A multi-scale approach for predicting the fire response of building barriers

Andrés Valiente, Blanca

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

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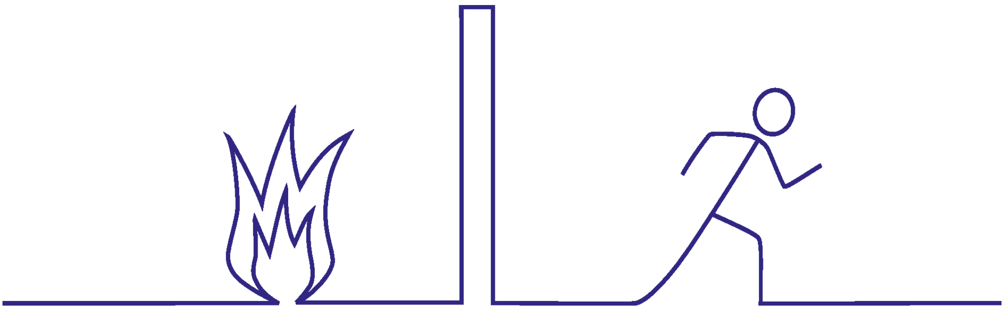
BLANCA ANDRÉS VALIENTE
DIVISION OF FIRE SAFETY ENGINEERING | FACULTY OF ENGINEERING | LUND UNIVERSITY



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Blanca Andres Valiente

DOCTORAL THESIS

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Opponent
Lars Schiøtt Sørensen
Associate Professor
Technical University of Denmark (DTU)

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Abstract

Building barriers are compartmentation elements in buildings that limit the passage of fire and smoke to adjacent spaces. They are key elements in the overall response of a building in a fire. The adequate fire response of building barriers is usually assessed by the fulfilment of standardized resistance to fire tests. However, building fire barriers might be exposed to very different fire scenarios than traditional standardized fire tests.

The work presented in the thesis consists on an experimental and numerical methodology to use the material thermal properties obtained through reduced scale testing to model the fire response of building barriers in larger scales. The methodology is applied to gypsum-stone wool and steel stone-wool layered composites. The characterization of stone wool properties at micro-scale is conducted with thermogravimetric analysis, micro combustion calorimetry and bomb calorimetry. The thermal conductivity of stone wool is obtained with modified slug calorimetry. At a composite scale samples are exposed to different heating exposures using radiant panels (H-TRIS), reduced scale furnace and full-scale furnace. The different heat exposures allow for identifying thermal degradation phenomena. Heat transfer models are developed increasing in complexity to account for the different phenomena. Those include: heat transfer, heat and mass transfer, kinetic reactions to account for the combustion of the organic content of the stone wool, kinetic reaction to account for the calcination reactions in the gypsum and the paper lining burning. An analysis of the uncertainties linked to assumptions in the input parameters for thermal modelling in standard fire tests is also presented. Finally, the degradation of the mechanical properties of gypsum plasterboard in fire are studied by performing three-point bending tests to pre-heated samples.

Key words: Fire, Building Barriers, Heat transfer, Experimental, Gypsum, Stone wool, Furnace, H-TRIS

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Blanca Andres Valiente

LUND UNIVERSITY

Supervisor
Prof. Patrick van Hees, Division of Fire Safety Engineering, Faculty of Engineering, Lund University, Sweden.

Co-supervisor
Dr. Nils Johansson, Division of Fire Safety Engineering, Faculty of Engineering, Lund University, Sweden.

Mr. Dan Lauridsen, Danish Institute of Fire and Security Technology, Hvidovre, Denmark

Opponent
Assoc. Prof. Lars Schiøtt Sørensen, Department of Civil Engineering, Technical University of Denmark.

Examining Committee:
Prof. Elizabeth Weckman, Department of Mechanical and Mechatronics Engineering, University of Waterloo, Canada.

Dr. Deborah Smith, Retired BRE Group Director of Science and Professional Development, BRE Building Research Establishment, UK.

Ass. Prof. Cristian Maluk, Senior Lecturer and Director of Research, The University of Queensland, Australia

Division of Fire Safety Engineering,
Lund University, P.O. Box 118, SE-221 00 Lund, Sweden.

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A great part of the work presented in this thesis was done as a visiting PhD student at Rockwool International and the Edinburgh Fire Research Centre at the University of Edinburgh. I would like to thank Kurt Munk for his support while performing the slug calorimeter tests. I am grateful to Juan P. Hidalgo and Luke Bisby for their support and guidance while performing the H-TRIS tests at the University of Edinburgh. Also thanks to the PhD students and postdocs during my stay, they made my time in Edinburgh very enjoyable.

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Although the work of this thesis is not directly related to my time as a guest researcher at the NFRL at NIST, I would like to show my appreciation as it has influenced me professionally and consequently a part of the work presented herein. I am grateful to Matt Hoehler, Matt Bundy, and Richard Gann for making this possible, and to all the colleagues for their very valuable input in diverse fire research topics.

Last but not least, I would like to thank my family and friends. Thanks for making my life so much fun.

Popular Science Summary

Building fires can be devastating in terms of human loss, asset, and environmental damage. The consequences of a fire in a building are very much dependent on the characteristics of the fire, and the ability of the building to withstand the fire. In the last century, Fire Safety Science and its understandings in fire dynamics, human behaviour in fire, material’s reaction to fire, and structural fire response has led to much safer building designs, saving innumerable human lives and improving buildings resilience. One of the key parameters in the overall fire response of a building is its ability to confine the fire to its room of origin, providing enough egress time for a safe evacuation and protecting the rest of the building from a fire. In this sense, the response of compartmentation elements is fundamental to the consequences of a fire in the building. Compartmentation elements are commonly referred as building barriers and are the boundary elements of a room: roof, walls, floor, and doors.

Building barriers are traditionally subjected to standardized fire tests for classification purposes. Standard fire tests expose construction elements to a temperature-time fire curve, and evaluate the fire response based on the fulfilment of a specific set of measurable outcomes. Commonly, insulation, integrity and stability criteria are evaluated with a pass-fail assessment based on temperature measurements on the unexposed side, gaps opening, and passage of flame and smoke. Standardized fire tests are a useful tool for classification purposes and comparing constructions to the same set of conditions. However, the conditions at which an element is exposed in a compartment fire might greatly differ from the ones in a standard fire test. Thus, a deeper understanding and prediction of the performance of construction elements to different fire exposures requires further analysis of the effect that different fire exposures have to the construction elements.

With the advancement of numerical tools, there is the possibility to model material response in fire. Modelling is a very useful tool, as variations on the materials or fire exposure can be analysed without requiring expensive and polluting tests. Modelling materials fire response, such as heat transfer modelling, are nevertheless complex. Materials undergo a series of degradation processes that affect their properties and integrity. It is common that heat transfer models are developed and fitted to experimental test data. Alternatively prediction methodologies can be based on tests and models developed at smaller scale. This is frequently referred to as a *Multi-Scale Approach.*

In this thesis, a prediction methodology is proposed based on a 'multi-scale' approach. It consists on an experimental and numerical methodology to use the material thermal properties, obtained through reduced scale testing, to model the fire response in larger scales. The methodology is applied to gypsum-stone wool and steel stone-wool layered composites. The characterization of stone wool properties at micro-scale is conducted with thermogravimetric analysis, micro combustion calorimetry and bomb calorimetry. The thermal conductivity of stone wool is obtained with modified slug calorimetry. At a composite-scale samples are exposed to different heating exposures using movable radiant panels (H-TRIS), reduced scale furnace and full-scale furnace. The different heat exposures allow for identifying thermal degradation phenomena such as, dehydration reactions of gypsum plasterboard and combustion of the organic content of the stone wool. Heat transfer models are developed increasing in complexity to account for the different phenomena. Those include: heat transfer, heat and mass transfer, kinetic reactions to account for the combustion of the organic content of the stone wool, kinetic reaction to account for the calcination reactions in the gypsum and the paper lining burning. Results show that the energy being released by the combustion reactions obtained at micro-scale testing are not always directly applicable at larger scale. Yet, a systematic approach for modelling and testing has been proven to be beneficial to understand and model the response of building barriers to heat exposure. An analysis of the uncertainties linked to assumptions in the input parameters for thermal modelling in standard fire tests is also presented. Finally, the degradation of the mechanical properties of gypsum plasterboard in fire are studied by performing three-point bending tests in pre-heated samples. Results showed a slight increase in strength of gypsum plasterboard at 80 °C, and a loss of 90 % of its strength at 300 °C.

The thesis summarizes and discusses the results from six scientific publications, appended to the thesis.

List of Publications

This thesis is a compendium of the work presented in six peer-reviewed publications. The publications are included in Annex A at the end of the thesis. The author's contribution to each of the publications is described in the following table.

Paper I	Andres B. and van Hees P. (2015) "Experimental and thermal analysis of wall assemblies exposed to standard and parametric fires", *Proceedings of the 1st International conference on structural safety under fire & blast (CONFAB 2015)*, Glasgow, 2-4 September 2015. Glasgow: ASRANet, Ltd. ISBN (Electronic): 978-0-9930121-2-9
Paper II	Andres B. and van Hees P. (2016) "Mechanical properties of gypsum plasterboards exposed to standard fires". *Interflam 2016 Proceedings of the 14th International Conference.*4-6 July 2016, Nr Windsor, UK, pp 1051-1062
Paper III	Livkiss K., Andres B., Johansson N. and van Hees P. (2017) "Uncertainties in modelling heat transfer in fire resistance tests: a case study of stone wool sandwich panels", *Fire and Materials 2017;41;799-807.* DOI: 10.1002/fam.2419
Paper IV	Livkiss K., Andres B., Bhargava A. and van Hees P. (2018) "Characterization of stone wool properties for fire engineering calculations", *Journal of Fire Sciences 2018. Vol 36(3) 202-223* DOI: 10.1177/0734904118761818
Paper V	Andres B., Livkiss K., Hidalgo J., van Hees P., Bisby L., Johansson N. and Bhargava A. (2018), "Response of stone wool insulated building barriers under severe heating exposures", *Journal of Fire Sciences 2018. Vol 36(4) 315-341.* DOI: 10.1177/0734904118783942

Paper VI	Andres B., Livkiss K., Bhargava A., and van Hees P. (2021), “Using micro-scale and solid material data for modelling heat transfer in stone wool composites under heat exposures”, *Fire Technology 2021*. DOI: 10.1007/s10694-021-01122-0

PAPER	AUTHOR’S CONTRIBUTION
I	The author assisted in the full-scale and small-scale tests. The author did the background literature study, and numerical modelling. The author wrote the paper.
II	The author developed the test methodology and performed the tests. The author performed the data analysis and wrote the paper.
III	The author did part of the literature study and data analysis. The author performed the functional analysis and wrote part of the paper. The author’s contribution is 50 %
IV	The author contributed in the design of the experimental work and performed some of the experiments. The author did not obtain the kinetic parameters. The author worked partly on the data analysis for thermal conductivity. The author did not write the paper. The author’s contribution is 25%
V	The author did the background study. The author designed the experiments and performed the tests. The author did the data analysis and wrote the paper.
VI	The author did the background and literature study. The author performed the modelling, the data analysis and wrote the paper.

Other publications not included in the thesis

Peer reviewed journal papers

- Andres B., Hoehler M.S. and Bundy M. F. (2019), “Fire resistance of cold-formed steel framed shear walls under various fire scenarios”. *Fire and Materials 2019; 1-13*. DOI: 10.1002/fam2744
- Hoehler M.S., Andres B., Bundy M.F. (2020), “Lateral resistance reduction to cold-formed steel-framed shear walls under various fire scenarios”. *Journal of Structural Engineering-ASCE 2020, 146(5):04020066*. DOI: 10.1061/(ASCE)ST.1943-541X.0002610

International conference papers

- Hoehler M.S. and Andres B., “Influence of fire on the shear capacity of steel sheathed cold-formed steel framed shear walls”. *10th International Conference on Structures in Fire (SiF 2018), Ulster University, Belfast UK, June 2018.*
- Andres B., Hidalgo J.P., Bisby L. and van Hees P., “Experimental analysis of stone wool sandwich composites exposed to constant incident heat fluxes and simulated parametric fires”. *Fire and Materials, San Francisco USA, February 2017.*
- van Hees P., Wahlqvist J., Andres B., Wilkens K., Bhargava A., and Livkiss K., “Analysis of fire barriers with respect to fires with combustible gases and liquids”. *Fire and Materials, San Francisco USA, February 2017.*
- Livkiss K., Andres B., Johansson N. and van Hees P., “Uncertainties in material thermal modelling of fire resistance tests”. *2nd European Symposium of Fire Safety Science, Nicosia Cyprus, 2015.*
- van Hees P., Andersson B., Guay F., Lauridsen D., Barghava A., Livkiss K., Andres B., Vermina Lundstrom F. and Wilkens K. , “Simulation of fire technical properties of products and construction barriers to support efficient product development in industry”. *Interflam, Nr Windsor UK, June 2013.*

List of Abbreviations

ASTM	American Society for Testing and Materials
CFAST	The Consolidated Model of Fire and Smoke Transport
CFD	Computational Fluid Dynamics
CFS	Cold-Formed Steel
DBI	Danish Institute of Fire and Security Technology
DSC	Differential scanning calorimetry
DTG	Differential thermogravimetry
EN	European Standard
EPC	Euclidean Projection Coefficient
ERD	Euclidean Relative Distance
FDS	Fire Dynamics Simulator
G	Gypsum
HRR	Heat Release Rate
H-TRIS	Heat-Transfer Rate Inducing System
ISO	International Organization for Standardization
MCC	Micro combustion calorimetry
NIST	National Institute of Standards and Technology
NFPA	National Fire Protection Association
NFRL	National Fire Research Laboratory
S	Steel
SC	Secant Cosine
SW	Stone Wool
TASEF	Temperature Analysis of Structures Exposed to Fire
TGA	Thermo-gravimetric analysis

List of Symbols

A	Pre-exponential factor (1/s), cross sectional area in Equation 7 (m^2)
c_p	Specific heat (J/kg K)
$c_p{}^m$	Specific heat of stone wool in Equation 7 (J/kg K)
$c_p{}^s$	Specific heat of steel in Equation 7 (J/kg K)
dH	Heat of combustion (kJ/kg)
E	Activation Energy (kJ/kmol)
F	Heating rate (K/s) or Force (N)
h_c	Convective heat transfer coefficient (W/m^2K)
$h_{c_{cold}}$	Convective heat transfer coefficient on the cold side (W/m^2K)
$h_{c_{hot}}$	Convective heat transfer coefficient on the hot side (W/m^2K)
k	Thermal conductivity (W/m K)
l	Thickness (m)
m^m	Mass of stone wool in Equation 7 (kg)
m^s	Mass of steel in Equation 7 (kg)
p_g	Pressure (Pa)
$\dot{q}_c$	Energy release rate due to combustion (kW)
$\dot{q}_l$	Rate of heat lost due to replacement of hot by cold gases (kW)
$\dot{q}''$	Heat flux (kW/m^2)
$\dot{q}''_{in}$	Incident heat flux (kW/m^2)
$\dot{q}''_{net}$	Net heat flux (kW/m^2)
$\dot{q}_r$	Rate of heat lost by radiation (kW)
$\dot{q}''_r$	Radiative heat flux (kW/m^2)
$\dot{q}_w$	Rate of heat lost to compartment boundaries (kW)
Q_{bi}	Energy released by the reaction of the organic content (kW/m^3)
Q_c	Energy released by the calcination reaction (kW/m^3)
Q_p	Energy released by the combustion of the paper (kW/m^3)
$\dot{Q}_{bi}$	Heat released by the reaction per unit volume (W/m^3)
R	Universal gas constant (8.3145 J/mol K)
r_p	Reaction rate (1/s)

t	Time (s)
T	Temperature (K or °C)
$\dot{T}$	Test heating rate (°C/min)
T_{amb}	Ambient temperature (K)
T_f	Temperature of the hot gases (K)
T_{ISO}	Standard fire curve temperature (K)
T_p	Reference Temperature (°C)
T_s	Temperature of the surface (K)
u_g	Velocity of air (m/s)
x	Distance (m)
Y_s	Mass fraction (-)

Greek Symbols

α	Conversion fraction (-) or absorptivity (-)
ρ	Density (kg/m^3)
ε	Strain (-)
ε_s	Surface emissivity (-)
ε_{cold}	Surface emissivity of the cold side (-)
ε_{hot}	Surface emissivity of the hot side (-)
ΔT	Temperature difference (K)
σ	Stefan-Boltzmann Constant (5.67×10^{-8} W/m^2K^4) or stress (N/mm^2)
κ	Permeability (m^2)
μ_g	Viscosity (Pa s)

Table of Contents

1. Introduction

Fire safety engineering is centred on providing fire safe solutions to the design of buildings and structures based on scientific principles (Purkiss and Li, 2013). There are two basic components in ensuring fire safety as regarded by the American National Fire Protection Association *NFPA* (NFPA 550, 2017), on one hand prevention of ignition, on the other hand managing the impact of fire (Figure 1). The fire impact management involves the management of people and property, referred to as manage the exposed in Figure 1, and the control of the fire growth, spread and structural stability, referred to as manage the fire in Figure 1 (Buchanan and Abu, 2016). Traditionally, prescriptive design of buildings provides a series of procedural rules that aim towards safer buildings (e.g. design rules such as maximum area of compartmentation, compliance of standardized tests or distance between emergency exits for evacuation purposes). However, in the last decades the appearance and consolidation of performance based designs has allowed more dynamic solutions for fire design (Hadjisophocleous and Bénichou, 2000). Performance based codes allow designers to set the safety objective, and design in order to achieve this objective based on available tools. Therefore, more versatile designs that serve specific solutions are allowed without compromising the safety of the building inhabitants or rescue activities.

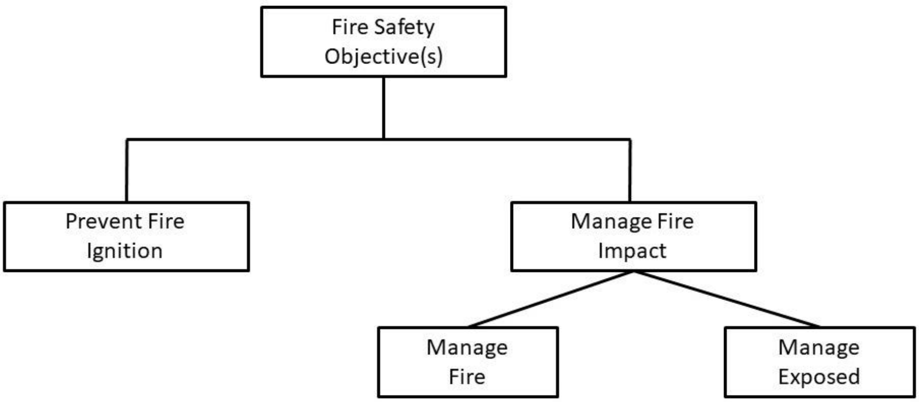


Figure 1: Fire Safety Concept Tree adapted from (Buchanan and Abu, 2016) **and** (NFPA 550, 2017)

1.1 Fire response of building fire barriers

The adequate fire response of buildings is appointed based on the ability of a structure to withstand a fire, firstly providing enough egress time for a safe evacuation of the building, and secondly for a safe fire extinguishment by the fire service, protecting material loss. In this context, compartmentation elements are essential components that limit the spread of fire and smoke between adjacent spaces and provide the necessary time for escape in buildings. These compartmentation elements are commonly referred to as *Building Barriers* or *Building Fire Barriers* in case they hold a certified rating (ISO 13943, 2008). Examples of compartmentation elements are walls, ceilings, floors, doors, etc.

