now, Scheldebouw uses the former one for most of the cases. [17]

2.2.2.2 Intumescing tape

Intumescing material is an essential thing on the list of sealant materials because normal sealant will melt after 200 °C but the gaps must be filled, with the expansion of the intumescing tape [Figure 2.13]. There are three main types of intumescent tapes (the following description about those three types is based on Scheldebouw's internal technical information):

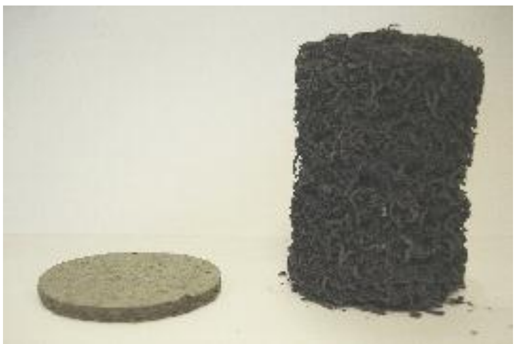

Figure 2.13 Intumescent tape before and after contact with fire

a. Tape based on hydrated sodium silicate

This kind of tape is always encapsulated in a rigid thermoplastic profile due to its high content of water. When exposed to fire this material is activated at a temperature of 100 °C – 120 °C. The profile starts intumescing and a rigid, non-combustible foam is then formed, which offers a high level of thermal insulation. The expansion of this tape can reach five times of its initial thickness and the

[17] Scheldebouw's internal experience, by Jean Paul Erkens.

pressure generated is around 1.5 N/mm^2. This provides an effective barrier preventing the leakage of flames, smoke or hot gas around the perimeter of the element. Example: Palusol from BASF.[17]

b. Tape based on ammonium phosphate

This type is mainly used for wood and wood-based materials to enhance the fire resistance. When exposed to fire the tape rapidly produces a large quantity of micro-porous, thermal insulating foam, thereby protecting the treated material. The reaction starts at a temperature of about 180 °C, and the expansion is at least 40 times of its initial thickness. The expansion pressure generated is neglectable. Since the material is not stable in permanent contact with water, it is only suitable for inside application. Example: Interdens by ODICE France.

c. Tape based on graphite

This is a graphite-based flexible intumescent seal. The graphite base can sometimes be contained in a thermoplastic support. The seal can be used in humid environment because it contains no water and is water-resistant. Intumescing reaction starts at 160 °C – 200 °C, and the expansion can vary between 11 and 50 times of the initial size. The pressure can reach 0.5 N/mm^2. Examples are Flexilodice by ODICE France (11x expansion) and Flextrem by Dornex Holland (50x expansion). And the latter is the most often used on in Scheldebouw due to its price-level in combination with the expansion.

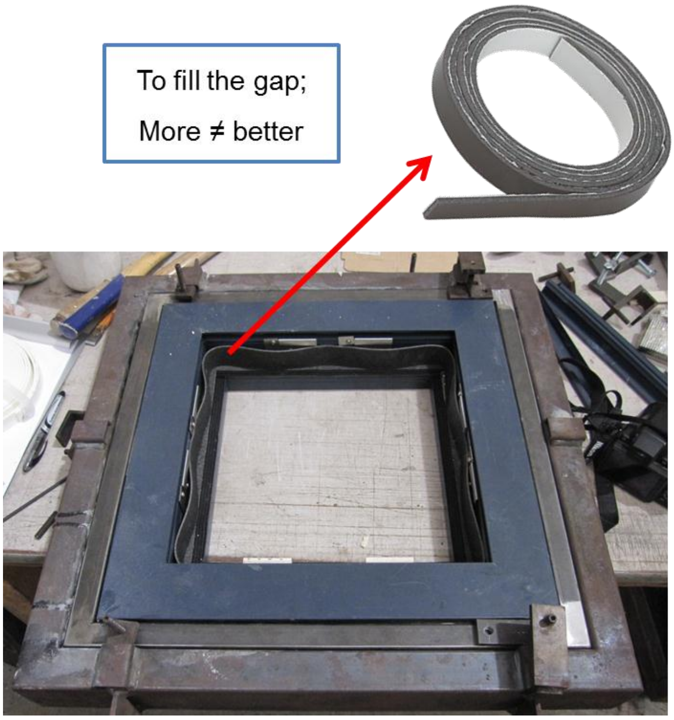

Figure 2.14 Intumescing tape in the window frame

Note of attention:

The intumescing tape is never the thicker the better [Figure 2.14]. Too much of it will also push the frames of the glass too much when it expands in a fire, which may cause distortion or deformation in structure so that there may come the glass detachment or growing gaps in risk of flame leakage. This could be one possible reason to explain why one test for “Stadskantoor Utrecht” failed [Figure 2.15], but the answer needs to be verified with further tests.

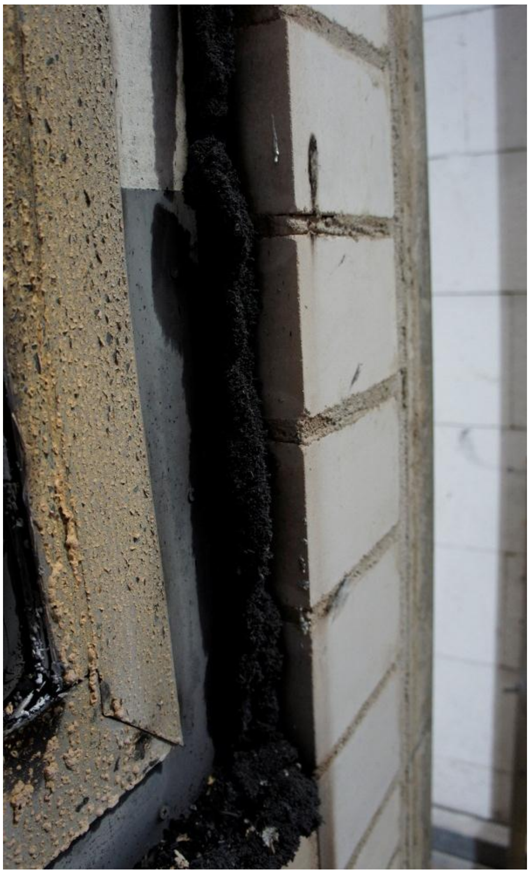

Figure 2.15 Intumescent sealant after Test 2

Figure 2.16 Too much intumescent tape in Test 1 (failed)

