Tactical approach to a travelling fire phenomenon

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Tiivistelmä

Tämän opinnäytetyö on tehty osana Pelastusopiston ja Aalto-yliopiston yhteishanketta, joka tutkii vaeltavan palon turvallista sammuttamista. Hankkeen tarkoituksena oli laajentaa näkökulmia rakennemitoituksesta sammutus- ja pelastustoiminnan tehokkuuden ja turvallisuuden suuntaan. Opinnäytetyön tavoitteena oli selvittää vaeltavan palon ilmiötä ja sen vaikusta metalli rakenteisiin, selvittää eri maiden sammutustaktiikoita hallipaloihin liittyen ja analysoida Aalto-yliopiston tutkijoiden tekemien FDS-simulointien tuloksia pelastustoiminnan näkökulmasta.

Opinnäytetyön yhteydessä toteutettiin kyselytutkimus sähköpostitse henkilöille, jotka valikoituivat kansainvälisestä ryhmästä, jossa keskustellaan pelastusalaan liittyviä kysymyksiä ja ilmiöitä. Kyselytutkimuksen tavoitteena oli saada selville eri maiden sammutustaktiikoita hallipaloihin liittyen. Vastauksia saatiin Ruotsista, Yhdysvalloista, Kanadasta ja Hong Kongista. Näistä vastauksista tehtiin koonti eri sammutustaktiikoista. Sammutustaktiikoista löytyi monia selviä yhtäläisyyksiä, mutta myös eroja teknisessä toteutuksessa. Näitä taktiikoita analysoitiin yhdessä Aalto-yliopiston tutkijoiden FDS-simulointien kanssa.

Opinnäytetyössä opittua tietoa voidaan soveltaa laajemmin pelastustoiminnassa ja hallipalojen sammutuksessa. Opittua tietoa voidaan myös soveltaa lisätutkimuksissa.

Avainsanat
Vaeltava palo, metallirakenteet, sammutustaktiikka, FDS-simuloinnit

ABSTRACT

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Abstract

This final project is done as part of Emergency Service Academy Finland's and Aalto University's joint arrangement that studies safe extinguishing of travelling fire. The goal of the arrangement was to extend viewpoints from structural dimensioning in the direction of extinguishing and rescue operations efficiency and safety. The goal of the final project was to clarify the Travelling Fire Phenomenon and its impact to metal structures, to find out extinguishing tactics from different countries touching warehouse fires and analyze the results of FDS simulations done by Aalto University's researchers.

During this final project, a questionnaire was implemented through email to person who were chosen from an international group discussing questions and phenomena related to rescue field. The goal of the questionnaire was to find out different extinguishing tactics touching warehouse fires. Answers were gained from Sweden, The United States, Canada, and Hong Kong. From these answers' a compilation was done about different kind of tactics. Many similarities were found from the extinguishing tactics but also differences in technical implementations were found. These tactics were analyzed together with the FDS simulations done by Aalto University's researchers.

The learned information of this final project can be applied more widely in rescue operations and in extinguish of warehouse fires. Learned information can be applied in further research.

Keywords
Travelling fire, metal structures, extinguishing tactic, FDS simulations

CONTENT

CONCEPTS AND DEFINITIONS

Travelling fire methodology (TFM)

Travelling fire methodology is a new fire phenomenon used to better understand the fire dynamics and the travelling character of the fire in an open space rooms, buildings, and compartments. Travelling fire methodology is used in structural design to understand the fire impact on structure farther away from the fire.

FDS (Fire Dynamic Simulator)

FDS is a computational fluid dynamics (CFD) model of fire-driven fluid flow. The software solves numerically a form of the Navier-Stokes NIST equations appropriate for low-speed, thermally - driven flow, with an emphasis on smoke and heat transport from fires.

Gas cooling

Firefighting tactic where hot smoke and gases are cooled with water spray and so affecting the fire. Right size water droplets and spray volume cools the gases and when vaporized takes out the space from air that flows into fire. Gas cooling is used with ventilation to get the best benefit out of the tactic.

Structure cooling

Firefighting tactic where hot surfaces and structures are cooled during fire. The water spray is aimed at the structures and surfaces that are affected by the fire and so cool them and keep them stable. The water spray that does not hit the structure can hit the fire and so reduce the heat release rate of the fire.