The fire resistance of a building element is defined as the ability to maintain its function when exposed to fire. Thus, the fire resistance of a building barrier is set according to the fulfilment of insulation, stability and integrity requirements (ISO 13943, 2008). Building fire barriers are subject to prescriptive standardized fire tests (for example (ASTM E119-16a, 2016; EN 1363-1, 1999; EN 1363-2, 1999; ISO 834, 1999) in order to obtain a fire rating before being launched into the market. The prescriptive pass/fail testing provides a tangible outcome and a common ground for comparing elements system behaviour under the same exposure. However, it has been largely discussed that standard fire tests do not represent realistic fire exposures (Harmathy, 1972). Whilst compartment fires present a growing, a fully developed and a decay phase in temperature (Buchanan and Abu, 2016; Lie, 2002), standard fires are characterized by a growth in temperature with time. Standard fire exposures may often be regarded as representative, or even as more extreme, than real compartment fires. Yet, in many cases standard fire exposures can lead to conservative outcomes (Kodur *et al.*, 2019) due to lower peak temperatures or the inexistence of a decay phase. It has been reported several times temperature fields measured in real compartment fires with a higher peak temperature than standardized temperature-time exposure (Andres *et al.*, 2019; Buchanan and Abu, 2016; Franssen and Iwankiw, 2016).

Figure 2 provides a schematic representation of the different phases of compartment fires compared to a standard fire (Buchanan and Abu, 2016; Kodur *et al.*, 2019). The temperatures reached in a compartment fire as well as the duration of the fire depend on the characteristics of the compartment, such as dimensions, fuel load, ventilation conditions, enclosure materials. Consequently, it is not possible to define one fire curve that will represent all plausible compartment fires.

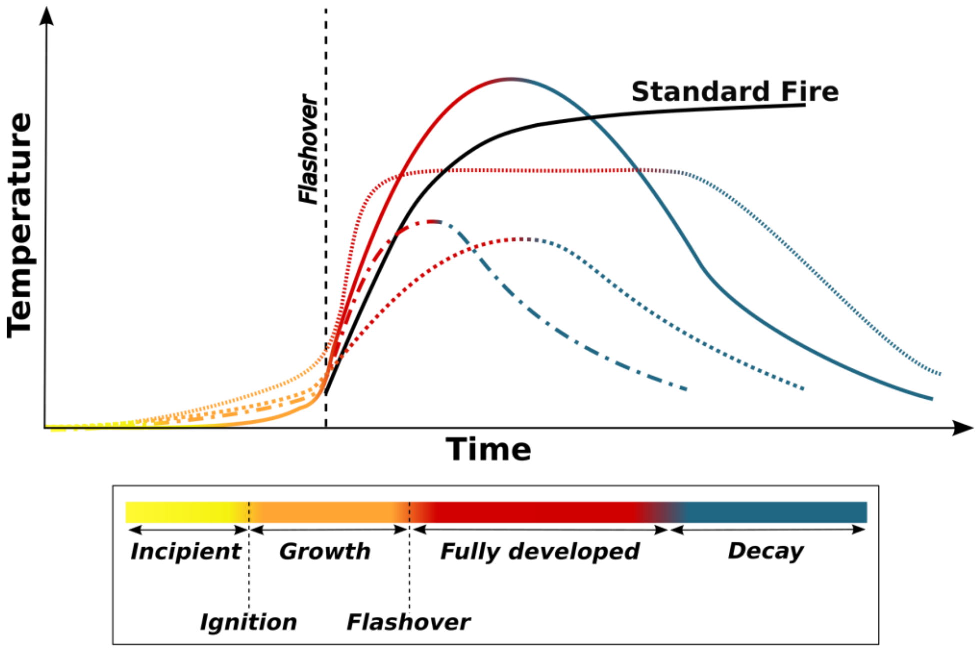


Figure 2: Phases in various hypothetical well-ventilated compartment fire scenarios compared to a standard fire (inspired by (Kodur *et al*., 2019)**)**

To evaluate the fire resistance of building elements it is most relevant to look at the post-flashover phases of the fire (Figure 2). Standard fire test results allows understanding the fire behaviour of a building element under a generic fire exposure, being especially useful when the end use conditions of the building element are unknown. On the other hand, performance based design allows for more realistic design fires based on the specific building characteristics. Tools are available to practitioners to define the design fires to their building elements from simple calculations methods to advanced computational models. Further information on those methods can be found in Section 2.2.

1.2 Modelling the fire response of building fire barriers

Since 1990s until today there has been a growing interest in predicting the behaviour of building fire barriers both in standard fire tests and in more realistic fire scenarios (Craft *et al.*, 2008; Keerthan and Mahendran, 2012; Manzello *et al.*, 2007; Takeda, 2003; Thomas, 1996). Accurate models would provide manufacturers with a tool to pro-actively redesign and improve their constructions before testing. Hence, it would reduce the economic and environmental costs of testing, as well as provide useful tools for the fire safety consultancy community to model the constructions under realistic fire conditions.

By definition, models are a simplified representation of reality. An ideal modelling of the fire behaviour of building barriers would include as accurately as possible all the phenomena that take place when the materials are exposed to heat. A complete approach for the fire response modelling of building barriers would comprise the areas shown in Figure 3 (inspired by (Ramroth *et al.*, 2006)). The figure presents a sequence of four models interconnected. A fire model would represent in this case the exposure or boundary conditions to the element (e.g. design fire or standard fire). A thermal model would mimic the heat transfer through the cross-section of the material/composites. A material model would be defined by the stress-strain relationships as a function of temperature, strength limits and maximum deformations. Creep and thermal expansion will also influence the material response. Finally, a structural model would predict the behaviour as an overall system.

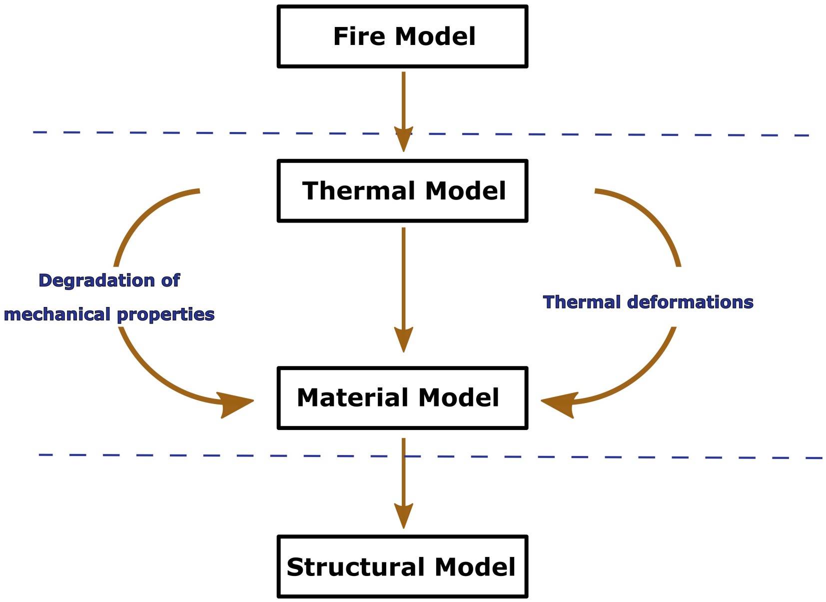


Figure 3: Fire modelling approach for builidng barriers (inspired by (Ramroth *et al.*, 2006)**).**

Albeit computational capabilities have drastically increased in the last decades, prediction methodologies still encounter challenges to model the behaviour of building elements exposed to fire. Modelling the fire behaviour of materials is extremely complex. Materials undergo degradation processes such as physicochemical changes and heat generation-absorption, that are difficult to capture in the numerical models (Kodur and Harmathy, 2002). Thus, the most common approach when modelling fire barriers consists on simple heat transfer models where complex phenomena are simplified by using empirical material properties that lump phenomena together (e.g. using effective thermal conductivity or specific heat to account for moisture transport (Keerthan and Mahendran, 2012)) or empirical considerations (assuming failure of cladding at a set temperature value (Clancy, 2001; Thomas, 1996)). Although these models may predict the temperature rise with reasonable accuracy for the scenarios they were obtained for, they have limited validity for other scenarios (Harmathy, 1983). Besides in many cases prediction methodologies tend to over predict results to ensure certain levels of safety when constructions are modelled instead of tested (Just *et al.*, 2010). While these safety margins are positive to enhance safety in end use applications, it limits its ability to understand and foresee more accurately failure and to support manufacturers in their product development process.

Alternatively to model by fitting empirical material properties to test data, calculation techniques can be based on smaller scale material testing. This methodology can be referred to as *Multi-Scale Approach* or scaling-up approach. The multi-scale approach has been repeatedly used by the fire safety community (Bustamante Valencia, 2009; Camillo, 2013; Marquis *et al*., 2010; Richter and Rein, 2020; Rogaume, 2019; Stoliarov and Li, 2016; Torero, 2013). A multi-scale approach leads to a better understanding of degradation processes when exposed to heat, and can result in prediction methodologies capable of capturing the phenomena materials undergo.

This thesis investigates the use of multi-scale testing and modelling as a tool to develop calculation methods for predicting the fire behaviour of building barriers focusing on heat transfer modelling. Using a *Multi-Scale Approach*, micro-scale testing such as thermogravimetric analysis (TGA), differential scanning calorimetry (DSC) or micro combustion calorimetry (MCC) can provide information about chemical reactions occurring in materials in terms of mass being lost or energy being released or consumed (Ghazi Wakili *et al.*, 2007; Olsen *et al.*, 2013). At slightly larger scale (i.e. few cm²) material properties such as thermal conductivity, density, thermal expansion, can be obtained (Bentz *et al.*, 2006; Ghazi Wakili *et al.*, 2015; Livkiss *et al.*, 2018; Olsen *et al.*, 2013; Rahmanian, 2011). The multi-scale approach is not free from limitations, as for instance when dimensions of the specimens tested increase or materials are placed in contact with other materials behaviours might differ. Examples are combustion reactions occurring or not depending on the availability of oxygen within the material, melting of insulation leaving a radiative cavities inside the assembly, cracking and falling off of claddings. Nevertheless, these limitations may be overcome by systematically testing materials and composites on different scales, increasing specimen dimensions, thus inherent complexities. This would imply involving micro-scales (i.e. few mg), solid material scale (i.e. few cm² samples), intermediate scales (i.e. less than 1 m² composite samples) and large scales (i.e. few m² samples). The full methodology used in this thesis is presented in detail in Chapter 4.

1.3 The Firetools Project

The work presented in this thesis was performed under the umbrella of the Firetools project (van Hees et al., 2013). Firetools was a collaborative project between the Danish Institute of Fire and Security Technology (DBI) and the Division of Fire Safety Engineering at Lund University, funded by the European Union's Seventh Framework program under Marie Skłodowska-Curie actions (Grant no. 316991) and DBI. The aim of the Firetools project was to provide models to predict the fire behaviour of building content, building products and building barriers based on the properties of the materials that compose them, and providing valuable tools to industry and fire practitioners for safer designs of buildings.

Figure 4 shows the scales involved in the Firetools project. The project included strategical testing of materials at micro-scale, material-scale and composite-scale, in order to serve as input data for developing and/or validate models at system-scale. The system-scale includes building content, building products and building barriers. This thesis work focuses on the building barriers and the scales highlighted in Figure 4. A more detailed description of the different scales and the multi-scale approach followed is included in Chapter 4.

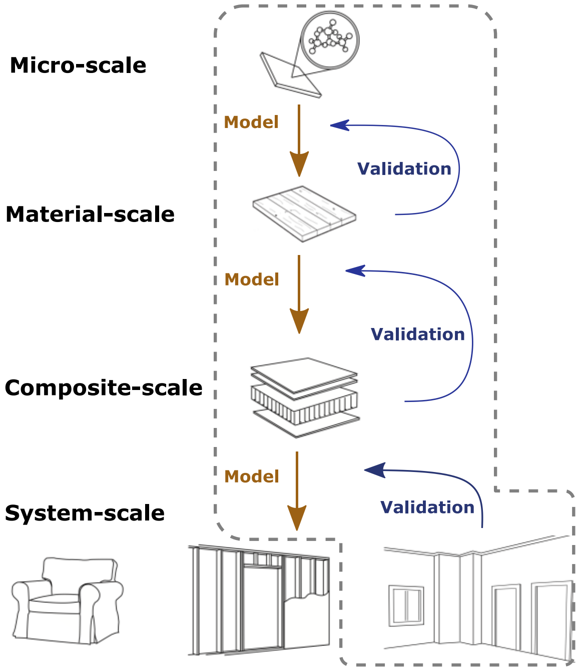


Figure 4: The Firetools project multi-scale approach

2. Theoretical Framework

One of the strategies to reduce the impact of fire in a building is to confine the fire to the room of origin and limit its spread. Compartmentation elements are commonly used to prevent fire spread. Their ability to withstand and confine a fire is referred to as fire resistance. This chapter presents the basics of standard fire resistance testing, it explores the challenges when defining a design fire scenario, and the link between the fire and the boundary exposure. It also presents a state of the art on numerical studies on lightweight gypsum wall assemblies, and identifies the gaps within the field.

2.1 Standard Fire Resistance

Following prescriptive design rules, the fire safety of a compartmentation element is guaranteed by selecting a fire rated element. A fire rated construction has been tested in a certified fire laboratory under a specific set of rules, and the criteria stated in the standard (e.g. (ASTM E119-16a, 2016; EN 1363-1, 1999; EN 1363-2, 1999; ISO 834, 1999) are fulfilled. These criteria are usually in three areas:

- *Thermal Insulation (I)*, the transmission of heat should be restricted. The temperature measured on the unexposed side of the construction is between the specified limits.
- *Integrity (E),* there should not be passage of hot smoke or flames to the unexposed side.
- *Stability (R),* there should not be total or partial collapse of the construction.

In standard fire resistance tests, specimens are placed as one of the boundaries of the furnace. Figure 5 shows an image of a standard fire resistance vertical furnace at the Danish Institute of Fire and Security Technology. The most common standard for fire resistance tests for building and maritime applications are ISO 834 (ISO 834, 1999) and ASTM E119 (ASTM E119, 2016). The specified temperature-time curve from the standard is achieved by heating up the compartment with gas burners. The temperatures to the exposed surface of the specimen are controlled by plate thermometers (Wickström, 1994) in ISO 834, and shielded thermocouples in ASTM

E119. Standard fire resistance tests provide the rating time up to which the construction has fulfilled the criteria (e.g. 60 minutes, 120 minutes).

Figure 5: Image of a Standard Fire Resistance Vertical Furnace at DBI *(Copyright: The Danish Insitute of Fire and Security Technology)*

The dimensions of the furnace limit the size of the specimens that can be tested and thus certified. Furthermore, tests are expensive and polluting. It is also unfeasible to test every construction in its final set-up configuration. In 1965, Harmathy provided a set of ten rules for a quick assessment on variations of the specimen tested (Harmathy, 1965), and they are represented in Figure 6. At present, direct and extended field of applications allow variations on products and/or end use applications from the ones that have been tested in the laboratory (EN 15725, 2010). The variations are based on worst case scenario or interpolation rules, and in some cases need to be consolidated by calculations methods.

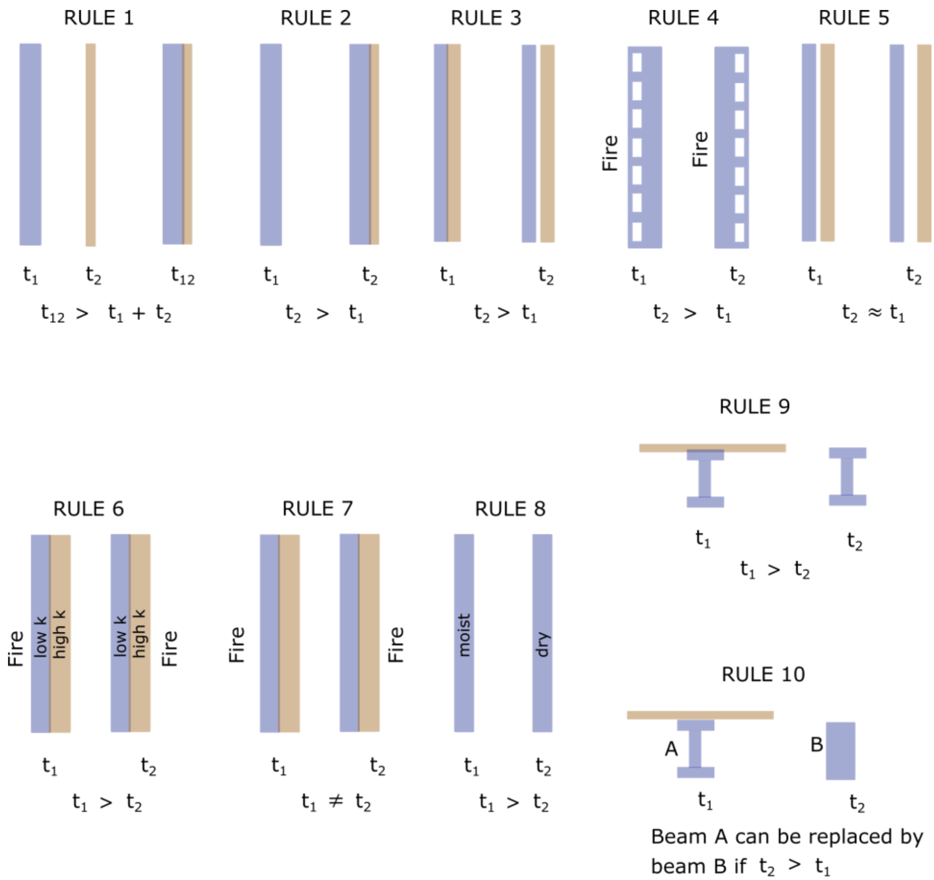


Figure 6: Harmathy's 10 rules of fire endurance rating (adapted from (Harmathy, 1965)**)**

Eurocode EN 1991-1-2 Actions on structures exposed to fires (EN 1991-1-2, 2011) contemplates the possibility of assessing the fire resistance of a construction by numerical calculations or tabulated data. For that purpose, it provides guidance on boundary parameters to consider for defining the exposure, and Eurocodes 2-5 (EN 1992-1-2, 2004; EN 1993-1-2, 2005; EN 1994-1-2, 2005; EN 1995-1-2, 2004) provide material properties input data for analysis and/or simplified calculations methods for concrete, steel, mixed steel-concrete, and timber structures. Often, the input parameters provided in Eurocodes have been calibrated against furnace tests and are interdependent (Zehfuß *et al.*, 2020). This means that the applicability to other fire scenarios, or variation of one of the parameters without further considerations might lead to model miscalculations.

2.2 Design Fires

Moving away from traditional resistance to fire test to performance-based design requires looking into other more realistic fire exposures and conditions. Fire practitioners willing to undertake this path need to define their design fire/s and assess if the project constructions (i.e. compartmentation elements) would behave according to their set objective, ensuring fire safety. One of the many challenges when undertaking a performance-based approach is to define the design fire/s and the exposure to the element.

Fires in compartments are characterized by a growing, a fully developed, and a decay phase (see Figure 2). Pre-flashover fires are looking at the first single items burning, their heat release rate, and how the fire progresses from one item to the next. Pre-flashover phases of the fire are especially important for setting evacuation strategies and ensure life safety. Eventually all the combustible elements in the compartment ignite (flashover) if the fire is large enough. Common assumptions to define flashover are temperature of the smoke layer reaching 500-600 °C (Karlsson and Quintiere, 2000), and heat flux to the floor 20 kW/m^2 (Peacock *et al.*, 1999). When flashover occurs, the room is filled with hot smoke and flames, and it is commonly assumed a uniform gas temperature within the compartment. Post-flashover fires are most relevant for ensuring compartmentation and structural stability. While pre-flashover fires are commonly described by Heat Release Rates (HRR), post-flashover fires are often defined by hot gas temperatures, and the evolution in time of these temperatures. A temperature-time definition of the exposure is easy to measure and to compare with standard fire tests.