2.2.2.3 Rockwool and Promatect

Insulation materials must be both fire rated and have low toxicity. Rockwool mineral fiber insulation, in this case, is widely used on an international level as a lightweight, adaptable and effective fire rated building product for passive fire protection systems design. Besides, with rockwool as insulation, an improved thermal comfort and a reduced noise level can be achieved. The thickness and density[18] of the rockwool insulation can be changed according to the requirement after calculation.

Another frequently used insulating material is Promatect insulating board. It is a kind of calcium silicate board containing a certain amount of bound water (10% up to 650 °C and 3% up to 850 °C). Acting as an aggregate, the anhydrous phase of wollastonite Ca_3 (Si_3O_9) increases the temperature resistance by absorbing a lot of heat during a fire. Besides, low thermal conductivity, high mechanical strength, non-wettability in contact with non-ferrous metals, good workability and processability are also outstanding features of this material.

2.2.3 Structural liability

From the structural angle, aluminium parts and most other materials will melt after some time due to

[18] Normally for fire-resistant use, the density of rockwool insulation is at least 70 kg/m^3.

the high temperature and, the structure will become weaker and dangerous and then finally collapses. To postpone the collapse beyond the time range (30min or 60 min) expected, the load-bearing capacity must be increased. And this can be done by adding additional reinforcements and connections made of steel (of which the melting point is high enough), such as a steel core inside of an aluminium mullion or transom, steel clamps [see Figure 2.17 and Figure 2.18] for holding glass within a window frame, and steel screws for a strengthened connection.