Horizontal ventilation

Horizontal ventilation is a ventilation technique where air flows into the building from openings in the wall like doors and windows and made holes in the walls. The hot smoke and gases flow out of the fire from other opening made into doors, windows, and made holes in the walls. The openings used to ventilate locates on the same level with the fire.

Vertical ventilation

Vertical ventilation is a ventilation technique where air flows into the building from openings in the walls like doors, windows, and made holes in the walls and where hot smoke and gases flows out of the fire from opening in the roof and structures above the fire.

Flow path

Flow path is used to understand the air flow during fire. The flow path is formed from the air flow during fire where cool air flows into the fire from openings and hot gases and hot air flows out of the fire from other openings. Flow path reflects the cool and hot air movement inside the building into flow path.

Wind driven fires

Wind driven fire is any fire where the wind effects an abnormal acceleration or spread of fire. Also, the direction of flow path. This is caused by any air movement that can affect the fire. Usually wind driven fires are observed in high risen building fires.

1 INTRODUCTION

High-risen buildings, open offices, warehouses, and many other buildings nowadays are made of long span open framed steel structures. These structural elements can lose their load bearing capacity when exposed to high temperatures. This implies that there is a need for a fire safety design that ensures the structure will resist fire.

Several design methods for fire safety have been created to study structure behavior during a fire. Conventional design methods assume homogenous temperature fields within a structure. Such an assumption might be valid for small compartments (< 100 m^2) but in larger compartments, fires generally create a non-uniform temperature field. Recently, Stern Gottfried and Rein presented the Travelling Fire Methodology to explain the behavior of fires in large, open plan structures.

The Travelling Fire Methodology proposes that in large compartments fire tend to move along the floor plates creating a non-homogenous temperature field. The method is used to analyze the behavior of the structure that is affected by fluctuating temperatures by the non-uniform burning. Travelling Fire Methodology separates the temperature field into two separate regions, the near field, and the far field. The near field is the burning region of the fire where the flames affect the structures, and the far field is the region remote from the fire where combustible gases affect the structures.

This means that a travelling fire can also affect structures further away of the local fire area. The travelling phenomenon of the fire can cause sudden bending and collapsing of the structure when it is affected by a long period of fluctuating heating and cooling cycles. These changes can happen as the fire moves across the compartment or during the firefighting intervention with water sprays where structures are cooled suddenly.

Open space compartments like large open offices and non-uniform fires in them pose several challenges to the basic compartment firefighting tactics. The danger of structural collapses and other unknown factors of the travelling fire can change the firefighting conditions rapidly. The current firefighting tactics need to be examined from the perspective of the travelling fire phenomenon to make firefighters' rescue work safer and more effective. It is important to learn more about the fire and structure behavior in large open space platforms so that the extinguishing can be done efficiently and safely depending on the situation. With right tactical decisions the fire spreading can be slowed down, and structures can retain their stability.

2 THE BACKGROUND OF THIS FINAL PROJECT

The topic for this final project comes from the Emergency Service Academy Finland's Research, Development, and Innovation service units *Travelling Fire* project. This project is done in collaboration with Aalto University and is part of Aalto University's research project 'Robust steel-frame buildings during and after fire' and is part of the Phase 2 'Safe intervention in travelling fires of steel-framed buildings.'

The goal of the Aalto University's research Phase 2 was to receive answers for three questions:
(1) What is the optimal and safe way to apply water suppression for a travelling fire in a large open structure?
(2) How does the rapid cooling affect the strength and stability of a long-span structure made of high-strength steel?
(3) Are there needs to update the education and instruction of fire suppression tactics?

The main research is done by two Aalto University's doctoral candidates Shakil Saani and Rahul Kallada Janardhan who are working on their doctoral degrees through this research. They will publish their research later. The subject will be about travelling fire phenomenon and structural response of cooling the metal beam structure of the building. The research is done to understand more about travelling fire phenomenon combined with firefighting and from these to understand more of the structural stability. These can be then transferred into fire designing methods of structures.

The Emergency Service Academy Finland's part in the research was to offer the operational viewpoint of the firefighting field and transfer the learned tactics and the results of the simulations done by the Aalto University's researchers to define effective firefighting tactics for managing large fires in buildings. To get a comprehensive understanding, tactics were studied from around the world.