Available tools to define design fires vary from simple calculation methods to computer models. Examples of simple calculation methods are parametric fire curves in Eurocode 1-1-2 (EN 1991-1-2, 2011) developed based on the Swedish Fire Curves by Magnusson and Thelandersson (Magnusson and Thelandersson, 1970). Annex A of Eurocode 1-Part 1-2 provide temperature-time curves for fire in compartments with less than 500 m^2 floor area, maximum height 4 m and no openings in the roof. It is assumed that the room fills in with hot gas uniform temperature defined based on:

- the opening factor of the compartment (defined as a relationship between the area of the opening and the total enclosure area)
- the thermal inertia of the compartment boundaries
- the design fire load
- the growth rate of the fire (slow, medium, fast)

Examples of computer models for post-flashover fires are single-zone models. Single zone models consider that hot gases in the room are well-mixed and thus there is a uniform gas temperature inside the compartment. They base their calculations in conservation of energy. In single zone models it is assumed that all the combustion takes place inside the compartment, and conservation equations are solved to obtain hot gas temperature. The heat balance is shown in equation 1. It includes the heat being produced by combustion of the fuel ($\dot{q}_c$), heat losses due to replacement of hot and cold gases($\dot{q}_l$), radiative ($\dot{q}_r$) heat losses through openings, and heat losses through the boundaries($\dot{q}_w$) . Figure 7 shows the terms involved in the heat balance.

$$\dot{q}_c = \dot{q}_l + \dot{q}_r + \dot{q}_w \quad (1)$$

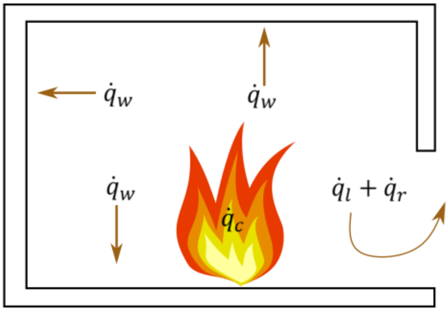


Figure 7: Heat balance in a well-mixed compartment fire (inspired by (Karlsson and Quintiere, 2000)**)**

Most single-zone models are traditionally two zone-models that can be used as single zone model or well-mixed. Examples are Ozone (Cadorin *et al.*, 2001), CFAST (Peacock *et al.*, 2015), Argos (Deibjerg *et al.*, 2003). An older post-flashover computer model is COMPF2 by Babrauskas (1979).

Advanced computational fluid dynamics (CFD) field models such as Fire Dynamics Simulator (FDS) (McGrattan *et al*., 2004) can also be used to predict post-flashover fires. However, their predictions are not as good for post-flashover fires as for pre-flashover fires (Buchanan and Abu, 2016; Pope and Bailey, 2006). Among others, it is difficult to capture the effect of air vitiation and re-radiation in the fire dynamics of post-flashover fires with enough resolution to be computationally feasible.

In modern open plan spaces, compartments can be so large that flashover and fully developed fire may not occur. Thus, in these cases the post-flashover uniform temperature assumption is no longer valid, instead the fire spreads between different combustibles in the compartment creating areas of higher and lower temperature exposures. These design fires are known as travelling fires (Stern-Gottfried and Rein, 2012a, 2012b). Travelling fires have been validated by analytical methods (Rackauskaite *et al.*, 2015) and CFD models (Anderson *et al.*, 2020).

Once the evolution of temperature-time of the hot gas layer is defined, the heat transfer through the boundary of the compartment and/or structural stability is the following step. The hot layer gas temperature needs to be translated into an exposure boundary. This requires a definition of the heat flux to the exposed surface by convective and radiative heat flux. Equation 2 depicts the heat flux to a boundary surface assuming negligible the contributions of the surroundings (Lattimer, 2016).

$$\dot{q}''_{net} = h_c\left(T_f - T_s\right) + \varepsilon_s \dot{q}''_r - \varepsilon_s \sigma T_s^4 \qquad (2)$$

The first term accounts for the convective heat flux, the second for the radiative heat flux to the surface ($\dot{q}''_r$), and the third term for the radiation losses from the exposed surface. h_c is the convective heat transfer coefficient, T_f is the temperature of the hot gases, T_s is the temperature of the surface, ε_s is the emissivity of the surface, and σ is the Stefan-Boltzmann constant. Despite the heat transfer coefficient and emissivity of materials being temperature dependent, frequently those values are assumed as constant, introducing uncertainty in calculations.

2.2.1 Fire severity and comparisons between fires.

The most common way of assessing the fire safe performance of a construction element is through standard fire testing. However, more and more, design fire scenarios are being used. Occasions in which the fire resistance is assessed under several fire scenarios are rare. Sometimes it might be important to look at several scenarios because it is difficult to foresee the most critical scenario. Further, there could be cases where it is valuable to have a wider spectrum of applications and risks taken into account, not only the worst case scenario (Andres *et al.*, 2019).

The severity of a fire can be defined as the measure of the destructive potential of a fire to an element (Buchanan and Abu, 2016). However, it is unclear how to compare the severity between fires. Ingberg (1928) proposed that the severity of the fire could be related to the fire resistance requirements comparing the area under the temperature-time curve above the 150 °C and 300 °C threshold (Drysdale, 1999), equal areas would mean equal fire severities. Comparing the area under the temperature-time curve might be insufficient to define the severity. For instance, a maximum temperature in a shorter period of time could be more demanding for certain types of structures. The fact that the radiative heat flux is a function of T^4 results in much larger radiative heat fluxes if the temperatures are higher. Other parameters such as ventilation conditions (Law, 1971) and the thermal inertia of the boundaries (Harmathy and Mehaffey, 1982) also influence the severity of the fire. Another possible way of comparing the fire severity is to relate it to the temperatures that would be reached in a protected steel member (Buchanan and Abu, 2016; CIB, 1986; Law, 1997)

2.3 Case study – fire response of gypsum wall assemblies

Lightweight gypsum assemblies are widely used in building constructions as building barriers. They are usually composed of one or several layers of gypsum plasterboard on each side, cold-formed steel or wood studs with a cavity between the boards that in some cases it is filled in with insulation (e.g. stone wool or glass wool insulation). Figure 8 shows the components on a lightweight gypsum plasterboard wall. Parameters affecting the fire behaviour of these assemblies are, among others, the number of gypsum board layers, the type of gypsum plasterboard (composition, thickness), the spacing between the studs, the type of jointing, the insulation or lack of insulation and the framing system. The most common degradation processes (Buchanan and Abu, 2016; Rahmanian, 2011) leading to failure in a fire event are:

- Heat transfer and failure due to insulation criteria.
- Gypsum shrinkage and consequent opening of joints, exposing the rest of the cross-section to an increased heat wave. In the case of wood studs, wood can start charring and the insulation may melt or shrink creating a cavity, and radiation to the exposed board may occur. In case of cold formed steel framing, the studs might create thermal paths and deform.
- Gypsum plasterboard crack exposing the rest of the structure to similar conditions than above.
- If simultaneous cracking appears it might lead to parts of the gypsum plasterboard to fall off.

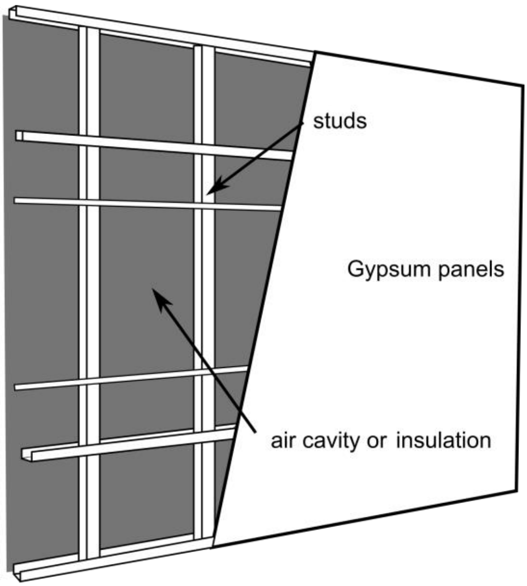


Figure 8: Components of a lightweight gypsum wall assembly

There have been numerous modelling attempts in the literature to predict the failure of gypsum building barriers exposed to fire. This section does not aim to present each of them, instead to give an overview of the initial efforts and achievements, in order to point out the steps ahead into designing better prediction methodologies.

One of the first models found in the literature dates from 1987, where Gammon (1987) presented a finite element model for loaded lightweight cavity assemblies exposed to standard fire. From mid 1990s until early 2000s numerous models were developed (Bénichou and Sultan, 2000; Benichou and Sultan, 1999). Modelling attempts started with cavity walls, without considering radiation and convection in the cavities (Collier, 1996), and then implementing them as vacuum or as fictitious material (Thomas, 1996)) using heat transfer software available (TASEF (Sterner and Wickström, 1990)). The complexity of the models would build up by including the degradation of the mechanical properties of the wood as a function of the temperature, or considering that after a temperature threshold the gypsum plasterboard covering would not be in place any longer. Köning and Walleij (1987) modelled insulated cavities with stone wool or glass wool, and included also the effect of moisture in the mechanical properties by applying reduction factors. Thermal properties were calibrated in order to account for mass transfer, heat generation, gypsum cracking or fall-off. WALL2D by Takeda and Mehaffey (1998) included the shrinkage of the gypsum, and further extended to WALL2DN (Takeda, 2003) for insulated walls including the shrinkage and melting of the insulation, opening of joints due to shrinkage and internal heat change due to water vaporization of wood and gypsum board. ADIDRAS built by Clancy to model heat transfer including opening of gaps, moisture effect and falling off (all considered by empirical parameters) (Clancy, 2001) and then linked to FIREFRAME (Young, 2000; Young and Clancy, 2001) for the structural response. Pohl and Clancy also developed an easy to use program to help practitioners do their own estimations of the fire resistance of their walls (Pohl and Clancy, 2000).

The main difference between modelling assemblies with wood or cold formed steel studs, is that wood studs can burn and contribute to the fire, whereas cold formed steel studs do not. A common approach when modelling heat transfer lightweight assemblies with cold-formed steel stud has been to disregard the steel (Batista Abreu *et al.*, 2014). Nevertheless, steel can behave as a thermal bridge between the hot exposed side and the cold unexposed side, especially if joints open.

The modelling efforts highlight the importance of considering certain phenomena occurring, such as effect of moisture in the construction, opening of gaps, re-entrant corners, charring of the wood, falling off of gypsum. These phenomena are usually taken into account by empirical considerations. For load bearing assemblies it is also a common approach to consider that the load is mainly carried out by the stud. Hence, the thermo-mechanical analysis is reduced to only the structural elements, and the contribution of gypsum plasterboard is disregarded. However, often gypsum partitions are non-loaded. A great contribution to the fire resistance of loaded and non-loaded assemblies is the ability of the gypsum plasterboard to stay in place, which is directly linked to the loss of mechanical properties. Nevertheless, the thermo-mechanical behaviour of gypsum plasterboards has been largely disregarded in previous studies. Furthermore, although different software should provide the same modelling output when the same principles are applied, Thomas (2010) showed how the same construction modelled with TASEF (Sterner and Wickström, 1990) and SAFIR® (Franssen *et al.*, 2000) provided different results because they differ in the way the convective heat transfer is considered.

Other modelling attempts have included mass transfer to account for evaporation cycles (Craft *et al.*, 2008; Weber, 2012) and dehydration reactions of gypsum plasterboards using reaction kinetics (Kolaitis and Founti, 2013; Kukuck, 2009). Kolaitis and Founti (2013) model the effect of moisture in a cavity using CFD simulations. Do et al. (2013) developed a computational non-linear thermo-mechanical model that combine heat transfer with a probabilistic model based on experiments to account for the effect of panels and stud attachment.

One of the biggest challenges in modelling the behaviour of building barriers is obtaining appropriate material properties at elevated temperatures. Further, only few modelling attempts have been validated against different fires (Shahbazian and Wang, 2014).

2.4 Research gaps

Based on the background description presented above, the following research gaps have been identified:

- The majority of the models found in the literature use fitted material thermal properties as input. Thus, the prediction of the models is intrinsically dependent on the test.
- Most of the models in the literature are validated only against standard temperature-time exposure.
- There are limited tests performed to building barriers in other fire scenarios than the standard fire curve. Hence, it is largely unknown the response in realistic fire conditions with a cooling phase compared to standard furnace exposures.
- Modelling building barriers using thermal properties and internal reactions of materials as input parameters has not been investigated in depth.
- There is a knowledge gap about the link between the thermal degradation and the mechanical degradation of materials.
- The contribution of gypsum thermo-mechanical behaviour in the thermal response of gypsum in lightweight fire barriers is largely disregarded.

In the following chapter the objectives of the thesis in relation to the identified research gaps are presented.

3. Research objectives

The overall objective of the work included in this thesis is to implement a multi-scale methodology to understand and model the behaviour of building barriers subject to different types of fire exposures. The methodology is based on employing material properties obtained at small-scales. For that purpose, a set of sub-objectives has been defined:

Sub-objective 1: To identify the similarities and differences in the response of the selected building barriers to different fire exposures, comparing standard furnace tests to alternative fire scenarios.

Sub-objective 2: To identify the main phenomena to be considered in modelling the fire response of the selected building barriers, and obtain the material properties needed to improve current modelling capabilities.

Sub-objective 3: To develop engineering heat transfer models using a multi-scale approach to predict the behaviour of the selected building barriers under different heat exposures.

Sub-objective 4: To develop a simple method to analyse uncertainties linked to modelling assumptions in modelling of standard fire tests, concerning the studied building barriers.

Each of the sub-objectives is further discussed in Chapter 5 together with the outcome of the publications.

3.1 Overview of publications

This thesis is a compendium of six publications. Figure 9 shows how each of the publications relates to each of the sub-objectives. The titles of the publications are:

- Paper I: Experimental and thermal analysis of wall assemblies exposed to standard and parametric fires (Andres and van Hees, 2015).
- Paper II: Mechanical properties of gypsum plasterboards exposed to standard fires. (Andres and van Hees, 2016)
- Paper III: Uncertainties in modelling heat transfer in fire resistance tests: a case study of stone wool sandwich panels (Livkiss *et al.*, 2017)
- Paper IV: Characterization of stone wool properties for fire engineering calculations (Livkiss *et al.*, 2018)
- Paper V: Response of stone wool insulated building barriers under severe heating exposures (Andres *et al.*, 2018)
- Paper VI: Using micro-scale and solid material data for modelling heat transfer in stone wool composites under heat exposures. (Andres *et al.*, 2021)

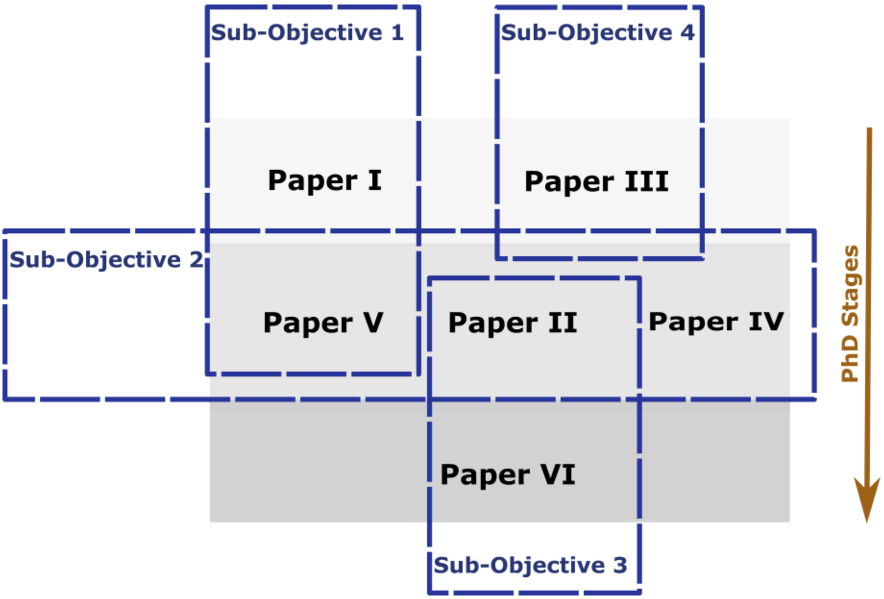


Figure 9: Diagram linking the publications to the research objectives

Paper I and Paper III correspond to the early stages of the PhD investigation. Paper II, Paper IV and Paper V correspond to intermediate stages of the PhD. Finally, Paper VI is the last publication and corresponds to the latest state of the PhD research. An introduction to each of the papers is included in Chapter 5, as well as a presentation of the results linking to the objectives.

3.2 Delimitations and limitations

The experimental and numerical analysis performed in this thesis involve only the following typologies of building barriers:

- Gypsum plasterboard cavity walls
- Gypsum plasterboard with insulation cavity:
    - Glass-wool insulation
    - Stone-wool insulation
- Steel-stone wool sandwich composites

These types of building barriers are extensively used in residential, office, industrial and commercial buildings (Andres *et al.*, 2019), being that the main motivation to be the focus of the study. Typical cross-sections of a lightweight gypsum wall assembly are composed of steel or wood studding, gypsum panels as claddings and an air cavity or insulation in the cavity.

The experimental analysis conducted is limited to the size of the specimens and the testing conditions. Most of the experimental work is performed to small-scale specimens. The deformations of the specimen tested depend in great measure on the size of the specimens. Larger specimens might have larger stresses that lead to bigger deflections and/or cracking of materials increasing the heat being transferred through the section. Also, outcomes in terms of measurements in tests are limited to the uncertainties and accuracy of the test methods.

Ideal modelling would include all the phenomena taking place in the materials. The complexity of such a modelling is currently not feasible, due to the difficulty to understand and capture certain phenomena. The numerical modelling included in the thesis is mainly one-dimensional heat transfer, in order to implement straightforward methodology that does not require excessive computational time. The one-dimensional assumption has been validated through experimental data or through sensitivity of the model. Two-dimensional modelling was used in the initial modelling to identify limitations in current modelling capabilities, and to validate the one-dimensional hypothesis. The data used for the modelling has either been obtained within the Firetools project, or retrieved from literature. Future recommendations include a three-dimensional analysis linked with the thermo-mechanical degradation of material properties as presented in the thesis.

4. Methodology

4.1 The Multi-Scale Methodology in Firetools

The Firetools Project overall goal was to provide modelling tools to bridge the gaps between fire testing and modelling, providing useful tools to industry and fire safety community. The methodology consists in predicting the behaviour at increasing scales from micro-scale to large-scale systems. Figure 10 shows a schematic representation of the modelling procedure followed in the Firetools project. In first place, the thermo-chemical reactions are identified, modelled and validated at micro-scale. Once validated, they are implemented at an intermediate scale for single materials, and then as composites. The methodology combines modelling and optimization based on physical assumptions drawn from the experimental work.

The different scales involved in the Firetools project are (Figure 4):

- **Micro-scale**: involving materials in the size of milligrams. The amount of material is small enough that only the thermochemistry of the material is at scope, assuming there is not heat transfer within the volume of material selected. Examples of micro-scale testing are TGA, Bomb Calorimetry, MCC, DSC.
- **Material-scale**: involving materials in the size of few squared centimetres. The size of the materials-scale allows for obtaining material properties and validate micro-scale modelling. Examples of these testing are cone-calorimeter, slug-calorimetry, heat flow meter.
- **Composite-scale**: involving layered composite materials or blended composite materials. The size varies from few cm^2 to few m^2. In Figure 10 the intermediate scale represents both the material-scale and composite-scale.
- **System-scale**: In the Firetools project the system-scale term refers to end use products as they appear in the building environment. Those are building content, building products and building barriers. Building content refers to movable elements within the building such as furniture, or electronic goods, building products were building elements from the reaction to fire perspective, and building barriers refer to compartmentation elements. In this thesis system-scale, full-scale and large-scale are used as synonyms.