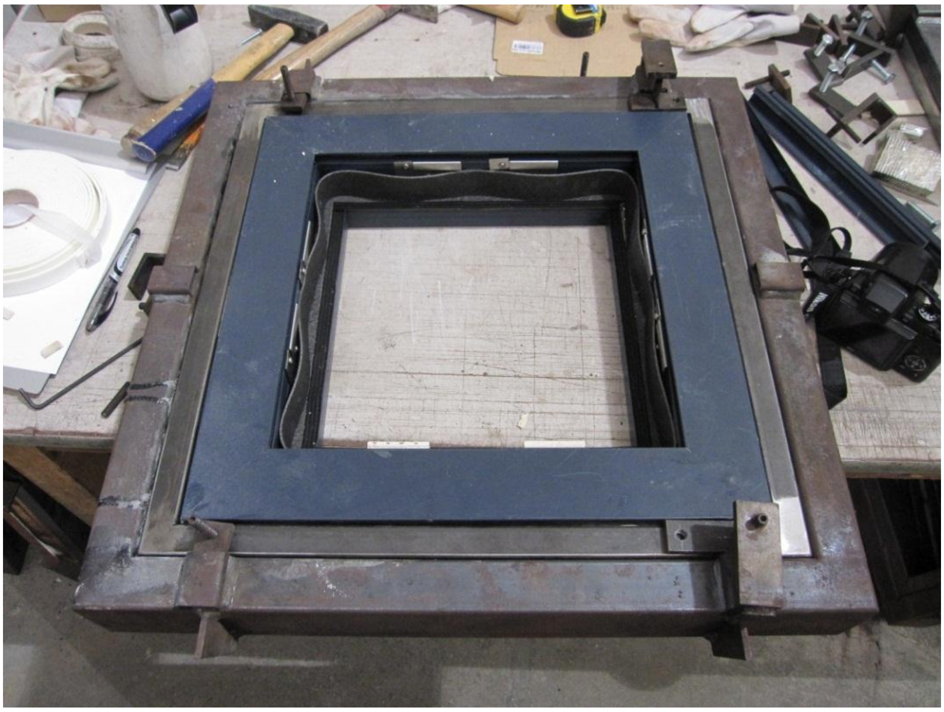

Figure 2.17 Steel clamps and intumescent tape in the frame

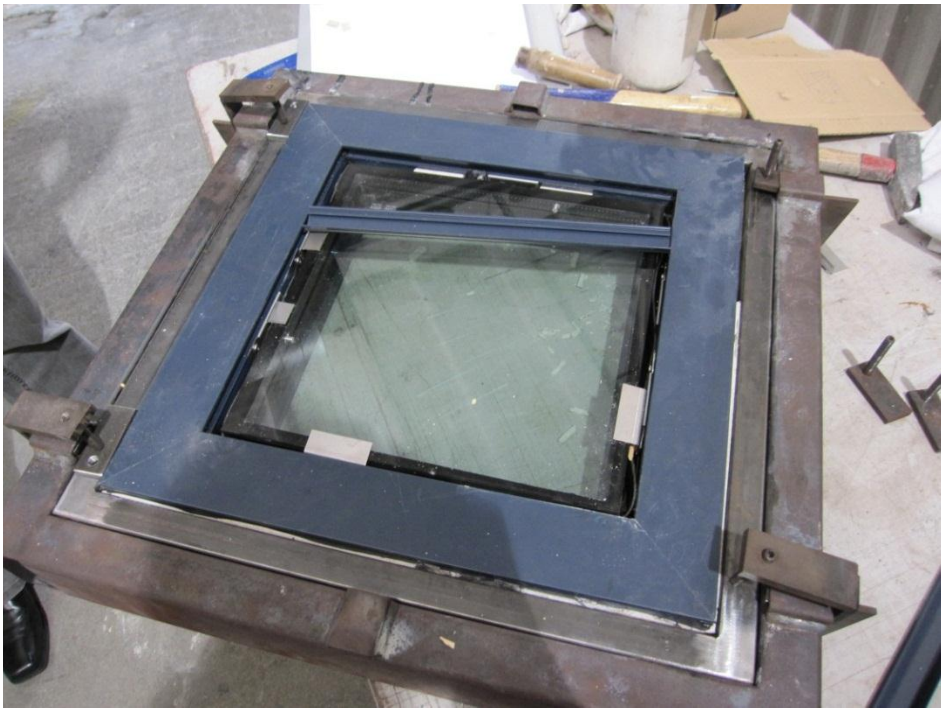

Figure 2.18 Steel clamps and intumescent tape (glass pane installed)

Chart 4.7 shows that for the first 15min an emissivity value of 0.3 is very good for the result, but later on because it involves phase change, deviation occurs. In Chart 4.8, it seems that using an emissivity value of 0.7 can reach a similar curvature with the one in the test after 15min, however, this never means that we should use change the value from 0.3 to 0.7 from 16min even if VOLTRA had this function, because in this case the reason for that the temperature-curve tends to become flat has nothing to do with emissivity change but the tendency of how the real fire goes. The higher the emissivity value is, the earlier the material will reach the maximal temperature as the fire curve inserted, and a value of 1 means it can reach the same curve as the fire curve without any postponement. Besides, if we use 0.7 from the beginning, due to an accumulation result, the temperature of aluminium in simulation will be too much higher than in real test, which is not correct to use for estimation.

4.2.4 Conclusion & question

a. Positions that need adjustments – tenacity checking

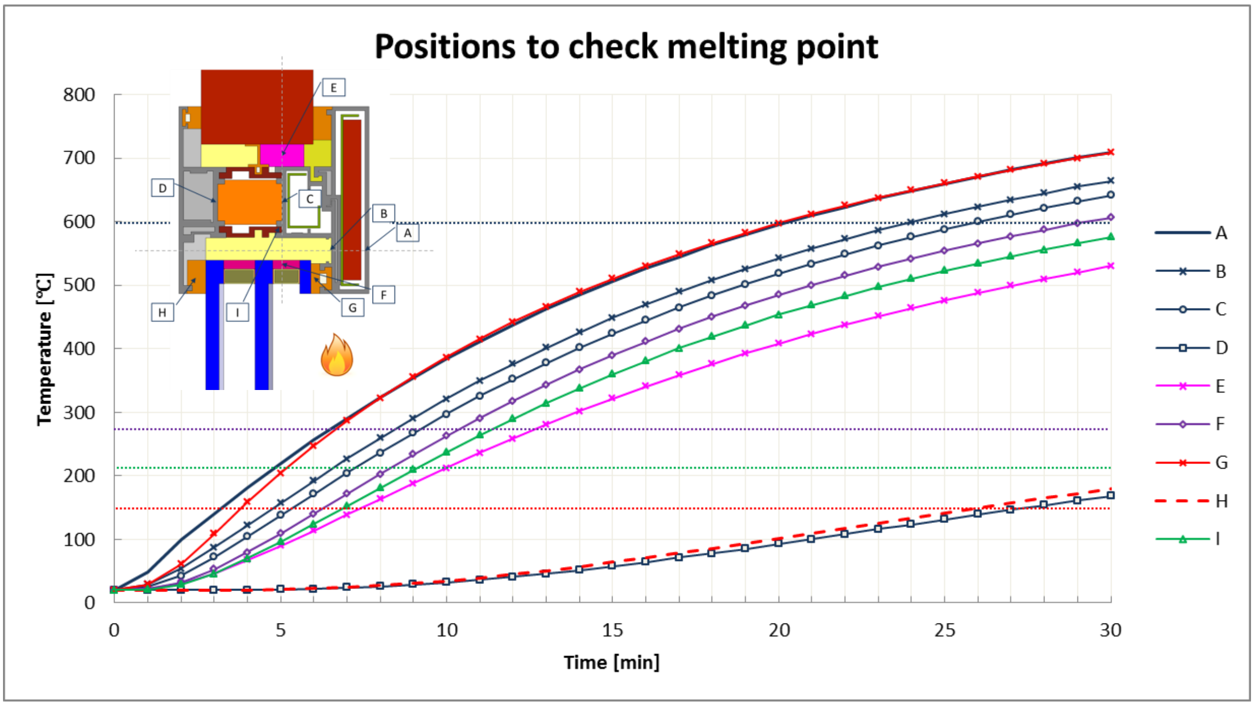

Chart 4.9 Checking for material tenacity

- Aluminium profile: Point A – D are different positions on the aluminium frame. Referring to information about melting point mentioned in Chapter 4.1.2, Point A melts around 20min, Point B melts around 24min, Point C melts around 26min, and Point D does not have a risk of melting. Therefore a conclusion could be drawn that the inner half of the aluminium frame needs additional reinforcements, among which, the two steel cores are only part of them.
- Structural silicone: Point E in the Sikasil SG-500 will melt after about 6.5min; therefore it needs extra components to keep the whole window frame in connection with the wall.
- Glass edge: Point F in the polysulfide will melt after about 10.5min and the hot melt butyl melts even faster; therefore steel clips for glass would be necessary. Glass spacers should have similar temperatures as Point F and aluminium ones would not be strong enough.
- EPDM gasket: Point G of the fire-side EPDM gasket will melt very fast within 5min and Point H of

the non-fire-side may also melt after about 25min; therefore additional connections would be necessary to prevent the glazing from falling off the frame or, when necessary to change the gaskets into more inflammable type.
- Thermal break: Point I in the polyamide will melt after about 9min so that the front and back parts of the frame should be connected with extra accessories.
- The whole system should stay upright with the rest of the materials that do not melt and extra structural supplements.

b. Conclusions for simulations

- Information about material properties that have been collected is verified to be sufficient and usable enough in this simulation; especially the influence of differed emissivity values has been grasped.
- The assumption model for glazing part in this case has been verified as workable.
- A model with minimal grids is usable in this simulation (difference <10°C compared with a background of under over 700°C).
- It is acceptable to build only part of the testing element in a simulation to simplify the modeling.
- If a simulation is done before the pre-test, there is no problem using a standard ISO fire curve and the estimation made to predict the temperatures in a test should be like this:

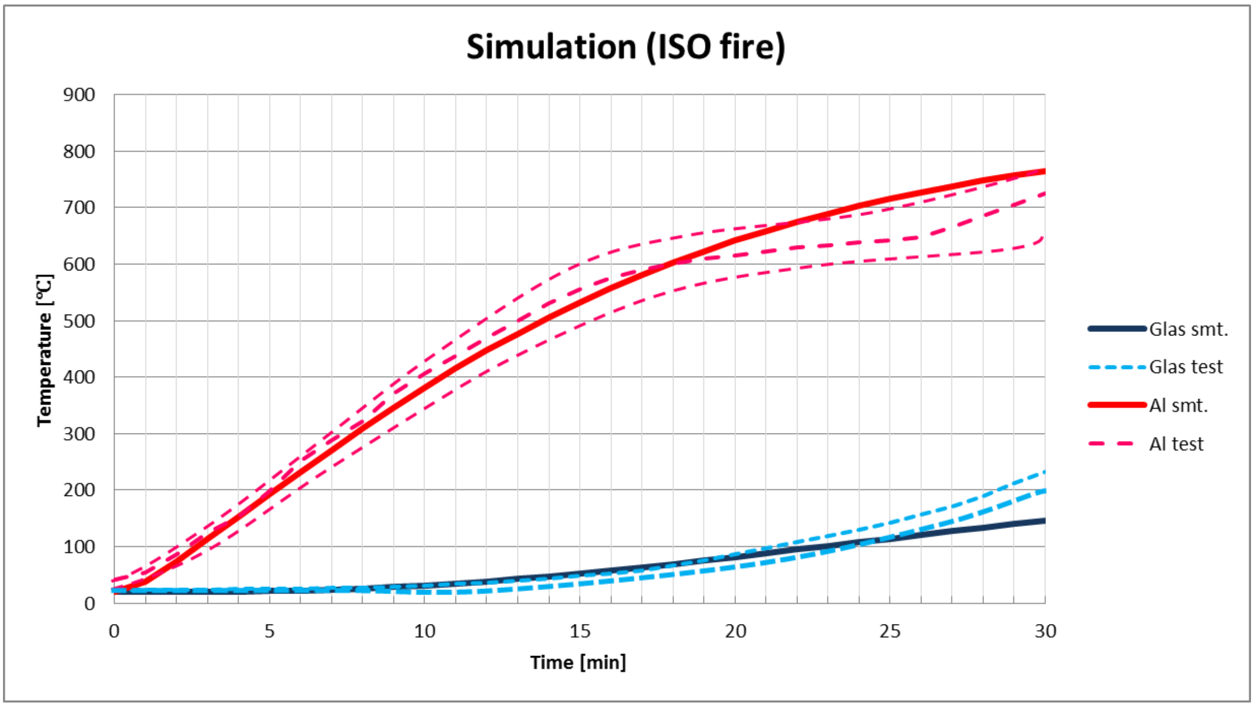

Chart 4.10 Estimation range

If in a simulation the temperature-curves of aluminium and glazing parts are calculated as shown in Chart 4.10, then in a real test, how the curves develop can be predicted close to the range of the dotted lines depending on the locations of the testing points in the furnace.

c. Space of improvement in simulation

- C1, C2 and C3 are three parameters used in cavity types in VOLTRA. This group of three values is given in norms at 10°C or 15°C, but they must change as temperature rises. In TRISCO manual it explains that C1 is the thermal conductivity of still gas, while nothing about C2 or C3 is available. For now the author has tried to use a function for C1, but the result has little changed. But the author has no idea about whether there would be a bigger difference if C2 and C3 all change with C1 due to lack of information.

- As mentioned earlier, it is not available to insert a function for emissivity value in VOLTRA at the moment. And even if it was possible, it is difficult to use because experience is necessary to decide from which moment the surface should be considered to change its emissivity for every relevant material.
- VOLTRA does not count the amount of bound water in a material like the Promatect board. If the program could be improved or if there is an alternative calculating way under current situation by manipulating other thermal properties to achieve the same effect needs further research.
- The same statement as in the last item but for phase change of materials, such as aluminium and intumescent tapes.
- VOLTRA only predicts temperature changes but provides no information on structural deformation. In Test 1, the inner side of the whole element expanded more due to much higher temperatures than outer side did and there was a big deformation towards fire-side, and within two or three minutes after the fire was stopped, the structure shrinked and came back towards the original position a little. One thing happened during this process was that the outer heat toughened glass pane broke and the deformation change could be a possible reason. Another thing was the extensions of glazing spacers were too much to keep spacers working. They bent a lot in the test and this may be a reason for the failure of the middle EW 30 glass pane. Thermal expansion and deformation are crucial factors for big elements.
- Maybe some of the functions that the author has inserted in the model do not have big influence and can be replaced by constant values as a further simplification of modeling, but this needs to be checked one by one and takes more efforts, therefore this will be done only if there is a necessity for some project in future.