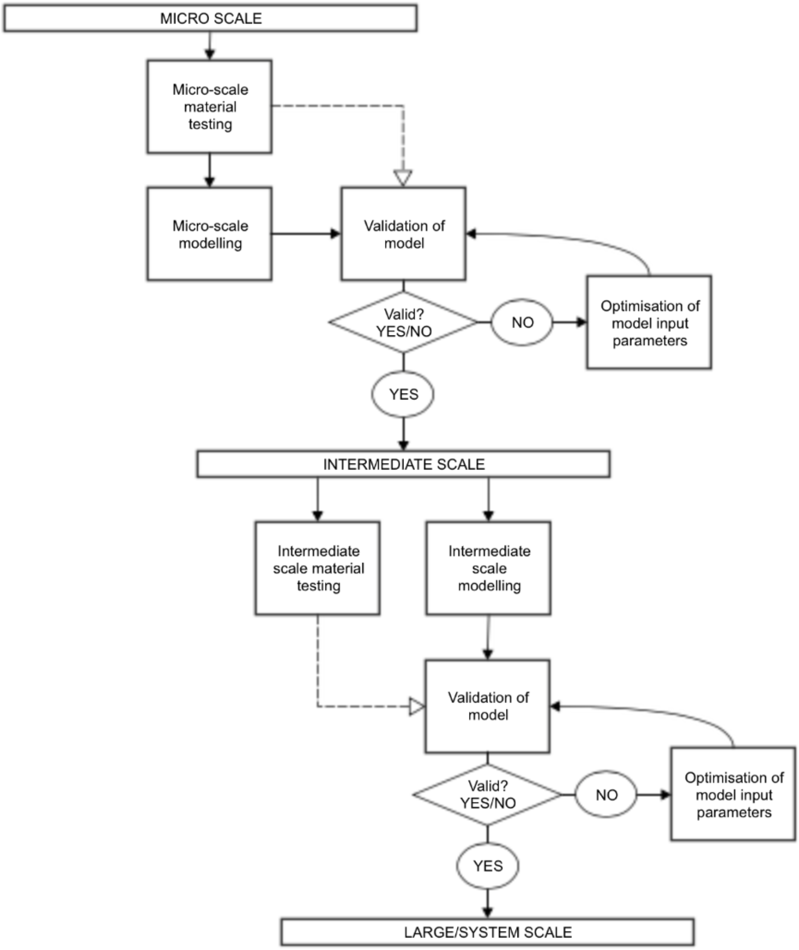


Figure 10: Flowchart of the modelling and validation approach in the Firetools project

4.2 The Multi-Scale Methodology for Building Barriers

The multi-scale approach for building barriers followed involves the different scales shown in Figure 4, and highlighted with a dotted line. The focus of the work included in this thesis consists of providing a methodology based on which model the thermal response of larger scale composite constructions under different heating conditions, based on material properties at reduced scale. However, a full approach to model building barriers should include as well thermo-mechanical response, deformations and material degradation. Within this thesis, thermal models are implemented and validated at all scales (Section 4.3), and the basis for coupling the thermal and thermo-mechanical models are provided (Section 4.4) , however extra effort is required to implement the coupled models. Figure 11 presents a summary of the experiments and modelling work at each of the scales included in this thesis. Additionally, a methodology to quantify the uncertainties linked to the assumptions in thermal modelling of standard tests is presented (Section 4.5).

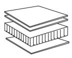
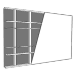
	Test	Objective	Test conditions	Model
Micro-scale 	TGA, MCC Bomb Calorimetry to stone wool	Reactions occurring in stone wool	5,10, 20 K/min for TGA Air and nitrogen for TGA 1 K/s in air for MCC	Energy from reactions
Material-scale 	Modified Slug Calorimetry to stone wool	Thermal properties of stone wool	5,15 K/min	Heat-transfer
	3 point bending to gypsum	stress-strain at high temperatures	24°C, 80 °C, 180°C, 200°C, 300°C, 400°C, 500°C Standard fire curve	Material thermo-mechanical model
Composite-scale 	Phase I- Composite Steel- Stone wool sandwich S-SW-S	SW response in composte	Low incident heat flux 7kW/m^2 High incident heat flux 60 kW/m^2	Heat-transfer Heat and mass transfer Energy from reactions
	Phase II- Composite Gypsum- Stone wool sandwich G-SW-G	Other phenomena: burning of paper lining moisture movement evaporation-condensation	Low incident heat flux 7kW/m^2 High incident heat flux 60 kW/m^2	Heat-transfer Heat and mass transfer Energy from reactions
	Phase III- Composite S-SW-S SW-S G-SW-G	Identify the phenomena in complex variable heat exposures	Standard fire curve Variable incident heat flux	Heat-transfer Heat and mass transfer Energy from reactions
System-scale 	Phase IV- Full Scale G-SW-G	Full scale system behaviour, effect of joints, thermal bowing, cracking of boards	Standard fire curve	Heat-transfer Heat and mass transfer Energy from reactions

Figure 11: Experimental and modelling work at each of the scales.

4.3 Thermal Modelling

This section presents a summary of the experimental and modelling work in each of the identified scales related to thermal modelling. Further details can be found in the appended publications.

4.3.1 Micro-scale

Micro-scale analysis was performed to stone wool. It includes thermogravimetric analysis (TGA), micro-combustion calorimetry (MCC), and Bomb Calorimetry to retrieve thermo-chemistry of stone wool. From this data, chemical kinetic parameters and heat of combustion were obtained.

Micro-scale testing

- **Thermogravimetric analysis (TGA)** (ASTM E1131-08, 2014)**:** is a thermal analysis method in which the variation of mass is measured while the sample is heated at a constant rate. Thus, TGA analysis provides the rate of change in mass as a function of temperature (or as a function of time at constant temperature) and can be used to obtain reaction rates. The samples used for TGA analysis should be small enough that it can be assumed there is no thermal gradient within the sample and thus heat transfer and reaction kinetics can be decoupled.

  TGA analysis was used to identify the thermal degradation reactions occurring in stone wool linked to the combustion of its organic content. Samples mass were between 5 and 10 mg, heating rates were 5,10 and 20 K/min, and tests were performed in air and nitrogen atmospheres (Andres *et al.*, 2017; Livkiss *et al.*, 2018). Additionally, simultaneous TGA with Differential Scanning Calorimetry (TGA-DSC) (ASTM D3418-15, 2015) was performed to one of the samples to evaluate if the reactions occurring were endothermic or exothermic. Figure 12 shows the TGA/DSC testing apparatus used in some of the tests.

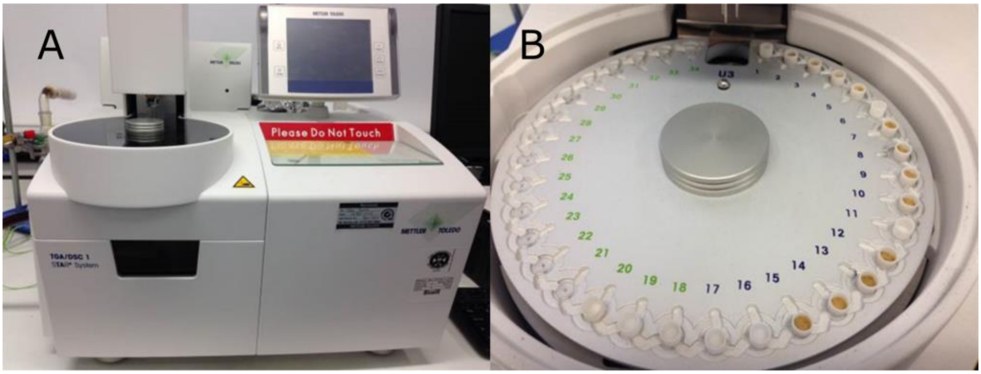


Figure 12: (A) METTLER-TOLEDO TGA/DSC 1 apparatus, (B) Stone wool samples prepared for testing.

- **Micro-combustion calorimetry (MCC)** (ASTM D7309-11, 2011; Lyon and Walters, 2002; Lyon *at al.*, 2013) is a method to measure the heat release rate (HRR) of milligram samples of materials by oxygen consumption calorimetry. It consists of two chambers. In the first chamber samples are heated up. In the second chamber the pyrolysis gases are mixed with oxygen and combusted. Samples were heated up at 1 K/s rate up to 600 °C in air atmosphere. MCC was used as an alternative to TGA to study the reaction kinetics of stone wool, and to obtain the net heat of combustion.

- **Bomb Calorimetry** (ISO 1716, 2010) is a constant volume calorimetry used to measure the total heat of combustion. Samples of approximately 1 g are combusted under a 30 bar pressure in pure oxygen. The energy released is based on the increase in temperature in a water vessel around the sample container. Bomb calorimetry was used to obtain the total heat of combustion of stone wool samples.

<u>Micro-scale modelling</u>

From the TGA test data in nitrogen atmosphere to stone wool one peak is observed between 250-350 °C in the mass loss curves. In the TGA and MCC test data in air atmospheres two peaks are observed in the mass loss and HRR curves respectively, the first one occurring between 250-350 °C and the second between 400-500 °C. The first peak is likely due to the pyrolysis of the organic content of the stone wool, and the second could be linked to the oxidation of the organic content residue.

The parameters characterizing the reaction of the organic content of the stone wool can be obtained from TGA (and MCC) test results. Within this thesis framework, the kinetic parameters used for modelling were obtained by Livkiss (Livkiss *et al.*, 2018) using Fire Dynamics Simulator (FDS)(McGrattan *et al.*, 2004). The equations used in FDS are:

$$E_{i,1} = \frac{er_{p,i}}{Y_{s,i}(0)} \frac{RT_{p,i}^2}{\dot{T}} \tag{3}$$

$$A_{i,1} = \frac{er_{p,i}}{Y_{s,i}(0)} EXP\left(\frac{E}{RT_{p,i}}\right) \tag{4}$$

Where E is the activation energy (kJ/kmol), A is the pre-exponential factor (-/s), T_p is the reference temperature (K), r_p is the reaction rate (-/s), $Y_s(0)$ is the mass fraction of the material undergoing the reaction, $\dot{T}$ is the test heating rate during the micro scale test (K/s), R is the universal gas constant (8.3145 J/(mol.K)), and the subscript i refer to the material component number.

The exothermic reaction occurring in the stone wool can then be defined using Arrhenius formulation as in equation 5, and the energy released in the reaction as equation 6:

$$\frac{d\alpha_i}{dt} = \alpha_i A_i e^{-E_{a_i}/RT} \tag{5}$$

$$Q_{bi} = dH_i \frac{d\alpha_i}{dt} \rho_{SW} \tag{6}$$

Being α the conversion fraction of the reaction, defined as the mass percentage of the reactants that varies between one and zero, and $\frac{d\alpha}{dt}$ the rate of conversion of rate of reaction.

4.3.2 Material-scale

At a material scale, the solid material properties fundamental for heat transfer modelling need to be defined. This includes thermal conductivity, specific heat, and density. The reactions identified at micro-scale are included in the one-dimensional heat transfer model in stone wool.

Material-scale testing

- **Modified Slug Calorimetry** is a transient methodology used to obtain the thermal conductivity of materials at elevated temperatures. Originally was used for fire resistive materials, and was developed by Bentz *et al.* (2006; 2007; 2008). It consists on placing two samples of the material sandwiched between two retaining plates and inside an oven. In the middle, between the two samples a slug with a thermocouple attached is placed to monitor the temperature evolution. Figure 13 shows the experimental set-up. The differences between the original method and the one used in the study are the area exposed, the thickness of the slug and the number of thermocouples used. The thermal conductivity (k) is obtained through inverse heat transfer calculation based on the temperature difference between the retaining plates and slug. The applied formula is:

$$k = \frac{Fl(m^s c_p^s + m^m c_p^m)}{2A\Delta T} \tag{7}$$

Where F is the heating rate (K/s), l is the specimen thickness (m), $c_p{}^s$ and $c_p{}^m$ are the specific heats at constant pressure for slug and stone wool, respectively (J/kg K), m^s and m^m are the mass of the slug and stone wool respectively (kg), A is the cross sectional area of the slug, and ΔT is the difference between the retaining plate and the slug temperature (K).

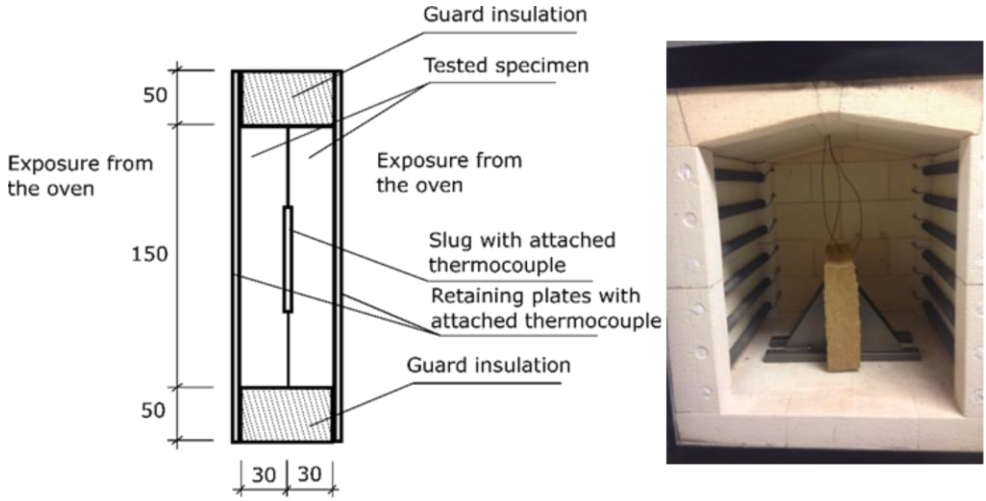


Figure 13: Modified slug calorimetry test set-up (Livkiss *et al.*, 2018)

The slug calorimetry methodology was used to determine the thermal conductivity of stone wool. Two heat cycles were applied. In the first cycle the sample was heated up to 600 °C temperature to combust the organic content, and the second cycle was used to derive the thermal conductivity values. The first cycle was then used to validate the energy due to the combustion of the organic content within the stone wool. Once the hypothesis were validated at solid material data scale, they were used to model composite scale.

Material-scale modelling

In order to validate the data obtained, one-dimensional transient heat conduction to the stone wool was modelled based on the heat conduction equation, including the heat being generated by the combustion of the organic content (Equation 8).

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + \dot{Q}_{bi} \quad (8)$$

where T is temperature (K), t is time (s), ρ is the density (kg/m^3), c_p is the specific heat (J/kg·K), k is thermal conductivity (W/m·K), and $\dot{Q}_{bi}$ ($\frac{W}{m^3}$) is the heat generated by the combustion of the organic content of the stone wool (from equation 6).

4.3.3 Composite and system full-scale

Figure 11 shows a summary of the experimental methodology followed to identify phenomena occurring in composites. At a composite-scale, it involved testing Steel-Stone Wool-Steel (S-SW-S) composites at a constant low (7 kW/m^2) and high (60 kW/m^2) heat flux exposure to identify if the reaction of the organic content, observed in the slug calorimetry, would also occur when having a steel shield. Gypsum- Stone Wool- Gypsum (G-SW-G) composites to identify other phenomena occurring in the gypsum, such as paper burning, moisture movement and/or evaporation condensation cycles. Finally, composite-scale tests with variable heat exposures to identify if the phenomena could also be seen in complex variable exposures in a reduced scale. It included variable heat flux exposures and standard temperature-time curve. These tests serve also as validation for the models developed under different heat exposures. At full-scale, tests were performed to G-SW-G wall assembly to compare with the reduced scale test data and validate model.

<u>Composite and full-scale testing</u>

- **Heat-Transfer Rate Inducing System (H-TRIS)** (Maluk *et al.*, 2016) is a testing methodology consisting in four propane-fired radiant panels placed on a linear motion system. The specimen is subjected to a radiative incident heat flux dependent on the distance between the panels and the exposed surface. Thus, any time variable radiative heat exposure can be applied only limited by the minimum distance to the specimen and the type and size of the radiant panels. The H-TRIS methodology was used to expose S-SW-S and G-SW-G composite to constant (7 kW/m^2, and 60 kW/m^2), and variable incident heat fluxes. Figure 14 shows an image of the H-TRIS set-up.

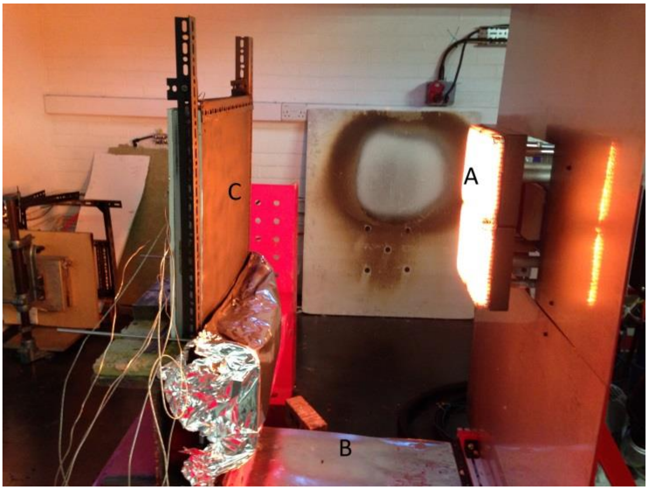


Figure 14: The Heat-Trasfer Rate Inducing System: (A) radiant panel, (B) motion system, (C) tested specimen.

- **Mid-scale furnace** used is a propane gas fired furnace of dimensions 1.46 × 1.46 × 1.5 m^3. Four plate thermocouples control the furnace temperatures. A concrete frame allows testing four specimens of 500 mm^2 at the same time. S-SW-S and G-SW-G composites of dimension 500 × 500 mm^2 were tested in this furnace under standard temperature-time fire curve. Figure 15 shows an image of the mid-scale furnace at DBI.

Figure 15: Mid-scale furnace at DBI *(Copyright: The Danish Insitute of Fire and Security Technology)*

- **Large scale furnace** used (Figure 5) has dimensions 3.2 × 3.2 × 1.5 m^3. It is lined with two layers of fire bricks. The temperature inside the furnace is achieved by 12 propane gas burners located in the wall, each burner has a power of 210 kW. The temperature inside the furnace is controlled by 16 plate thermocouples following the standard temperature-time fire curve.

Composite and full-scale modelling

- **Heat transfer modelling**

  The heat transfer was modelled as transient one or two dimensional heat conduction. Materials were regarded as solids and there was no consideration of porosity and convective heat transfer through the media. Equation 9 shows the heat conduction equation, where T is temperature (K), t is time (s), ρ is the density (kg/m^3), c_p is the specific heat (J/kg·K) and k is thermal conductivity (W/m·K). The models were developed in COMSOL Multiphysics® (COMSOL Multiphysics, 2018)

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) \quad (9)$$

  Figure 16 shows a schematic representation of the boundary conditions for the heat transfer, where the exposed side is referred to as 'hot', whereas the unexposed side as 'cold'.