4.3 Simulation 2: Stadskantoor Utrecht, EW 60 (o→i)

The element of Floor 7 for the pre-test shares the same profiles as Floor 6 but is 900mm lower in height; plus the final temperature of an outside fire is over 300°C lower than an inside fire in the test, the pre-test for EW 60 (o→i) was quite a success and there is no need for further design adjustment. Therefore there would be no interest in elaborating this type, if any, referring to the one for Floor 6.

For the simulation model done for this type, the only problem lies in the glazing part. Unlike the element of Floor 6, this one has a smaller dimension in height, therefore, the float glass pane in the triple glazing did not fall way soon in the pre-test but until the 24min. This fact results in the problem with schematizing the model. We cannot exclude the float pane from the beginning of the calculation in the model and as mentioned before VOLTRA does not deal with geometry change automatically. Any similar change like this much be realized by an equivalent calculation method if possible, such as to insert a function for the material property change or an existing power or temperature. However, in this case, the changed geometries involved do not only include the float glass pane but also the coating on it and the cavity enclosed by it, resulting in a very complicated situation, which the author has not yet found a solution that could be equivalent to it. This could be considered as another function limitation with this program.

4.4 Experiment for more information

4.4.1 Introduction

Since in a real fire test there are many factors influencing the result recorded, like in Test 1 we did for “Stadskantoor Utrecht”, a structural damage at a certain moment, the positional relationship to flames in the furnace of a measuring point, some unclear interaction between a material and its surrounds, etc., it would be too complicated to see how precise the VOLTRA calculation can reach in a corresponding simulation. Therefore, the idea of this experiment is to take a much simpler piece of physical model, test it under temperatures not too high to cause any damage, and model it in VOLTRA to learn its accuracy and again to further verify whether some material information or assumptions the author has made for modeling are workable. In a word, it is used to gain more information about simulation and reality. Of course, this experiment has limitations as well, but at least it can be much easier controlled than a real big test.

4.4.2 Preparation & testing

The element:

Considering the testing conditions we could have in our university, the element chosen is a sample piece of triple glazing for “Stadskantoor Utrecht” that we get from the supplier. Parameters are listed as follows:

Figure 4.27 Testing element: a piece of triple glazing in A4 size

Dimension in plan: 297mm X 420mm

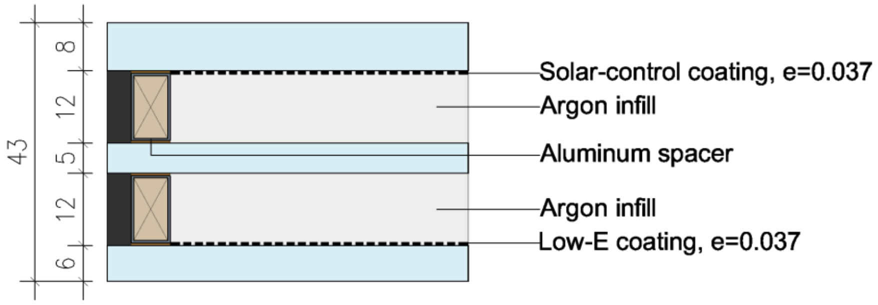

Figure 4.28 Details of the glazing piece

The equipment:

A wooden box is made as a furnace with a heat gun fixed on top of it. Along the perimeter of the glazing piece, rockwool is inserted to guarantee a good insulation to separate the heating side and non-heating side. Temperatures of P1, P2 and P3 are to be collected.

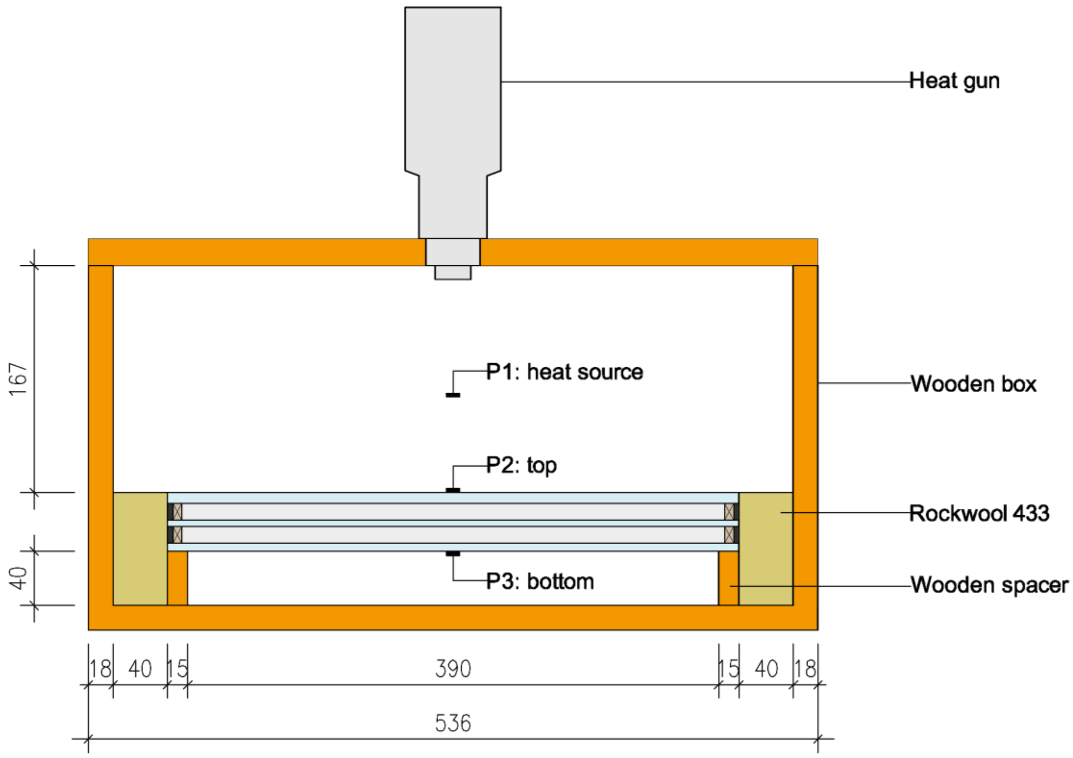

Figure 4.29 The equipment used to execute the test

The Test:

The following series of pictures illustrate how we carried out the test. The test lasted for 75 minutes in total. The top pane cracked after 5 minutes, but it did not fall down and stayed in place during the test. Temperatures were recorded manually per minute.

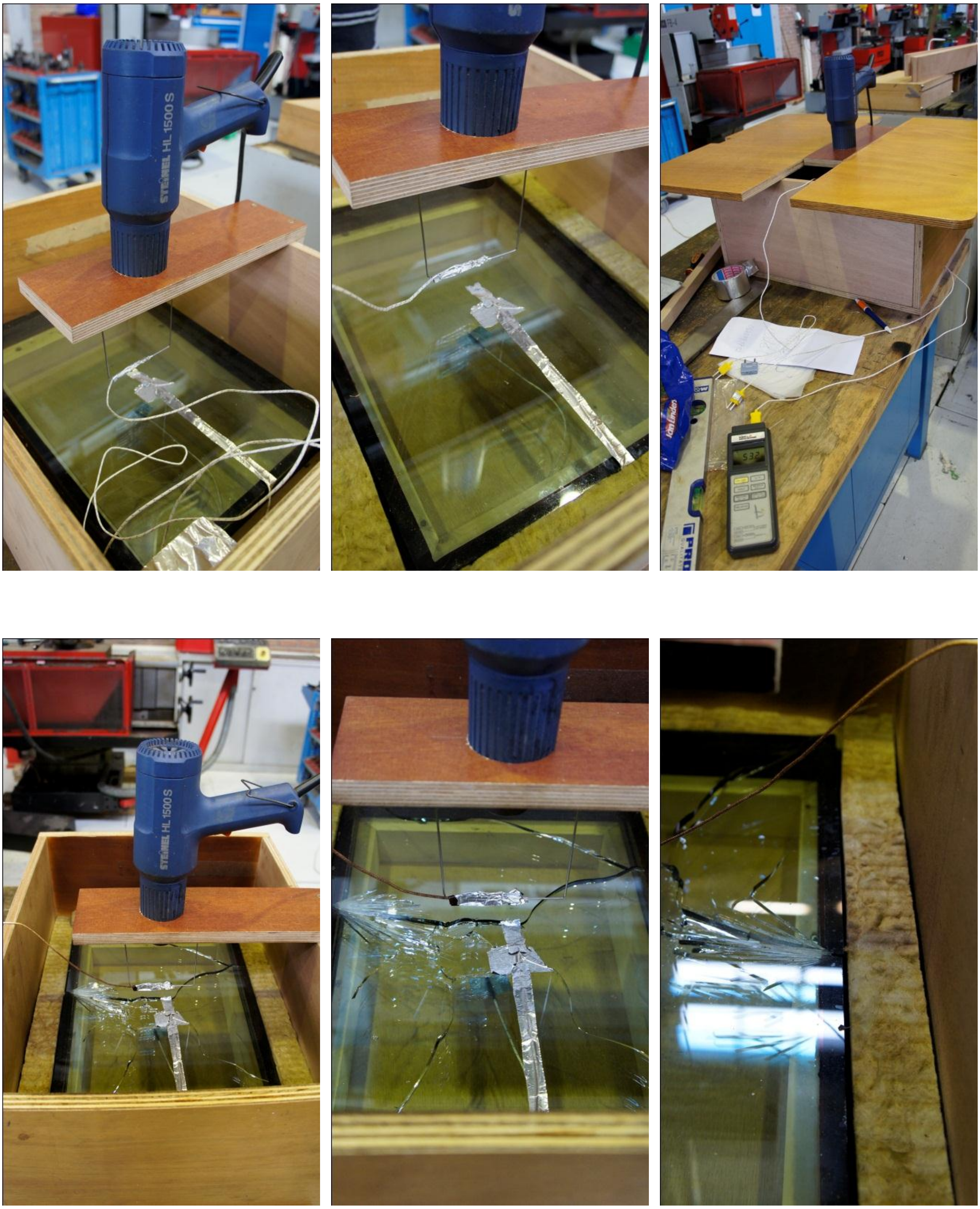

Figure 4.30 Snatches of the test

Complexity:

In this experiment, good results have been achieved because the testing element was already a much simple piece and no much structural damage happened during the test, and in the model we adjusted the gas of the first glazing cavity into air according to the fact that the top pane cracked within five minutes. On the one hand, this verifies the method and assumption, the way we applied theories when modeling are correct. On the other hand, theory works perfect whilst reality never does. Take the small accident happened to the top pane for a detailed explanation. It cracked fast, so we knew the argon leaked away short after the test started; it did not fall down, therefore we knew the cavity was still there and the coating layer worked throughout the test. However, the program does not deal with structural change. Imagine what if the pane cracked in the middle of the test? What if it fell down? And what if we tested the element vertically and then it fell away, or locally? These scenarios about the glass are not possible to predict which one would really happen in a test and some of them are hard to simulate in a model with VOLTRA. Needless to say as for a real complete façade element, there are more components and much more complicated situations would happen in a fire test, more severe temperatures and more structural damages. All these factors drag the real test result away from theory, where difficulties of a good prediction via simulations are adding. This has to be solved step by step. For now what we can do is to use simulations and pre-tests at the same time and refine both of them for a better prediction before a final product is made.