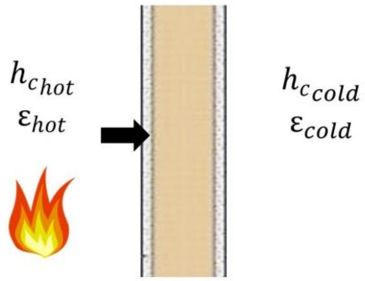


Figure 16: Boundary conditions for modelling purposes

For modelling furnace tests, the boundary conditions are represented as radiative and convective boundaries, following equations 10-11. The exposure temperature (T_{ISO}) is assumed to be the incident blackbody radiation temperature from the furnace exposure (Wickström, 2016).

$$\dot{q}'' = h_{c_{hot}}(T_{ISO} - T) + \sigma\varepsilon_{hot}(T_{ISO}^4 - T^4) \qquad (10)$$

$$\dot{q}'' = h_{c_{cold}}(T_{amb} - T) + \sigma\varepsilon_{cold}(T_{amb}^4 - T^4) \qquad (11)$$

The exposure in tests performed with radiant panels (H-TRIS) is applied as an incident heat flux set from the radiant panels and thermal losses due to the radiation and convection to the environment as shown in Equation 12.

$$\dot{q}'' = \alpha\dot{q}''_{in} - h_{c_{hot}}(T - T_{amb}) - \sigma\varepsilon_{hot}T^4 \qquad (12)$$

- **Heat and mass transfer modelling**

  A simplified mass transfer is implemented to model the passage of hot air in stone wool when there is no impermeable cladding protecting the stone wool. The model is implemented by:

  - Assigning a pressure boundary of 20 Pa on the exposed side, which is the target pressure difference between the inside and outside of the furnace in standard ISO 834 fire testing for horizontal specimens.
  - Calculating the velocity of the flow by Darcy's law (Equation 13)

    $$u_g = -\frac{\kappa}{\mu_g}\frac{\partial p_g}{\partial x} \qquad (13)$$

    where u_g is the velocity of the air, κ is the permeability of the stone wool (assumed as 10^{-9} m^2), μ_g is the viscosity of the air at atmospheric pressure (Pa·s) and p_g is the pressure in Pa.
  - The heat transfer in the stone wool is calculated with heat transfer in porous media, where it is assumed there are a solid and a gas phase. The velocity in the gas phase is then coupled with conservation of energy (Equation 14)

    $$(\rho c_p)_{eff}\frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\left(-k_{eff}\frac{\partial T}{\partial x}\right) - \rho_g c_{p,g}\frac{\partial}{\partial x}\left(u_g\frac{\partial T}{\partial x}\right) = 0 \qquad (14)$$

    $(\rho C_p)_{eff}$ and k_{eff} are the effective density, specific heat, and thermal conductivity considering only the apparent stone wool properties. The first in the equation represents the energy storage, the second term the heat conduction in the stone wool, and the third term the convection in the pores due to hot air passing through.

- **Heat generated by reactions in the material**

  The energy released by reactions occurring in the material such as: combustion of the organic content of the stone wool (Q_{bi}), calcination reactions of gypsum plasterboards (Q_c) and combustion of the paper lining of the gypsum plasterboard (Q_p), are taken into account as energy terms in the transient heat conduction equation (see equation 6). The rate of energy released is based on Arrhenius formulations. The parameters for stone wool are obtained at micro-scale, and for gypsum plasterboards they are retrieved from the literature. Figure 17 shows where each of the terms is taken into account in the modelling.

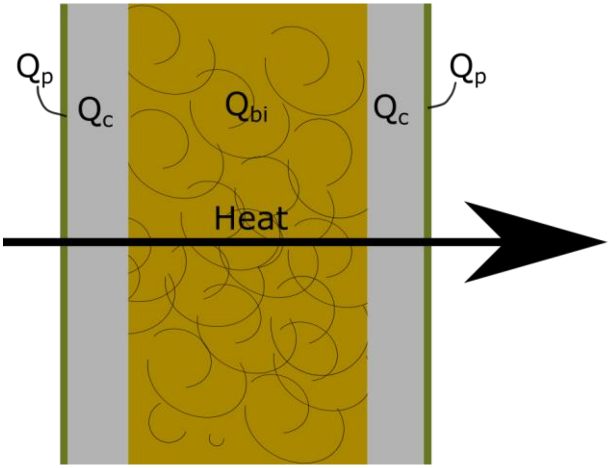


Figure 17: Energy reactions taken into account to model in Gypsum-Stone Wool-Gypsum construction

4.4 Thermo-mechanical properties for gypsum

The next step to achieve full-scale system behaviour modelling is to couple the thermal to the structural model (see Figure 3). For lightweight gypsum assemblies it has been a common approach to disregard the mechanical component of gypsum plasterboard for modelling the structural response at high temperatures. Thus, only consider as the structural components the wood or cold formed steel studs. This assumption is conservative and justified by the simplicity of the model. However, gypsum plasterboards are providing resistance in the structure, especially against lateral loading (Hoehler *et al.*, 2020). The thermo-mechanical response of gypsum plasterboards is important also in non-load bearing constructions, as their cracking and fall-off leads to opening of gaps, compromising the ability of the building barrier to contain the fire.

In order to include gypsum plasterboards in the thermo-mechanical modelling of lightweight gypsum assemblies in fire, appropriate material models are needed. However, there is a lack of definition of methods to obtain stress-strain relationships of fire resistive materials at elevated temperatures, and very few researchers have looked into the topic (Rahmanian, 2011). The material properties at elevated temperatures are intrinsically dependent on the testing method, and results need to be linked to the testing conditions (Pettersson, 1988).

An experimental test set-up was built to obtain the indirect tensile strength of gypsum plasterboards based on three point bending tests. Samples of 235×60×9.5 mm^3 were simply supported on both ends, and were exposed to constant temperatures of: 80 °C, 180 °C, 200 °C, 300 °C, 400 °C and 500 °C and loaded until failure at a rate of 4 N/min and 0.4 N/min (for temperatures above 300 °C). From these tests the stress-strain relationships were defined. Further tests were performed to samples exposed to standard temperature-time curve on one side, and loads of 10 N, 20 N, 40 N, and a variable load of 4 N/min to validate the material thermo-mechanical model. Figure 18 shows a schematic of the methodology. The validation of the material model and the applicability to larger scales has not been proven yet.

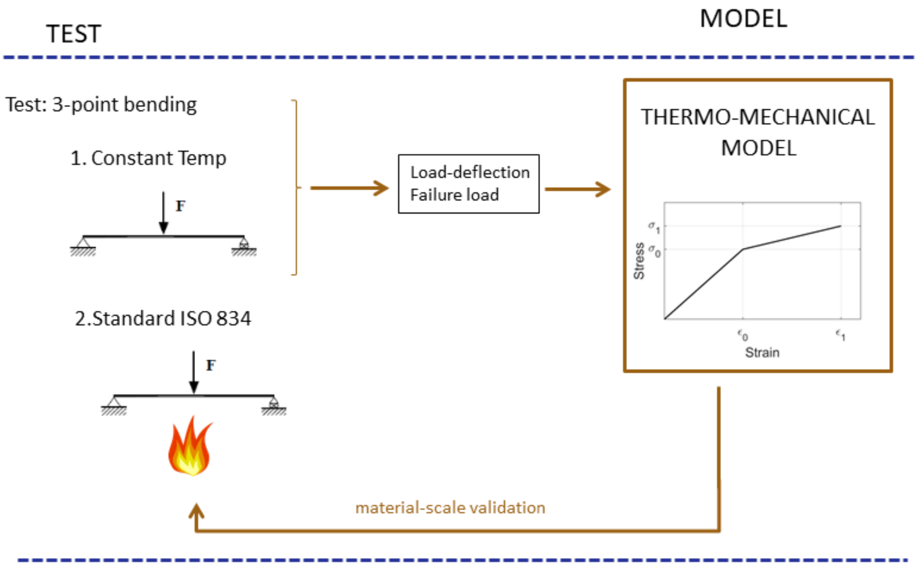


Figure 18: Diagram of the thermo-mechanical tests performed to gypsum plasterboards

4.5 Uncertainties in material thermal modelling

This thesis work aims to predict larger scale system behaviour of building barriers based on small-scale tests combined with modelling. The goal is to demonstrate that a methodology based on material thermal degradation, rather than empirical approximations can provide a better understanding of how material behave at full-scales in fire scenarios. Thermal modelling is intrinsically dependent on material thermal properties and boundary conditions. Even if the thermal properties are obtained through small-scale testing, the test methods, precision of instrument, and heterogeneity of materials will turn into uncertainties in the model predictions. Likewise, assumptions in boundary conditions will compromise the outcome of the models.

Hence, a methodology was developed to identify the output sensitivity of thermal modelling to the uncertainties in the input parameters. The methodology was applied to one dimensional heat transfer of stone wool-steel sandwich composites under standard temperature-time exposure, but it could potentially be used in any other type of constructions or exposures.

The method analyses the global and local sensitivity of the model to the input. The global sensitivity of the model to the input parameters is performed by using Monte Carlo approach to randomly select the input parameters from a specified range. The sensitivity of the model was studied in five steps:

- All input parameters varied
- Boundary parameters varied
- Stone wool properties varied
- Unexposed side boundary parameters varied
- Exposed side boundary parameters varied

The unexposed side temperature was recorded during the simulation. Results compare the midrange failure time (A), the difference between maximum and minimum failure time (B), the temperature range at midrange failure time (C), the maximum temperature range (D), the temperature standard deviation at the midrange failure time (E), and the maximum temperature standard deviation (F). Figure 19 shows a schematic of the results parameters for the global analysis

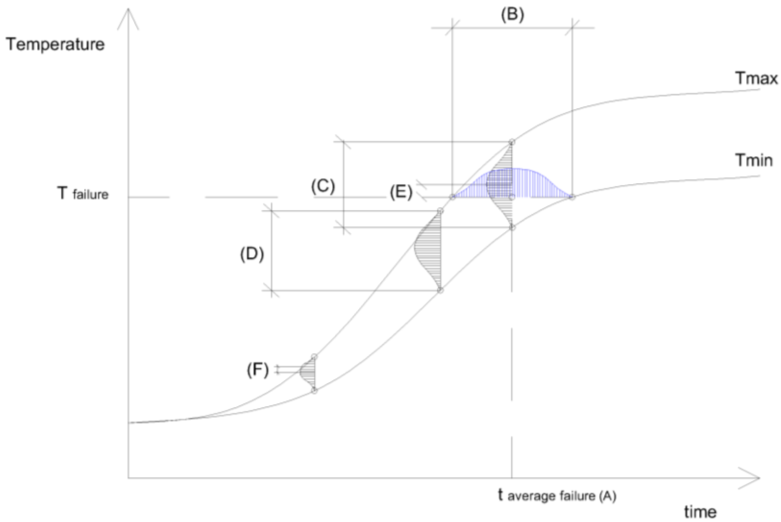


Figure 19: Parameters for the global sensitivity analysis

The local sensitivity was performed varying individually one input parameters at a time to its maximum and minimum value. The resulting temperature time curves are quantitatively compared using functional analysis (Peacock *et al.*, 1999). Following functional analysis, the distance and the angle between curves from the data point values can assess the difference between the model predictions.

5. Results

In section 5.1 a short introduction to the six appended papers is provided. The results of the papers are then used to address the research objectives of this thesis in section 5.2.

5.1 Introduction to the appended papers

Figure 20 shows a schematic of the content of each of the papers included in this thesis work in accordance with the different scales presented in Section 4.

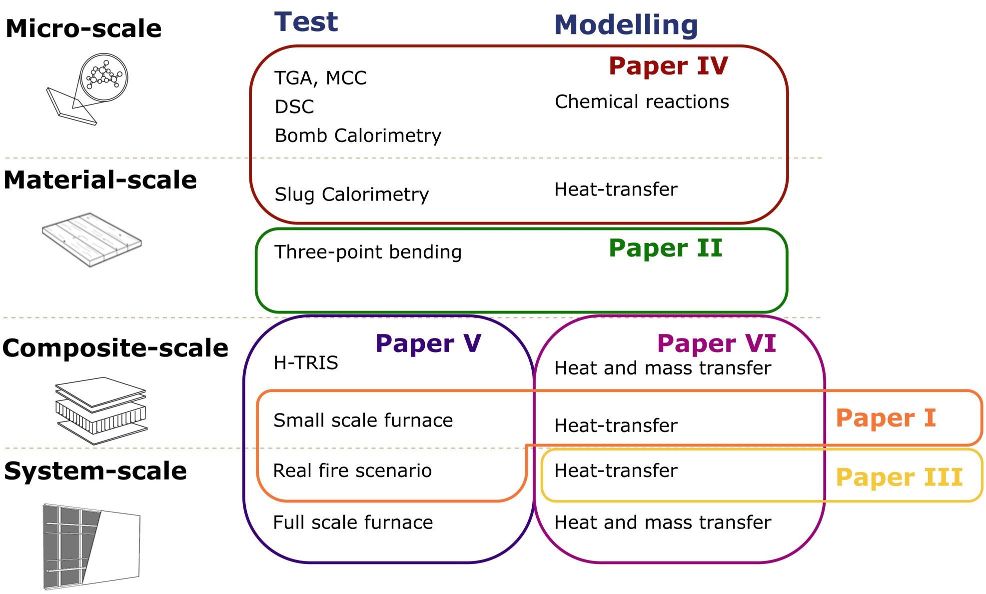


Figure 20: Diagram showing the content of the papers included in this thesis work

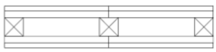
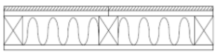
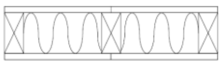
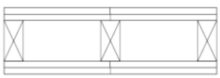
5.1.1 Paper I – Experimental and thermal analysis of wall assemblies exposed to standard and parametric fires

The objective of Paper I was to experimentally assess the response of fire rated gypsum-plasterboard building barriers to different fire exposures at composite-scale and system-scale. The four typologies of barriers included were:

- a double layer of gypsum plasterboard with air cavity and wood stud (Assembly A),
- a stone wool insulated wall with one layer of gypsum on one side and one layer gypsum and one layer calcium silicate board on the other side (Assembly B),
- a glass wool insulated assembly with one layer of gypsum plasterboard (Assembly C),
- a double layer of gypsum plasterboard with air cavity assembly (Assembly D).

The cross-sections of the specimens are shown in Table 1. The specimens had dimensions of 500×500 mm², and were subjected to ISO 834 and Hydrocarbon temperature-time exposures. Additionally, Assembly B (Table 1) was tested in a compartment fire. In the compartment fire, the assembly was one of the room enclosure walls and had dimensions of 2.14×2.3 m². The fire in this case was a 100 L heptane pool fire, placed 500 mm away from the tested wall.

Table 1: Cross-section of the specimens tested in Paper I

ASSEMBLY	CLASS	CROSS-SECTION	WOOD-STUD	INSULATION	LINING
A	EI 60		45x45 mm^2	-	13 mm gypsum 15 mm gypsum
B	EI 60		70x45 mm^2	Stone Wool	10 mm calcium-silicate 13 mm gypsum
C	EI 60		95x45 mm^2	Glass Wool	15 mm gypsum
D	EI 90		95x45 mm^2	-	2x 15mm gypsum

Furthermore, in Paper I a two-dimensional heat transfer model was developed using empirical properties from the literature for Assembly C. The objective was to identify if material properties available in the literature could successfully be used to predict the response in ISO 834 temperature-time exposure and Hydrocarbon temperature-time exposure.

5.1.2 Paper II – Mechanical properties of gypsum plasterboards exposed to standard fires

The objective of Paper II was to study the loss of strength of gypsum plasterboards as a function of temperature. The paper presents an experimental set-up on material-scale to perform three-point bending tests to samples of 235×60 mm² after being heated up to a constant elevated temperature, reaching steady state. Further, the testing methodology allowed for transient heating following standard temperature-time exposure, and transient loading at a varying constant rate. Figure 21 shows a schematic of the experimental set-up. Stress-strain relationships are obtained based on the load-deflection curves.

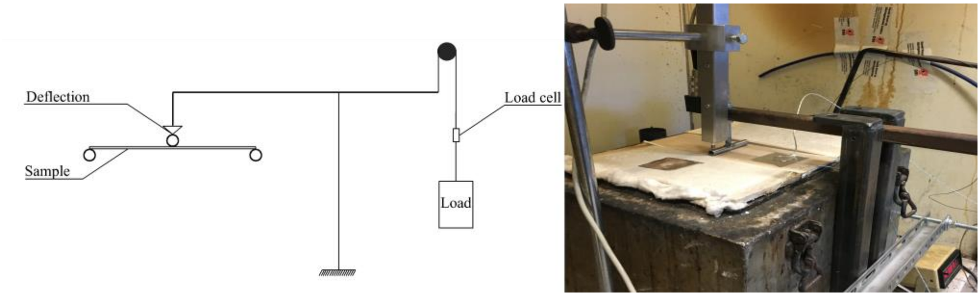


Figure 21: Experimental set-up for the three-point bending tests.

5.1.3 Paper III - Uncertainties in modelling heat transfer in fire resistance tests: a case study of stone wool sandwich panels

Paper III presents a methodology to study which parameters are most influential when performing one-dimensional heat transfer analysis on steel-stone wool sandwich composites exposed to a standard temperature-time curve. The predicted temperature on the unexposed sample is used as the output for comparison of the results. The one-dimensional heat conduction model is initially compared to test results of 500×500 mm² specimens of stone wool core of 50 mm thick sandwiched by two steel sheets of 0.65 mm.

Once calibrated, the study is conducted in two steps. On one hand, the global sensitivity of the model to the input parameters is studied by varying the input parameters simultaneously following a Monte Carlo approach for sampling the input to the model. Table 2, Table 3 and Figure 22 show the varied values of the input parameters. For the local sensitivity analysis, the input parameters are varied to their maximum and minimum values from Table 2 and Table 3. The local sensitivity is then studied by performing a functional analysis to the results.

Table 2: Boundary parameters in Paper III

PARAMETER	FIXED VALUE	MIN. VALUE	MAX. VALUE	DISTRIBUTION
h_{hot} [W/(m²K)]	25	20	60	Uniform
h_{cold} [W/(m²K)]	4	4	10	Uniform
ε_{hot}, [-]	0.9	0.8	1.0	Uniform
ε_{cold}, [-]	0.65	0.55	0.75	Uniform

Table 3: Material properties in Paper III

MATERIAL	PROPERTY	FIXED VALUE	MIN. VALUE	MAX. VALUE	DISTRIBUTION
Steel	c_p	0.5	Not varied		
	ρ	7850	Not varied		
Stone wool	k [W/(mK)]	T dependent property, varied ±10% (Figure 22)			Uniform
	c_p [J/(kgK)]	840	756	924	Uniform
	ρ [kg/m³]	105	103	107	Uniform

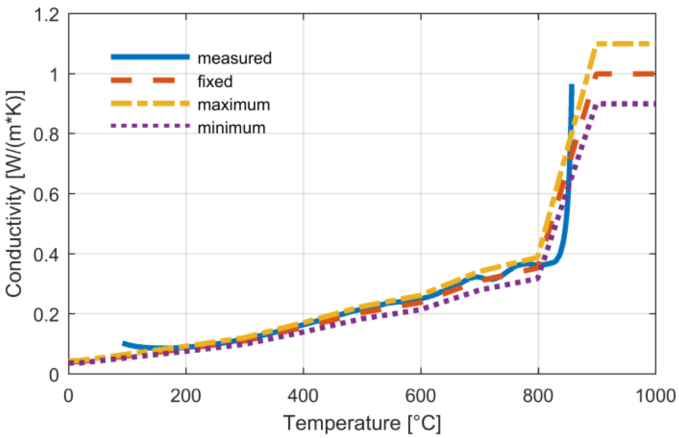


Figure 22: Stone wool thermal conductivity values used in Paper III

5.1.4 Paper IV – Characterization of stone wool properties for fire engineering calculations

The objective of Paper IV is to obtain the thermal properties that characterize the physics occurring on stone wool products when exposed to heat, in order to perform heat transfer calculations. Stone wool is considered an incombustible material. Only a small percentage of its weight is organic content that can undergo combustion. In some occasions when exposed to fire, it is possible to observe a peak in temperatures due to the energy being released by the small amount of organic content.