Anyway, in sum, from a general perspective, the simulation result by a 2D model plus a little manual calculation proved rather usable, verifying as well the modeling method, which has been developed from Test 1 for “Stadskantoor Utrecht”.

6 Conclusion & Recommendation

This research on simulation and design concerning fire-rate façade has values of guidance in general for typical aluminium curtain wall system, but since those customized designs by Scheldebouw are different from project to project, measures of modeling and fire-resistant strategy provided in this research should be applied flexibly. Furthermore, along with the advancement of architectural design, façade system and material renovation, there would result in new challenges for making the design fire-rated, of which the experience needs to be updated with the times.

As for the melioration of the whole engineering process, it needs efforts and cooperation of multi-sides. Take the project involved in this research for example, Scheldebouw can make the final façade product fire-resistant on the basis that the manufacturers of the glass and composite walls have guaranteed a good quality of the fire-resistance of their each product. And a prediction can be better also via an improved simulation program, of which the process needs collaboration between the user (the façade engineer) and the developer. No accomplishment can be made with only a single force.

Reflection: What can go wrong?

In retrospect of each move of the realization of this building from the very beginning of an architectural design till the current stage, it is easier to see through all the imperfections in the process of reaching the fire safety requirements. It is true that no project is perfect in reality; however, some errors could have been avoided with awareness beforehand. Therefore what does matter is to be aware of these errors[39] so that future projects could be improved, in which way, making the impact play a role.

a. Architectural design

The whole difficulty of realizing the fire-resistance of the façade derives from the architectural function-arrangement, which is decisive to many follow-up issues, especially to the fire safety plan. In this project, the decision of putting conference space on Floor 6 undoubtedly has increased the difficulties to engineering work significantly due to the bigger fire-resistant façade elements caused by the higher ceilings, which means the whole project is much more expensive. However, unfortunately it is already too late to revise this, since normally in reality the conversation to the architects has been closed after they delivered the design to DGMR and Fire Station and, the façade engineering company can only take what has been suggested by DGMR and try many possibilities in engineering to realize the design.

Therefore, the author is thinking that if the architects knew about the consequence from an early stage, would it a different decision that they made for putting the meeting rooms other than on the sixth floor? They might have other reasons for F6 to have meeting space, but if together with the

[39] The errors summarized here are only limited within Project Stadskantoor due to the limitation on available projects of this research.

consequence of the relevant fire strategy being weighed, maybe they would have a wiser function organization with space of a bigger floor height positioning not as part of the fire-separation regions. After all, as one of the important channels to meliorate the design and its production, it is always reasonable and helpful for a decision-maker to be aware of the results of his decision from the beginning.

Having this question in mind, the author initiated an interview by phone to the architect of this project, Mr. Wouter Ijssel de Schepper from Kraaijvanger B.V. It was learned that the architect started this project in December, 2006, when it was only a few months later after he had graduated from TU Delft. Therefore he had no much experience as an architect in practice at that time, not to mention to have the fire issue well considerated. But after understanding the whole engineering story from the author, Wouter said he would have absolutely made a different layout for the meeting space other on Floor 6 if he had the awareness before, and so would he bear this fire safety issue in mind for future projects.

However, on the other hand Wouter also mentioned the difficulty of acquiring such information in advance sometimes as an architect. First of all, it needs the architect to be familiar with so many related regulations so that for a normal building project, he could have a basic idea about how the building would be separated in fire safety aspect before an official plan made by the fire department; but as for a high-rise or other special building, a unique plan will be made by a professional fire safety consultancy and it is hard to know that before a business has actually been established. But anyway, he said it was interesting to know this feedback from engineering and the problem would be rectified gradually as architects get more experienced in practice.

b. Façade design

Two aspects may have a big influence towards a success of a fire-rated façade element, the outside appearance, mainly referring to the dimension of profiles, and the construction arrangement inside of the profiles.

The first matters because tolerance of different materials caused by thermal expansion and deformation under high temperatures is much larger than under a room temperature, which means it is safer for the profiles to have a larger overlap of the glass from the edge. In this case when Scheldebouw took over the project from the architect, they adjusted the dimension of profiles a little wider already in order to make it possible for engineering work, since the architect had drawn them even narrower before due to his pursuit of a maximal transparency and lack of engineering knowledge. But what Scheldebouw has adapted is challenging their minimal limit of profile dimension in order to achieve the architecturally aspired visual effect. So actually if the architect could allow a larger space, the risk of a failure in a fire test for the both types of façade would have been reduced a lot. For instance, to the full-glazed element façade, the glass would not have come out of its frame even when it sank a few millimeters if the frame was wide enough to cover the shift in the pre-test.