In Paper IV, a modified version of the slug calorimetry methodology is used to obtain the apparent thermal conductivity of stone wool. Micro-scale testing (TGA, MCC and Bomb Calorimetry) is performed to characterize the kinetics occurring in the material. The modelling of heat transfer of stone wool is performed by combining the thermal conductivity obtained from the slug calorimetry testing and the kinetic reactions due to the combustion of the organic content (as shown in section 4.3). This modelling allows the decoupling of both phenomena and further understand the combustion of the organic content of the stone wool.

5.1.5 Paper V – Response of stone wool insulated building barriers under severe heating exposures

Paper V presents an experimental analysis of the behaviour of gypsum-stone wool and steel-stone wool layered composites under different heating exposures. The aim of this paper is to systematically increase the complexity of the tested specimen to be able to identify the phenomena occurring at larger scales than the scale at which material properties are obtained. Thus, serving as a basis for assumptions in material thermal modelling at larger scales.

Tests are performed under four different heating exposures: 7 kW/m² incident radiant heat exposure, 60 kW/m² incident radiant heat exposure, variable heat exposure (simulating a realistic fire exposure with a heating and a decay phase), and standard temperature-time exposure. Prior micro-scale testing identified the temperature ranges for the reactions occurring in the stone wool (Paper IV). Thus, based on pre-screening thermal modelling, the low incident radiant heat exposure of 7 kW/m² was selected so no reactions on the stone wool would occur. On the contrary, with the high incident heat exposure of 60 kW/m² all the organic content of stone wool would react.

The composite and system-scale testing apparatus used in the investigation include a movable radiant panel (H-TRIS), mid-scale furnace and large-scale furnace. More details on the experimental set-up were given in section 4.3. Figure 23 shows a summary of the constructions tested and the heat exposures.

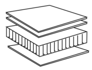
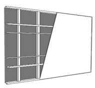
Scale	Composite	Phenomena	Heat exposure
Composite-scale 	Phase I- Composite Steel- Stone wool sandwich S-SW-S	SW response in composte	Low incident heat flux 7kW/m^2 High incident heat flux 60 kW/m^2
	Phase II- Composite Gypsum- Stone wool sandwich G-SW-G	Other phenomena: burning of paper lining moisture movement evaporation-condensation	Low incident heat flux 7kW/m^2 High incident heat flux 60 kW/m^2
	Phase III- Composite S-SW-S SW-S G-SW-G	Identify the phenomena in complex variable heat exposures	Standard fire curve Variable incident heat flux
System-scale 	Phase IV- Full Scale G-SW-G	Full scale system behaviour, effect of joints, thermal bowing, cracking of boards	Standard fire curve

Figure 23: Summary of the composites tested and the heat exposures

5.1.6 Paper VI – Using micro-scale and solid material data for modelling heat transfer in stone wool composites under heat exposures

Paper VI combines the outcomes of Paper IV and V to model the heat transfer and heat and mass transfer of stone-wool steel, and stone-wool gypsum composites under different heating conditions. It investigates the suitability of using material properties obtained at smaller scale, and reaction kinetics parameters. The paper focuses on studying how increasing the complexity of the model to include phenomena identified at material-scale testing might provide better predictions in some occasions, while in other it does not. The modelling efforts include the combustion of the organic content of the stone wool, a diffusion term to account for the passage of hot air through the stone wool, calcination reactions in gypsum plasterboards, and energy release by burning of the paper lining of gypsum plasterboard.

5.2 Addressing research objectives

The research sub-objectives (SO) presented in Section 3 are addressed here based on the results from the six appended papers.

SO 1: To identify the similarities and differences in the response of building barriers to different fire exposures, comparing standard furnace tests to alternative fire scenarios.

Sub-objective one is addressed in Paper I and Paper V. Both of those papers present an experimental analysis where the same constructions are subjected to different heat exposures.

The building barriers selected in Paper I were of known fire rating based on the Swedish Fire Protection Guide (Bengtsson *et al.*, 2012). The same typology of constructions were tested under the standard ISO 834 and Hydrocarbon fire curve, to check if the rating criteria was fulfilled in both cases. Table 4 shows the relative temperatures reached on the unexposed side at the rating times for ISO 834 and Hydrocarbon. The temperature value is the average of two thermocouple readings. Also, the percentage of the difference between the ISO 834 and the hydrocarbon test result is given. From the perspective of the classification times, the walls fulfilled the insulation criteria. However, the tests were performed at a reduced scale of 500 × 500 mm², the influence of thermal bowing and boards cracking and falling off could lead to significantly different results.

Table 4: Relative temperature reached at classification times (the cross section of the assemblies is shown in Table 1)

Assembly	ISO 834 (°C)	Hydrocarbon (°C)	%
A	42	55	26
B	40	55	30
C	51	65	23
D	47	47	0.11

In Paper I, Assembly B was also exposed to a compartment pool fire test. In this scenario Assembly B was one of the compartment walls while the other walls were CFS stud walls with 70 mm glass fibre insulation and a mineral board. The fire source consisted of a 100 litres heptane pool fire in steel drum container without a lid. The steel drum was placed 0.5 m away from the wall. Figure 24 shows the experimental set-up for the compartment fire. The drum was located closer to the edge of the wall opposite the opening of the compartment, leading to non-uniform temperatures in the exposed wall.

Figure 24: Experimental set-up for the compartment fire.

The exposed temperature-time curves in Paper I and the relationship between the standard exposures and the pool fire test are shown in Figure 25. The temperatures plotted in the pool fire test are the maximum and the minimum values of the thermocouple array, being at 0.1 and 1.1 m from the ceiling. The compartment fire test lasted for 105 minutes, but around 40 minutes the ceiling and boundary compartment (not Assembly B) failed and modified the expected temperature-time exposure. In Figure 25 time zero corresponds to flashover, considering it occurs when the maximum temperature of the hot gas layer reaches 500 °C. This figure is slightly different than in the appended paper, where the zero axis was considered at the start of the test rather than at the time of flashover.

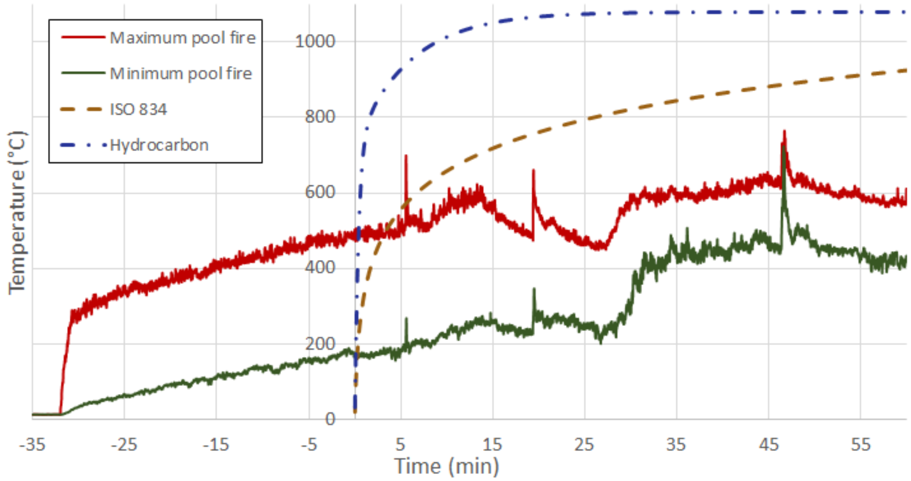


Figure 25: Temperature-time exposures in Paper I

Figure 26 shows the temperature measurements on the unexposed side of the Assembly B in the compartment pool fire scenario. Thermocouples TC1 and TC2 were located on the upper part of the wall, thermocouples TC4 and TC5 on the lower part of the walls, and thermocouple TC3 in the middle. The exposure in the compartment fire test was not uniform, thus neither were the unexposed side temperatures readings. Thermocouple TC1 was closer to the pool fire, thus provides higher temperature. At the rating time of the wall (60 minutes), temperatures on the upper gas layer reached a maximum of 87 °C, higher than under reduced scale standard fire testing. The temperatures on the lower gas layer were below those obtained in ISO 834 standard fire testing. However, the rating criteria were still fulfilled within this pseudo-realistic fire scenario.

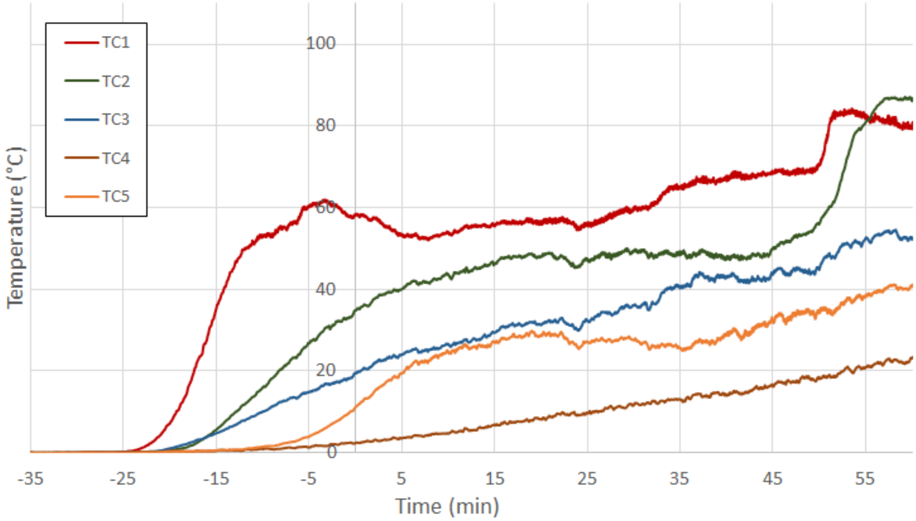


Figure 26: Unexposed side temperature of Assembly B in the pool fire scenario.

In Paper V the experimental analysis focused on exposing stone wool insulated sandwich constructions, with steel or gypsum claddings, to different heat exposures. Figure 27 shows the different heat exposures plotted as the unexposed side temperature of the exposed steel panel in the S-SW-S composites. Tests were performed on samples of 500 × 500 mm², and one large-scale furnace test of 3 × 3 m².

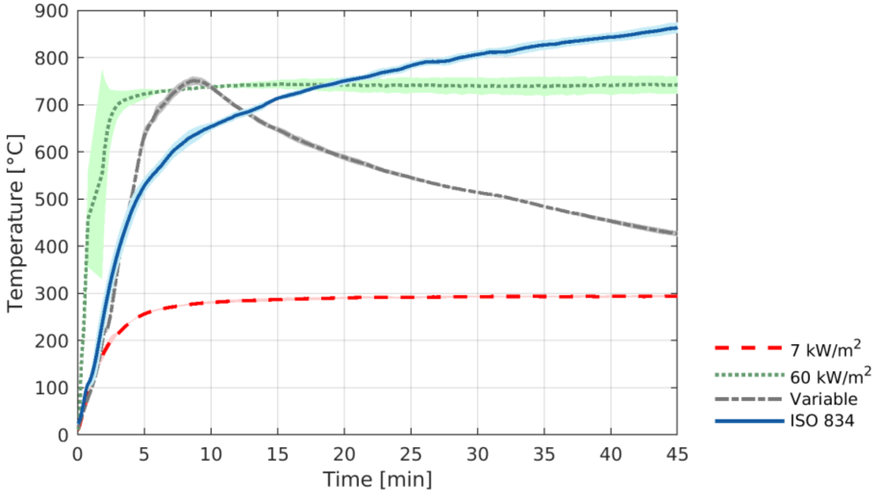


Figure 27: Heat exposure as temperature measured on the unexposed side of the steel panel. The line represents the mean value, and the colored are the deviation between tests.

The experimental methodology was based on adding complexity to the test set-up stepwise, either by adding complexity to the construction tested or to the heat exposure.

At a low constant radiant incident heat exposure of 7 kW/m² in S-SW-S composite no reaction of the organic content of the stone wool would occur. Thus, simple heat transfer through the stone wool is identified with a smooth increase of temperature. At a high radiant incident heat flux of 60 kW/m² all the organic content should be reacted based on the micro-scale test results, and a peak in temperatures is observed after 50-60 minutes into the steady state in S-SW-S composite. This peak could be due to the combustion of the organic content of the stone wool.

In the tests performed to G-SW-G at low radiant incident heat flux 7 kW/m² the two step calcination reaction of gypsum is observed, and a plateau at 100 °C corresponding to the evaporation of water. At a high radiant incident heat flux of 60 kW/m² the calcination reaction happens faster and it is followed by a steep temperature increase and a sharp peak that could be due to the combustion of the organic content of the stone wool, or the combustion of the paper lining.

Tests performed under variable heat exposure using H-TRIS methodology showed a steady increase on temperature for the S-SW-S composite, and a bump in the temperature readings around 30-40 minutes that could be linked to the combustion of the organic content. For the G-SW-G the two step calcination reaction and steep increase in temperatures due to either the combustion of the organic content or the paper lining was observed. Tests performed under ISO 834 did not show the effect of combustion of paper lining or organic content of the stone wool.

Results from Paper V show that small-scale tests are very useful tools that can reproduce heat transfer at larger scales provided there are limited mechanical deformations. The results also highlight the need of better understanding the conditions under which fire tests are performed and how ambient and boundary conditions affect the fire response of constructions (e.g. the availability of oxygen to undergo combustion). Furthermore, in Paper V it was also investigated the experimental limitations due to sample size effect, testing apparatus, thermocouple attachment methods.

The main outcomes from Paper I and Paper V with regards to the response of building barriers to different fire exposures are:

- In standard testing the test specimen is exposed to a uniform thermal environment, while in compartment fires the exposure can be very uneven.
- Different temperature distributions in the exposed surfaces might lead to deformation, thermal stresses and induced failures different that the ones foreseen in standard fire testing
- Heterogeneity of materials, and constructing deficiencies would also affect how building barriers respond to fire.
- Testing is limited to specific dimensions.
- Standard fire testing provides a good classification tool, and helps understanding the behaviour of constructions in fire even in reduced scale. However, standard test results need to be understood with its limitations specially when extrapolating to other fire exposures.

SO 2: To identify the main phenomena to be considered in modelling the fire response of the selected building barriers, and obtain the material properties needed to improve current modelling capabilities

Sub-objective two is addressed in Paper II, Paper IV, and Paper V. In Paper V the main phenomena needed for modelling stone wool layered composites are identified. In Paper II and Paper IV the thermo-mechanical properties of gypsum plasterboards and the thermal properties of stone wool are respectively obtained.

Models capable of reproducing the response of building barriers to fire, need to capture the phenomena taking place on them. The most significant physical process occurring is heat conduction. Heat conduction in solids is dominated by thermal conductivity, specific heat and density (see equation 9). Thus, the definition of these parameters together with the boundary conditions to which the building barrier is exposed are fundamental in prediction methodologies. More sophisticated heat transfer modelling might include convection and radiation if materials have a porous media, or there are cavities within the construction.

From the experimental analysis performed in Paper I and Paper V, the following phenomena were identified as relevant to be included in the thermal modelling in addition to heat conduction.

- Gypsum behaviour:
    - Calcination reaction, and evaporation condensation cycles
    - Paper burning
    - Influence of the mechanical behaviour of the boards, and eventual fall-off
- Stone wool:
    - Reaction of the organic content in the stone wool
    - Air diffusion occurring inside the porous media of the stone wool

Some of the required properties needed to improve modelling capabilities were obtained within this thesis framework.

The thermal conductivity of a wide range of stone wool products were obtained in Paper IV. A modified slug calorimetry was used to obtain the thermal conductivity. Two heating cycles were used, during the first heating cycle the organic content of the stone wool was combusted, and the second cycle was used to obtain the thermal conductivity. Figure 28 shows the values obtained for four different types of stone wools analysed, with densities varying between

36.8 kg/m³ and 153.6 kg/m³. Despite the densities of the stone wool being significantly different, the thermal conductivity gave similar values with a maximum deviation of ± 20 % from the mean value up to 800 °C. For further modelling purposes at larger scales the same value of thermal conductivity was used for the different types of stone wool

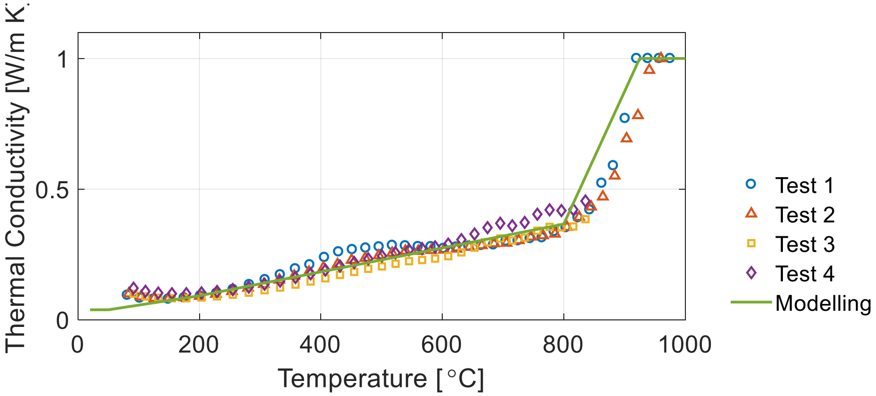


Figure 28: Thermal conductivities for the stone wool products versus the simplfied thermal conductivity used for modelling purposes. Test 1 corresponds to stone wool of 36.8 kg/m³, test 2 to stone wool of 60.7 kg/m³, test 3 to stone wool of 105.1 kg/m³ and test t to stone wool of 153,6 kg/m³.

The thermochemistry and kinetics of the reactions occurring in stone wool were obtained in Paper IV by performing Bomb calorimeter, MCC, and TGA tests and obtaining the Arrhenius parameters to characterize the reactions. Figure 29 shows an example of the mass loss and the differential thermogravimetric (DTG) curves of a stone wool of 36.8 kg/m³. DTG curves are obtained as the first derivative of the mass with respect to temperature. In the Figure 29 it is possible to observe one peak in the DTG curve under nitrogen atmosphere between 250-350 °C. Two peaks are observed in air atmosphere, the first between 250-350 °C, and the second between 400-500 °C. The first peak is likely due to the pyrolysis of the organic content of the stone wool, and the second peak due to the oxidation of the organic content residue. Between 700-800 °C a peak of weight gain is observed that could be linked to the crystallization of the stone wool fibres. Based on the micro-scale testing kinetic reaction parameters were obtained for each of the stone wools. However, in the larger scale modelling only one set of parameters was used to model the energy released by the reaction of the organic content of the stone wool, provided that a sensitivity analysis showed a minor difference in the result by using the different parameters.