As for the second aspect, Scheldebouw has made three mistakes in their engineering work. For the composite façade, one was with a wrong estimation about the pressure of the intumescent tapes in use and another was an underestimation towards the influence on glass' behavior caused by a deformation, which are both pure design mistakes. But the third one with the full-glazed element façade about the corner connection was due to a communication error between different groups. In Scheldebouw a system firstly is developed by the system design group and later delivered to the project team to apply it to the building, then when it fits well the design will be sent to make production drawings. So when the design was delivered from the system design group to the project team, the corner connection was not explicated clearly. It was hard to figure out the correct measure only from those 2D drawings because there were too many lines, but should be explained to the one who will make the 3D production drawing. Since the project team misunderstood with the connection, it was impossible for them to describe it to make a correct production drawing, which resulted in the failure in practice. To avoid similar mistakes requires engineers to be very precise about each link where there is a risk of misunderstanding.

c. Production

From drawings on paper to products in reality, tolerance exists as well. It is not possible for the installation of different elements of a system to have the exact same positions as in the drawings. Tolerance can reach ±2mm only for the glass panes[40] and ±1.5mm for assembly[41]. However, when working with a scale of millimeters in façade engineering, such tolerance is unneglectable. In this project, it was hard to tell if this factor had influenced much the testing result, but it could be one reason since the final failure was a result of accumulation of all errors. In the revised design, the steel clips are made 5.5mm longer at the top, therefore it can be imagined, if taking the maximum, a tolerance of ±3.5mm does matter in this case. Unfortunately, normally even a façade designer is aware of the danger of this but not workers in the factory, which raises a higher requirement to the designer dealing with the reserved space for tolerance and a good communication with workers if available.

[40] According to the information in the datasheet provided by Schott

[41] According to the production experience of Scheldebouw

7 Bibliography

RENCKENS, J., (1998) Façades & Architecture: Fascinations in Aluminium and Glass
HERZOG, T., KRIPPNER, R.&LANG, W. (2004) Façade construction manual
KNAACK, U., KLEIN, T., BILOW, M. & AUER, T. (2007) Façades principles of construction
WATTS, A., (2004) Modern Construction: Façades
HANUS, F., (2010) Analysis of simple connections in steel structures subjected to natural fire
CSR BRADFORD INSULATION, (2008) Design guide: Fire protection
CIB, (2001) Rational Fire Safety Engineering Approach to Fire Resistance of Buildings
FRANSSEN, J., (2010) Simulation of the behavior of a window frame exposed to fire
NORMS: EN13501-1; EN13501-2; EN1364-4; EN1993-1-2; EN1995-1-2; EN1999-1-2

Sources of pictures

Figure	Source
1.1	http://207.44.228.231/marin/De%20Rotterdam17.jpg
1.2	http://www.kraaijvanger.nl/media/projects/stadskantoor_utrecht/KRA_DJP_SKU_topview2_m.jpg
2.1	Drawings from Scheldebouw
2.2	http://www.webprodie.nl/userfiles/brandex.nl/E_NEW%20web.jpg
2.3	http://www.webprodie.nl/userfiles/brandex.nl/EW_NEW%20web.jpg
2.4	http://www.webprodie.nl/userfiles/brandex.nl/EI_NEW%20web.jpg
2.5	Made by the author
2.6	Made by the author
2.7	CSR Bradford Insulation Group, *Design guide: fire protection*, P10
2.8	http://www.worldarchitectnews.com/rainbow-architectural-concept-of-sugamo-shinkin-bank/exterior-façade-sugamo-shinkin-bank/
2.9	CSR Bradford Insulation Group, *Design guide: fire protection*, P10
2.10	http://www.shadinglouvres.com/projects/north-west-vista-college-accd/img-north-west-vista-header.png
2.11	http://www.safti.com/images/selector_resist_diagram.jpg
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2.14	Made by the author
2.15	Photograph by the author
2.16	Photograph by the author
2.17	Photograph by the author
2.18	Photograph by the author
3.1	A drawing from Scheldebouw
3.2	A drawing from Scheldebouw
3.3	Exported image of the model made by the author with VOLTRA
3.4	Exported image of the model made by the author with VOLTRA

3.5	Exported image of the model made by the author with VOLTRA
3.6	Exported image of the model made by the author with VOLTRA
3.7	Exported image of the model made by the author with VOLTRA
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4.1	http://www.kraaijvanger.nl/media/projects/stadskantoor_utrecht/KRA_DJP_SKU-ext-laag_m.jpg; http://www.composietgevels.nl/wp-content/uploads/2011/09/dubbel-geveldeel-blog.jpg
4.2	Screenshot of a video from http://www.youtube.com/watch?v=CPWlOAoUM6U; Redrawn by the author
4.3	*Report B.2006.0676.00.R004* from DGMR, P158
4.4	A drawing from Scheldebouw
4.5	Schematic diagrams made by the author
4.6	Schematic diagrams from Scheldebouw
4.7	Schematic diagrams from Scheldebouw
4.8	Image from VOLTRA reedited by the author
4.9	Exported image of the model made by the author with VOLTRA
4.10	Redrawn by the author
4.11	Photograph by the author
4.12	Photograph by the author
4.13	Photograph by the author
4.14	Photograph by the author
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4.19	Exported image of the model made by the author with VOLTRA
4.20	Image from VOLTRA reedited by the author
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4.37	Exported image of the model made by the author with VOLTRA
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5.5	Made by the author
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5.8	Made by the author
5.9	Made by the author
5.10	Made by the author
5.11	Reedited by the author
5.12	Made by the author
5.13	Made by the author
5.14	Made by the author
5.15	Made by the author
5.16	Made by the author
5.17	Photograph by colleagues in Scheldebouw who visited the test
5.18	Photograph by colleagues in Scheldebouw who visited the test
5.19	Made by the author
5.20	Made by the author
5.21	Made by the author

Useful websites

http://www.protectionincendie.com
http://www.crit.archi.fr
http://www.otua.org
http://www.flashover.fr
http://www.bbri.be
http://www.schott.de
http://www.microtherm.uk.com/passive/EXEN/site/eng_firecurves.aspx
http://www.safti.com
http://www.promat.nl

Appendix: Scaled drawings (A2 size)