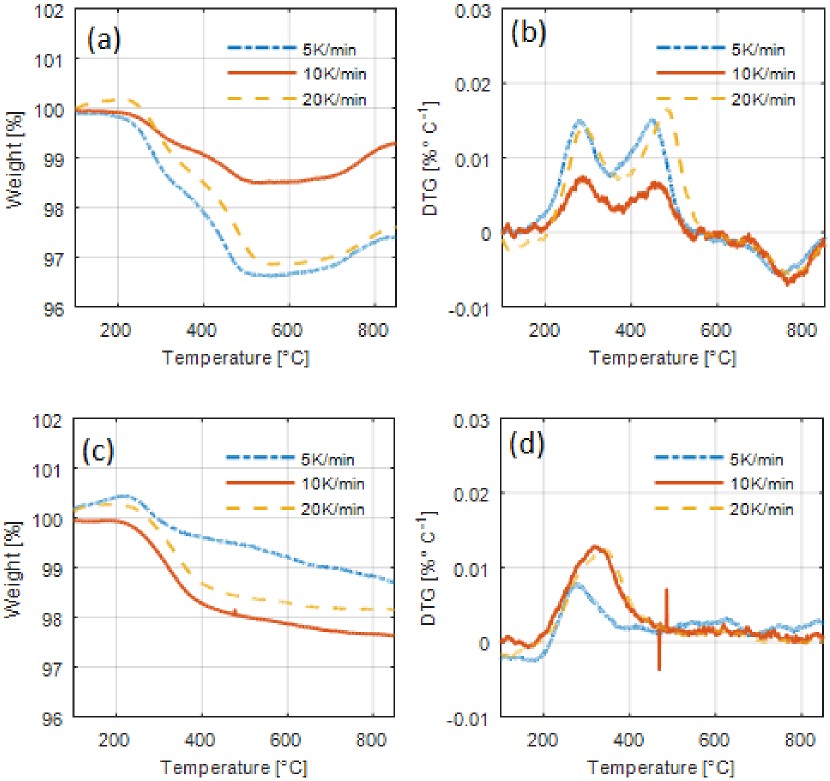


Figure 29: Thermal decomposition of stone wool of density 36.8 kg/m³ in air and nitrogen atmpsopheres: (a) TG loss in air, (b) DTG in air, (c) TG in nitrogen, (d) DTG in nitrogen.

In Paper II, a characterization of the loss of strength of gypsum plasterboards with temperature was conducted. Three-point bending tests were performed to samples of 235×60×9.5 mm³. The results of the tests include load-deflection curves, maximum load and maximum deflection for isothermal conditions (at 24 °C, 80 °C, 180 °C, 200 °C, 300 °C, 400 °C and 500 °C), time to failure and unexposed side temperature for standard fire exposure.

Tests performed under constant isothermal conditions showed an increase in strength of about 10 % at 80 °C, prior to the first calcination reaction. At 200 °C, between the first and second calcination reaction of gypsum, there is a 20 % reduction of strength, and of 95 % above 300 °C. Tests performed under ISO 834 testing showed that the load applied to the board had an effect on the maximum deformation. For load values below 20 % of the ambient failure load, the load applied did not have an effect on the failure time, however it did for the greater load of 40 N, where the time was reduced from close to 5 minutes, to less than two minutes. The deflection profiles show a plateau which length varies depending on the applied load.

As presented above, Papers II, IV and V have helped to identify main phenomena to be considered in modelling building barriers under heat exposure, and obtain the material properties needed to improve current modelling capabilities.

SO 3: To develop engineering heat transfer models using a multi-scale approach to predict the behaviour of the selected building barriers under different heat exposures.

Sub-objective 3 is addressed in Paper VI and Paper II. Paper VI provides heat transfer models for stone-wool layered composites. Paper II provides a material model for gypsum plaster board that can be further used to link the thermal model to a thermo-mechanical model.

Initial modelling of Paper I provided evidence of the need of models based on material properties that are capable of predicting heat transfer in composites under different heat exposure. In Paper VI heat transfer models were developed to capture the phenomena taking place in the materials. The process consisted of step-wise building up the complexity of the models. The constructions modelled were stone wool layered composites with steel and gypsum claddings. The modelling work includes:

- Energy released by the combustion of the organic content of the stone wool
- Diffusion term to account for passage of hot gases through the porous media of the stone wool.
- Calcination reactions on gypsum plasterboards
- Energy released by the combustion of the paper lining of gypsum plasterboard

The results showed that the developed heat transfer model is capable of predicting unexposed side temperatures in steel-stone wool-steel composites at a constant low heat exposure of 7 kW/m², in variable heat exposure and under the ISO-834 fire exposure. At a high constant heat exposure of 60 kW/m² the model over-predicts the temperature. Including the energy released by the combustion of the organic content of the stone wool provided an unrealistic value of the temperatures in early stages of the exposure. This could be linked to the fact that micro-scale tests are performed in dissimilar conditions than larger scale tests. Effects such as cladding protecting from air entrainment or low oxygen content in the furnace could limit the reaction occurring in the organic content of the stone wool. The reaction of the stone wool was then limited by a total amount of heat that can be released per second. This assumption provided more realistic results in the modelling of steel-stone wool-steel composites.

A steel-stone wool composite without steel cladding on the exposed side was modelled under an ISO 834 fire exposure. Those tests were performed in a small furnace where ambient air was being provided in the combustion chamber. In this case heat transfer, and heat and mass transfer models were developed, including the combustion of the organic content of the stone wool. The heat and mass transfer model provided best agreement with the test results under this exposure. This is because the non-existence of a cladding on the exposed side allows the hot gases from the furnace enter the through the stone wool and combust the organic content. However, this reaction happens also slightly different than at small-scale, and there is the need of limiting the maximum amount of energy being released.

When modelling gypsum-stone wool-gypsum composites the calcination reactions were considered either by including them in the specific heat value, or by modelling them by kinetic model using Arrhenius equation. Both approaches lead to similar results. Including the combustion of the organic content of the stone wool in the model (limiting the maximum amount of energy released) resulted in better predictions of the peak temperature at a high constant heat exposure of 60 kW/m² and in a variable heat exposure. However, this peak was not observed in the standard fire test probably due to the fact of a low oxygen content on it. Including the energy released by the combustion of the paper lining had a negligible effect.

Paper II presents a material model for gypsum plasterboard. The stress-strain relationships are derived based on the bending tests at isothermal conditions. Three different behaviours where identified: (1) elasto-plastic with hardening for temperatures below the first calcination reaction, (2) elastic for temperatures between the first and the second calcination reaction, and (3) elastic-perfectly plastic for temperatures above the second calcination reaction and burning of the paper lining. An engineering model was built for the thermo-mechanical response of gypsum plasterboards. Figure 30 shows the material models developed, and Figure 31 the degradation of the modulus of elasticity with temperature.

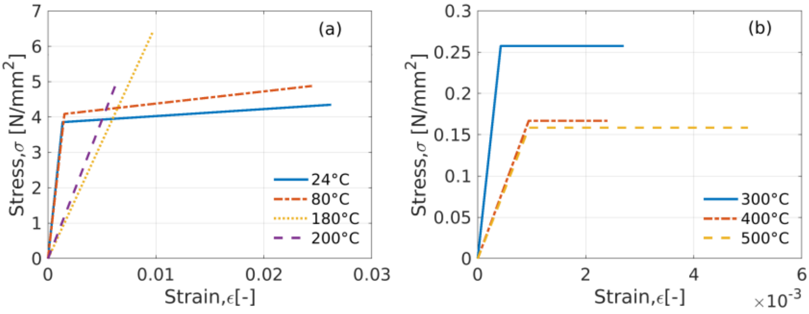


Figure 30: Stress-strain relationships developed for gypsum plasterboard at elevated temperatures

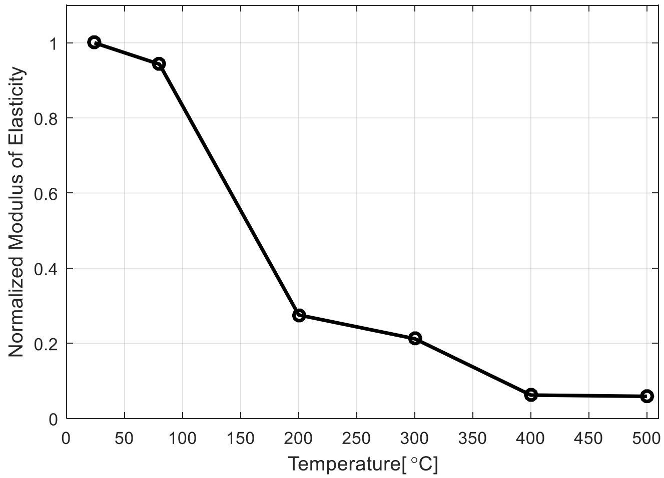


Figure 31: Degradation of the modulus of elasticity with temperature

SO 4: To develop a simple method to analyse uncertainties linked to modelling assumptions in modelling of standard fire test, concerning the studied building barriers.

Heat transfer modelling requires input values for boundary conditions and material thermal properties. The selection of these input parameters will strongly influence the modelling predictions. In Paper III, a simple method to analyse the uncertainties liked to material thermal modelling of stone wool-steel composites under a standard fire exposure was developed.

For the global sensitivity analysis, the Monte Carlo approach was used. The input parameters were varied between the maximum and minimum values shown in Table 2 and Table 3, and following the specified probability distribution functions, and a total of 10000 simulations were performed for each varied input case. The analysis was performed for three different thicknesses of stone wool (10 mm, 50 mm and 100 mm). The 10 mm thickness is an unrealistic value, however it was used in order to understand how changes in the cross-section thickness influence the significance of the input parameters.

The global sensitivity analysis showed that the model was more sensitive to variations in the boundary parameters than to the stone wool properties, from the considered input parameters. Furthermore, the exposed side boundary condition parameters lead to the least variation of the temperature at failure time for thicknesses 50 mm and 100 mm. This means that the model is less sensitive to errors in these values than for unexposed side boundary conditions. However, if the thickness of the construction is significantly smaller, the exposed boundary conditions become more important. These results highlight that there is a need to better characterize the unexposed side boundary conditions for material thermal modelling in standard fire tests. Figure 32 shows the temperature range at the failure time when the input parameters are varied using the Monte Carlo approach.

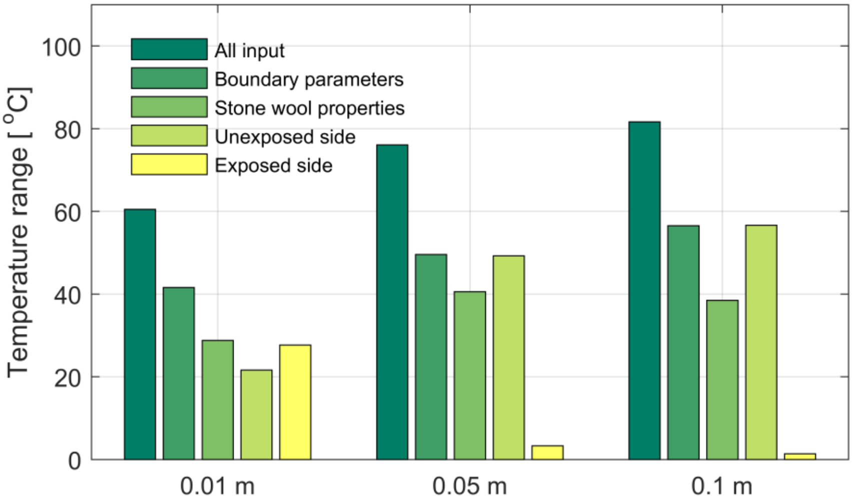


Figure 32: Temperature range at the time of failure, taken from 10000 simulations for three different construction thicknesses for the 5 cases described

For the local sensitivity analysis, each of the parameters is varied to its maximum and its minimum value, while the rest of the parameters are kept as their fixed values (see Table 2 and Table 3). Then, the local input parameter sensitivity is obtained by comparing the two data sets by the Euclidean Relative Distance (ERD), the Euclidean Projection Coefficient (EPC) and the Secant Cosine (SC). The analysis is also performed to three different thicknesses of the stone wool, and are shown in Figure 33. The ERD parameter shows the relative difference between the values in two data sets. An ERD value of zero means that the data sets are identical. The EPC parameter represents a shift value between both data sets. An EPC close to one means the two data sets are identical in tendency. An SC parameter of one indicates that the shape of the curves is identical.

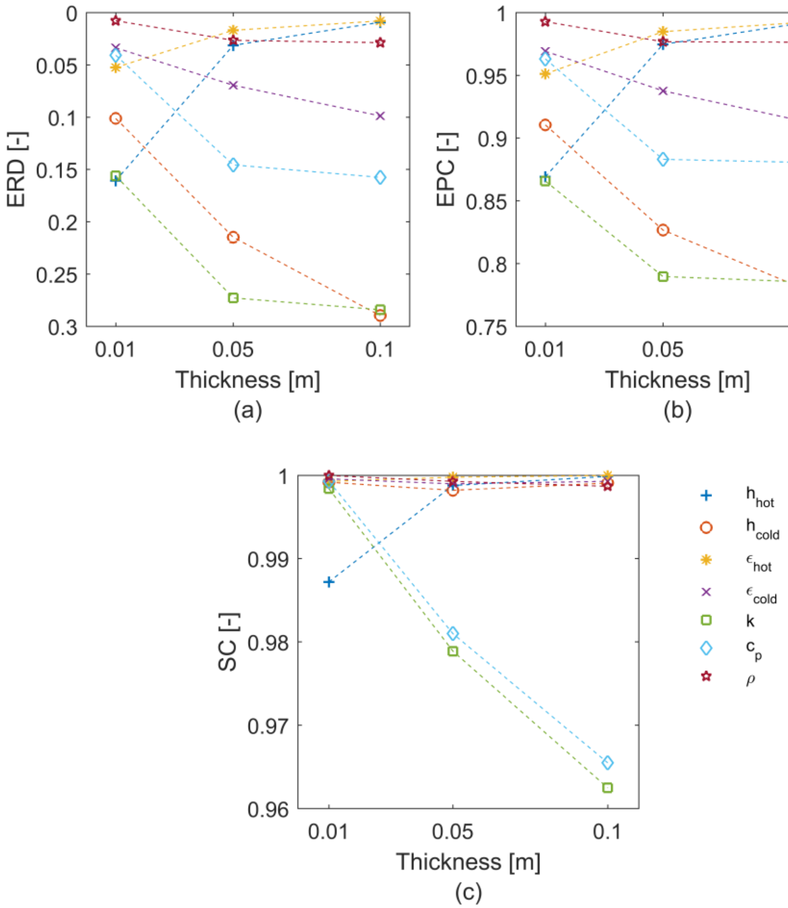


Figure 33: Results of the local sensitivity analysis: (a) Euclidean Relative Distance (ERD), (b) Euclidean projection coefficient (EPC), (c) Secant Cosine (SC)

Similarly as for the global sensitivity analysis, the local sensitivity analysis shows that the most influential parameters vary with the thickness of the stone wool considered. For the small thickness the most influential parameter is the convective heat transfer coefficient on the hot side (h_{hot}). However, for the thicker constructions the convective heat transfer coefficient on the cold side is more influential (h_{cold}). For constructions thicker than 50mm, the thermal conductivity (k) is the most influential single parameter, followed by specific heat (c_p) and convective heat transfer coefficient in the cold side (h_{cold}).

The results have shown how small changes in input parameters lead to uncertainties in the modelling outcome, and that the relevance of each individual parameter depends on the thickness of the construction, thus on the simulation time. The presented conclusions are intrinsically dependent on the thermal characteristics of the materials and the heating conditions studied. However, the presented methodology could be used for any type of construction and heating conditions

6. Discussion

This thesis work includes an experimental investigation and modelling of the fire response of a selected group of building barriers. Section 0 discusses the loop-feedback between testing and modelling, the methods used, the outcomes and the limitation of the work presented. For simplicity, the discussion has been divided between experimental methods and modelling work.

6.1 The interactive process of testing and modelling

The definition of the testing and modelling has been a dynamic process in which initial testing and modelling have defined the goals to develop a phenomena oriented experimental program and its subsequent modelling.

Initial testing in Paper I involved four different types of fire rated building barriers under different heat exposures. The main goal was to compare its response and identify plausible limitations between experimental analysis in a reduced scale and a larger scale. These initial tests were also used to model the heat transfer response based on material thermal properties from the literature. The question arose whether the readily available literature data would be enough to model different fire scenarios.

Hence, an experimental investigation was developed in which micro and small-scale tests were designed in order to understand the thermal degradation of the materials (Paper IV). TGA, MCC and Bomb calorimeter tests were used to identify the reactions occurring in stone wool. A modified slug-calorimetry was used to obtain the thermal conductivity of stone wool. Three-point bending tests were used to define the loss of strength of gypsum plasterboards at elevated temperatures (Paper II).

From the thermal degradation analysis to the stone wool, it was identified the temperature range at which thermo-chemical reactions occur in stone wool. Thus, a composite-scale experimental program was defined in order to capture those reactions occurring at the micro-scales (Paper V). Modelling prior to testing was performed in order to identify the constant radiative heat fluxes to be used in the radiant panel to capture or not the combustion of the organic content in the stone wool.

Later on in Paper VI, more extensive work on modelling was performed by including phenomena such as: reaction of the organic content of the stone wool, calcination reactions, pressure driven mass transfer, and burning of the paper lining. Figure 34 shows a schematic of the different phases of the testing and modelling process used in this thesis.

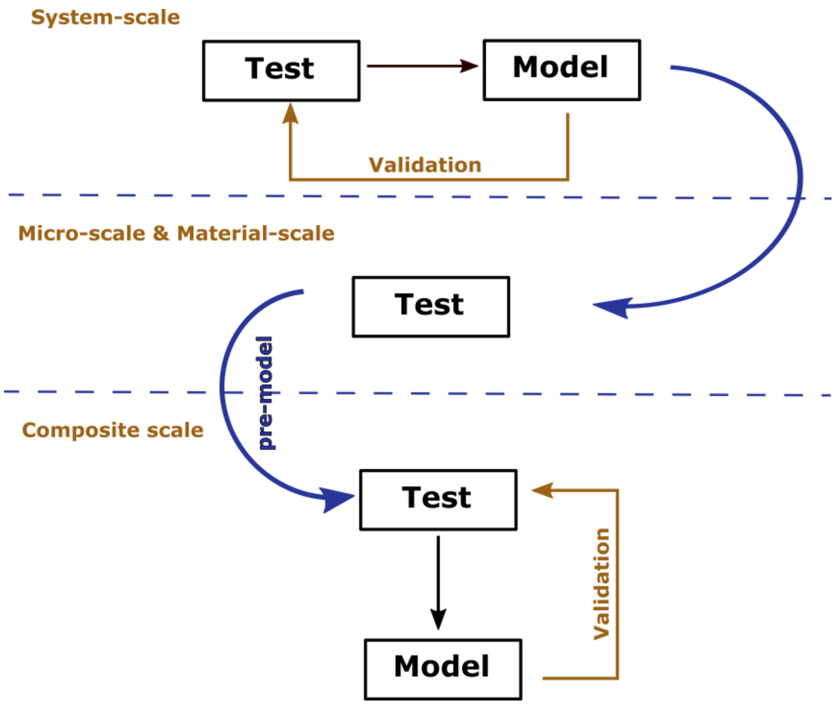


Figure 34: Steps in the interactive process of testing and modelling

6.2 Experimental methods

Micro-scale test methods and Material-scale methods

Bomb calorimetry and MCC were used to obtain the heat of combustion of stone wool. Bomb calorimetry (ISO 1716, 2010) provides the gross heat of combustion in a pure oxygen environment, which might not be representative of what occurs in real compartment fire where the oxygen content is much lower. MCC tests (ASTM D7309-11, 2011) were performed in air environment. Results were slightly different between values reported from bomb calorimetry and MCC. It could be that the reaction linked to the crystallization of the stone wool fibres was not captured in the MCC tests because of reaching a lower maximum temperatures. MCC and TGA (ASTM E1131-08, 2014) test results showed high noise in the retrieved data. This can be linked to the low percentage in organic content that is reacting in the stone wool. Tests on the organic component of the stone wool could have provided less noise in the data, however that material was not directly available. TGA tests were performed in air and nitrogen atmospheres, which allows to identify pyrolysis and oxidative reactions.

A modified slug calorimeter (Bentz, 2007;Bentz *et al.*, 2006; Bentz *et al.*, 2008) was used to obtain the thermal conductivity of stone wool at elevated temperatures. The modification from the standard were the area and thickness of the slug, and the number of thermocouples used to monitor the temperatures. There was one thermocouple in each of the retaining plates and in the slug. In the modified slug calorimetry tests it was assumed that one-dimensional heat transfer occurs symmetrically from both sides of the specimen. This assumption was justified by the fact that the specimen is located in the centre of the oven and cladded by the restraining plates. The effective thermal conductivity was calculated based on a one-dimensional heat conduction assumption, lumping together any radiation or convection that could occur in the porous matrix. Constant values of specific heat and mass of the stone wool and the stainless steel slug were assumed. The thermal conductivity was calculated based on test results at 5 K/min, during the second heating cycle. In the first heating cycle the organic content of the wool was combusted, so the test results were not appropriate to calculate the thermal conductivity. One of the limitations of the test method is that uncertainties in the assumed specific heat and mass will result in an error in the deduced thermal conductivity. The thermal conductivity values obtained are only valid after the heat has penetrated the sample. Another limitation from the experimental set-up was that the heating was not linear. However, this was overcome by using the experimental values when obtaining the thermal conductivity.

Gypsum plasterboards are fragile materials with much lower strength in tension than in compression. Due to its brittleness, direct tensile tests are of limited feasibility. Hence, bending tests were designed to obtain the reduction of strength at elevated temperature. Three-point bending tests were used as opposed to four point bending tests for its simplicity. Three-point bending tests have been used by previous authors (Cramer *et al.*, 2003; Rahmanian, 2011). However, the punctual application of the load in the specimen might damage the sample, and results would be biased if a heterogeneity in the material is present at the loading point. Thus, four-point bending test might provide more reliable and repeatable results. Only a handful set of tests were performed using the developed methodology to only one type of gypsum boards. Further tests are recommended to validate the results, limit random errors, and quantify systematic errors from the components: linear transducer, load cell, dimensions of the samples, location of the loads, electronic signals, etc. Also the applicability of the test set-up to other types of boards should be studied. For the isothermal conditions, the samples were preheated in an electric oven for one hour, until it was considered they reached steady state. Later, they were taken out from the oven and left at ambient temperature for 10 minutes. This procedure was followed to have a consistent way of testing. However, during the cooling down the material could undergo a degradation process including cracking that would affect its resistance. Ideally, tests should be performed while the boards are kept in steady isothermal conditions. The direction of the fibres and the paper lining played an important role on the strength of the boards. The contribution of these parameters to the fire resistance of gypsum plasterboards should be further investigated.

Composite and system-scale test methods

The test methods used in this thesis to evaluate the heat transfer through the cross-section of the selected building barriers include: a reduced-scale furnace of dimension 1.46×1.46×1.5 m^3 where samples of 500×500 mm^2 were tested, a movable radiant panel (H-TRIS) where samples of 500×500 mm^2 were tested, a large-scale furnace of dimensions 3.2×3.2×1.5 m^3 where the wall tested was 3×3 m^2, and a compartment test where the tested wall had dimensions of 2.14×2.3 m^2.

In early stages of the fire exposure in full-scale tests, the building barrier response is dominated by heat transfer. Once higher temperature values are reached, the materials undergo severe degradation that can lead to deflections and mechanical failures of the materials (e.g. cracking, fall-off) that will greatly influence its response. Such severe degradation effects cannot be observed in relatively small size constructions. Thus, the composite reduced-scale test methods are only valid as an extrapolation tool of full-scale tests, limited to the assumption of one dimensional heat transfer. In order to validate this assumption thermocouples were placed in different locations of the cross-section and minimum deviation was found between them. Furthermore, temperature measurements from small-scale tests and large scale tests were compared showing good agreement. Further effects than heat transfer are difficult to be extrapolated from reduced-scale tests because dimensions of the components, connection between different materials, mechanical stresses and orientation of the board will influence its response. The specimen’s orientation, whether vertical or horizontal, also influences the convective heating and cooling of the specimens, the gas movement within the constructions, and deformations due to gravitational loads.

The different testing procedures provided the heating exposures by a radiant panel (H-TRIS), a gas furnace, an electric furnace, and a heptane pool fire. Those different exposures imply different radiative and convective boundary conditions, oxygen concentrations and pressure differences. All those parameters need to be taken into account when comparing results from different experimental set-ups.

The gas combustion inside furnaces leads to complex heat transfer between the burners, the furnace boundaries, the sample tested and the gas phase. The determination of view factors and convective heat transfer coefficients is cumbersome. However, if temperatures inside the furnace are controlled by plate thermometers as required in the standard ISO 834, the effective thermal exposure defined by the plate thermometer can be assumed as the exposed temperature of the specimen, as opposed of having to determine convective and radiative boundaries (Wickström, 2016). The convective and radiative boundary conditions from radiant panels in open spaces (e.g. H-TRIS) are easier to determine (Maluk, 2014).

In standard furnace tests the pressure difference between the inside and outside of the furnace is 20 Pa, and might govern pressure difference mass transport in porous media. In H-TRIS tests the pressure difference is zero, as both sides are in open space, the mass transport could dominated by buoyancy effects.

The availability of oxygen is a fundamental parameter affecting combustion. In the majority of the furnace tests performed the oxygen availability is about 6%, which is much lower than in ambient conditions (21%). In a fully developed compartment fire, the availability of oxygen will vary in different stages of the fire, from ambient values prior to flashover and very low values during the fully developed phase of the fire. Figure 35 shows an example of the oxygen concentrations fires measured in a kitchen compartment fire (B. Andres et al., 2019). The oxygen concentration values reported in the fully developed phase of the fire vary between 10 % and almost zero.

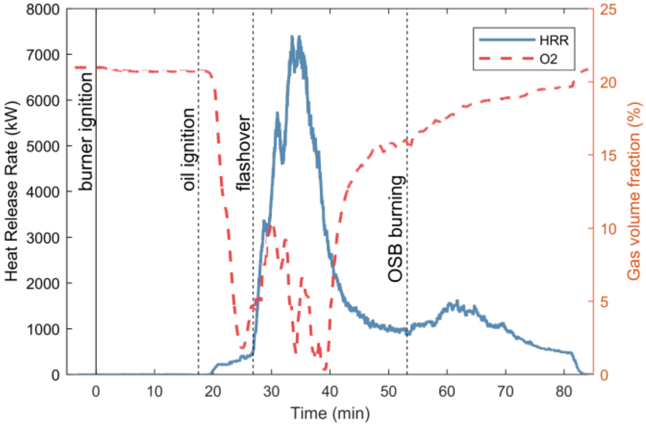


Figure 35: Heat release rate and oxygen concentration during a real compartment kitchen fire (from (Andres *et al.*, 2019)**)**

Figure 36 shows the temperature on the unexposed side of steel-stone wool composite with and without steel cladding on the exposed side, tested in a small-scale electric furnace in which ambient air is being supplied into the combustion chamber (Andres *et al.*, 2017). The figure shows the potential effects on the unexposed side temperature of having enough oxygen to undergo combustion together with pressure driven mass transport.

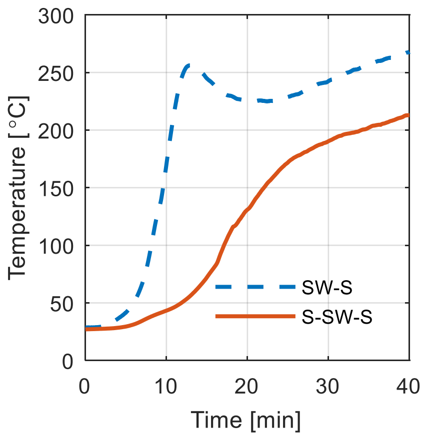


Figure 36: Temperature on the unexposed side of a stone wool-steel composite with and without steel cladding on the exposed side, tested in an electric furnace (from (Andres *et al.*, 2017)**)**

Another important parameter to account for experimental limitations is the instrumentation. Test results strongly depend on the measurement devices. In this thesis, the temperatures have been measured by type K thermocouples in all the experimental set-ups. In the full-scale fire tests, two different attachment methods of the thermocouples to the unexposed side of the wall were compared. One group of thermocouples were attached according to EN 1363:1999 method, were a copper disc thermocouple is attached with a glued pad. The second group of thermocouples were attached using aluminium tape. Figure 37 shows the average measured (lines) and standard deviation (shaded area) of the temperatures measured on the unexposed side with both attachment methods. Results show that thermocouples attached with aluminium tape gave on average of 11% higher readings.

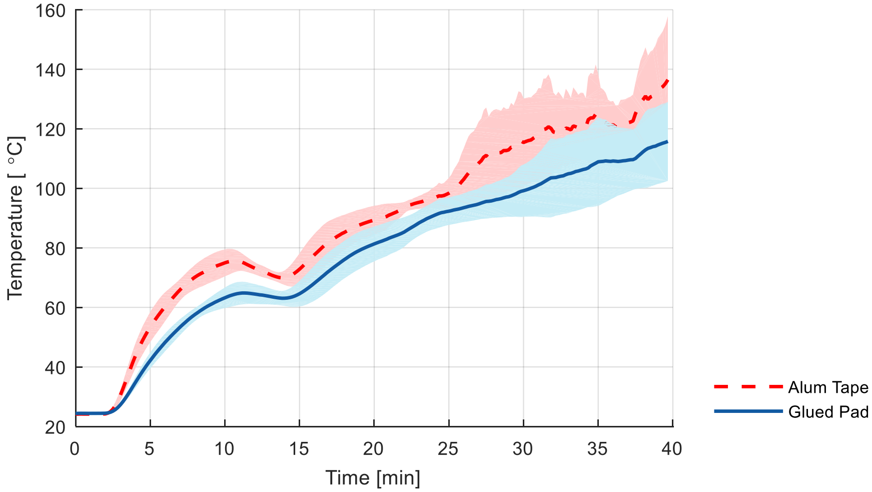


Figure 37: Unexposed side temperatures of gyspums stone wool building barrier measured with thermocouples attached with two different methods (from (Andres *et al.*, 2017)**)**

6.3 Models

There is an inherent relationship between the modelling assumptions and the material properties used. Depending on which phenomena are being explicitly accounted for in the modelling, the material properties need to be defined. As an example, calcination reactions in gypsum plasterboards have been taken into account as temperature variable specific heat, and as an external energy source with a kinetic reaction model in this thesis.

The modelling assumptions imply a limitation on the validity of the models, which need to be taken into account when using the models in other conditions than the one they have been developed for. In many cases, increasing the complexity of the models to account for specific phenomena require the definition of input parameters that bear an error. Thus, more complex models do not always imply more accurate predictions (Bal and Rein, 2013).

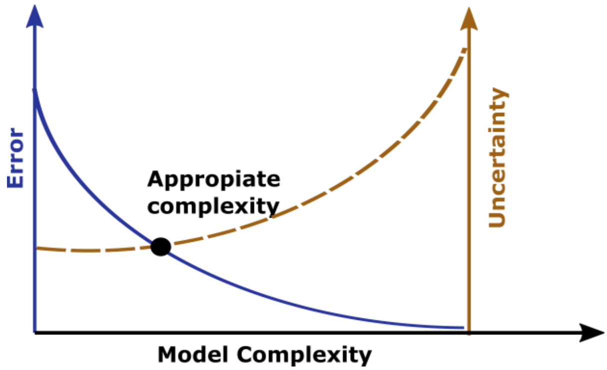


Figure 38: Appropriate level of model complexity (adapted from(Bal and Rein, 2013)**)**

The developed heat transfer models are one-dimensional and they disregard complex geometries in the constructions or studding. The one-dimensional assumption was validated in the test, by thermocouples placed in different location to ensure the main direction of heat transfer. Additionally, two-dimensional models were compared to one-dimensional to further validate the assumption. Thus, the models presented are only valid in applications were the main direction of heat transfer is through and where the influence of surrounding materials is minimal. The heat transfer models do not include the mechanical degradation or falling-off of boards. The models are considered valid as long as there are no failures, or large deformation in the construction.

The thermal model requires a set of boundary conditions to define the heat exposure to the material, and the cooling on the unexposed side. Those conditions are considered as radiative and convective boundaries in the thermal model, which requires either the possibility to calculate or assumptions on parameters such as convective heat transfer coefficient and emissivity. The definition of those parameters imply uncertainties in the modelling outcome. Likewise, the material thermal properties used to model heat transfer through the construction imply certain assumptions. For instance the thermal conductivity of stone wool obtained with the modified slug calorimetry is an effective thermal conductivity that lumps together possible radiation or convection inside its porous matrix. However, its applicability to model the different heat exposures has been proven. On the other hand, including the energy released by the reactions occurring in the stone wool in the heat transfer model did not provide better predictions when the stone wool is cladded by an impermeable material (e.g. steel cladding), or in furnace tests with low oxygen content. Even in the cases where the reaction occurs it releases less energy than what it is observed in micro-scale testing. Further investigation is needed to link the conditions between larger composite-scales and micro-scale tests, as well as an investigation of the environmental conditions in a furnace test or in real compartment fire scenarios.

In this thesis, a material model for gypsum plasterboard was developed, providing stress-strain relationships at elevated temperatures. However, further work is needed to prove the validity of the developed material model to responses in transient heat exposures. Additionally the effect of crack formation due to shrinkage, thermal expansion and creep needs to be further investigated.

7. Conclusions

The overall objective of this work has been to implement a methodology to understand and model the behaviour of building barriers subject to standard fires and alternative fire exposures. This has been achieved by applying a multi-scale approach for testing and modelling the behaviour of a handful set of building barriers under different heat exposures. The work is a combination of numerical and experimental methods aiming for a better understanding of material thermal degradation phenomena, and the interaction between materials in a composite. The main novelties of the presented work are:

- Systematic experimental investigation of material behaviour in different scales, and under different heat exposures. Micro-scale tests (MCC and TGA) on stone wool samples in a controlled atmosphere environment have shown reactions occurring in the stone wool that could be linked to the combustion of the organic content. Slug calorimeter tests, used to retrieve thermal conductivity, also showed an increase of temperature that could be linked to an internal reaction occurring in the stone wool. Testing stone wool as part of a layered composite, with steel and gypsum cladding exposed to different levels of heat, helped identifying phenomena such as, combustion of the organic content, dehydration reactions of gypsum plasterboard, and burning of paper lining.
- Building on complexity of heat transfer modelling using material properties obtained at a reduced scale. Based on the material properties obtained at micro and small-scale, heat and heat and mass transfer with energy released by reactions occurring in the material were obtained. Results have shown how smaller scale test results are not directly applicable at larger scales as environmental conditions differ. Hence, not always building up in model complexity leads to better modelling predictions. Yet, a systematic approach for modelling and testing has been proven to be beneficial to understand and model the response of building barriers to heat exposure.
- An experimental set-up to perform three-point bending tests to samples previously heated. These tests characterize gypsum plasterboards mechanical properties degradation with temperature. Further, the built set-up allows for testing under variable heat and load simultaneously. Results

showed a slight increase in strength of gypsum plasterboard at 80 °C, and a loss of 90 % of its strength at 300 °C.

- A method for understanding the most influential parameters when conducting heat transfer analysis. The methodology was applied to steel-stone wool composites exposed to the standard temperature-time exposure. It provides basis to foresee which parameters are affecting the heat transfer, and allocate the efforts on defining the most important parameters to achieve better modelling predictions.

The prediction methodology and the models developed presented herein, can be used for product development to support industry before performing expensive and environmentally damaging classification tests. Further, testing and modelling under different heat exposures is the way forward to understand constructions behaviours in different fire scenarios. Instead of focusing the analysis on a singular case scenario, it can support informed decisions on the consequences of a set of fires defining a spectrum of risk.

8. Future Work

Based on the work performed within this thesis framework, the following topics are identified for further investigation.

Characterization of fire testing conditions

The exposure to materials while undergoing fire tests is complex. The exposure in fire tests is achieved by using radiant panels, gas or electric furnaces, pool fires and so on. The type of heat exposure will affect the heat being transferred to the specimen in terms of convective or radiative boundaries. Furthermore, the surrounding environmental conditions to the specimen are also important. For instance, the availability of oxygen to undergo combustion. When performing fire tests it is necessary to assess how well the testing conditions will represent the fire scenario we are aiming for. Further, when models are developed and validated against test results a series of assumptions are undertaken in the areas of material properties and boundary conditions. Those assumptions are somehow interlinked and further analysis needs to be conducted to better characterize exposure in fire testing and relate it to realistic fire conditions.

Using material properties retrieved at micro and material-scale to model larger scales

The direct use of material properties obtained at a reduced scale to characterize reactions occurring in the material when exposed to heat at larger scale has led to over-predictions of the temperatures. Hence, implying that the reactions as characterized at smaller scale have limited applicability at larger scales. Further work to assess the differences between tests performed at different scales is recommended.

Building up in model complexity

The modelling conducted in this thesis has been limited to heat and heat and mass transfer. However, in reality deformations and thermo-mechanical stresses are present in constructions exposed to fire. Further work is suggested to validate the thermo-mechanical model developed for gypsum plasterboard by coupling a thermal and a structural FE model.

There is also the need to develop systematic ways of testing the thermo-mechanical response of building materials (in particular protection boards), as the fire resistance of a construction is in many cases inherently dependent on them. This is for example the case on timber constructions, where the encapsulation is ensuring in many cases their fire safety. However, protective boards are typically rated under standard fire exposure and dissimilar behaviours in other type of exposures can lead to undesirable levels of risk. A systematic analysis of the effect of cooling phases in the degradation of thermo-mechanical properties would provide a better understanding of their encapsulation protection in realistic fire conditions. Furthermore, cracking of fragile materials due to thermal expansion, shrinkage and creep need to be further investigated.

Validation of models under different fire scenarios, building risk associated to different scenarios

The models presented herein need to be further validated, including more test data to be able to quantify experimental error, and uncertainties linked to material heterogeneities, measurements devices, environmental conditions and overall uncertainties in the system. Application of the models to other heat exposures and potentially other materials also needs to be investigated.

A multi-scale approach for modelling and testing can be useful for the industry by supporting product development. Further, it can characterize the response of building constructions under a wider range of fire exposures, helping defining a spectrum scenarios rather than just one worst-case scenario. This would help moving towards probabilistic analysis of fire safety rather than deterministic, and facilitate the use of risk levels.

Increase in modelling capabilities

It is expected that the growth of computational capabilities together with large amounts of data will lead to better modelling capabilities. In the latest years, a growth in the field of artificial intelligence and data analysis has led to modelling predictions that tend to simplify complicated physics to be treated as simple data points. The future entails for hybrid modelling, where simplified physics will be combined with data analysis, to provide more accurate and efficient modelling predictions.

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Annex – Appended Papers

Paper I	Andres B. and van Hees P. (2015) “Experimental and thermal analysis of wall assemblies exposed to standard and parametric fires”, *Proceedings of the 1st International conference on structural safety under fire & blast (CONFAB 2015),* Glasgow, 2-4 September 2015. Glasgow: ASRANet, Ltd. ISBN (Electronic): 978-0-9930121-2-9
Paper II	Andres B. and van Hees P. (2016) “Mechanical properties of gypsum plasterboards exposed to standard fires”. *Interflam 2016 Proceedings of the 14th International Conference.*4-6 July 2016, Nr Windsor, UK, pp 1051-1062
Paper III	Livkiss K., Andres B., Johansson N. and van Hees P. (2017) “Uncertainties in modelling heat transfer in fire resistance tests: a case study of stone wool sandwich panels”, *Fire and Materials 2017;41;799-807.* DOI: 10.1002/fam.2419
Paper IV	Livkiss K., Andres B., Bhargava A. and van Hees P. (2018) “Characterization of stone wool properties for fire engineering calculations”, *Journal of Fire Sciences 2018. Vol 36(3) 202-223* DOI: 10.1177/0734904118761818
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