2.1 Used research methods

To learn more about the firefighting tactics of different countries emails were sent to contact persons who were chosen from a group of persons that discusses firefighting topics and are involved in research and education of the field of firefighting in their countries. These persons were chosen by Marko Hassinen who works as a Senior Research Scientist in the Research, Development, and Innovation Services unit of the Emergency Service Academy Finland, who sent a heads-up message about the topic and questions.

The questions were sent to these contact persons about firefighting tactics and main things to consider when fighting large building fires. The answers were used to gain a common idea of different kind of tactics and approaches when fighting a large building fire. These tactics with the learnings of the Aalto University's research were used to learn new ways to approach large building fires that travel further from the main fire in the open space.

2.2 Topic delimitation

Through the Aalto University's research, the topic of this final project was delimited to a warehouse building called 'Ruukki building'. The simulations of the Aalto University's doctoral candidates were based on this building and especially on the metal beam structures that were also used in the Ruukki building. The firefighting tactics were studied based on the Ruukki building and fires inside that type of building.

Travelling fire methodology is a resent method to simulate and design buildings. The fires that travel are not studied very much and is not a well-known phenomenon in Finland. Travelling fires could also occur in tunnels and open space building especially in high-risen buildings. The travelling character of the fire could be attached to many types of fires especially where the air movement is a major factor during the fire. The travelling fire phenomenon covers many different kinds of fires and it can be taken into account in many kinds of building fires.

3. CONVENTIONAL FIRE ANALYZIS METHODS

3.1 Standard temperature-time curve

The first standard temperature-time curve was published 1917 to be used for presenting fire safety design of structures and it forms the basis of several standards such as the ISO 834, ASTM E119 and BS 476 standards. The standard temperature-time curve was developed by collating the results from various post-flashover fire tests. These standards have been the basis for fire rating systems in most building standards and codes around the world.
"The tests that fed into the development of the standard fire were intended to represent worst case fires in enclosure to determine if the structure could withstand burnout". (Fire Safety Journal 54 2012, 76-77.)

This part of the ISO 834 specifies a test method for determining the fire resistance of various elements of construction when subjected to standard fire exposure conditions. The test data thus obtained will permit subsequent classification based on the duration for which the performance of the tested elements under these conditions satisfies specified criteria (Standard ISO 834-1, 2014.)

For classification tests the ISO 834 standard has its own standard temperature-time curve for standard fire exposure conditions. For every tested element, the curve is the same and the fire burn uniform. This allows for a direct comparison between standard fire tests of components rather than giving an indication of how long the component will survive in the fire. (Standard ISO 834-1, 2014.)

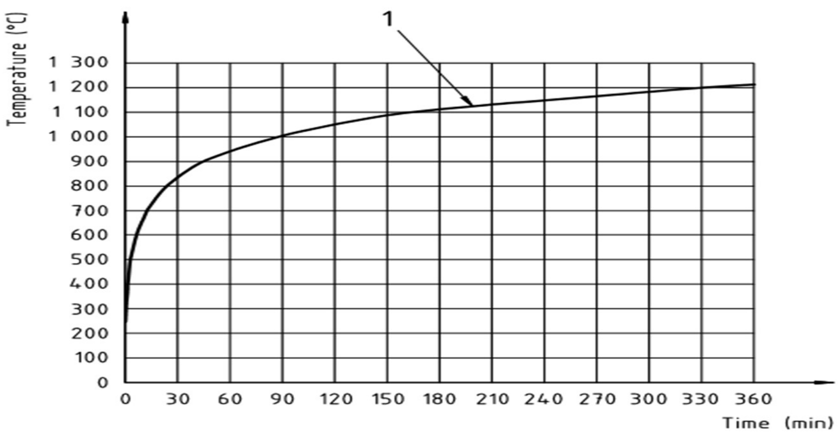

Figure 1. ISO 834 standards temperature-time curve (Standard ISO 834-1, 2014)

3.2 Parametric temperature-time curve

Another method for structural fire engineering is using the parametric temperature-time curve. Parametric temperature-time curve considers fuel loads, compartment linings, ventilation factors and the features of surfaces. These were added after a small enclosure test and the better understanding of fire dynamics. The assumption for parametric fires is that the temperature of the compartments is uniform. This limits its use to post flashover fires in a small compartment. (Fire Safety Journal 54 2012, 75.)

The european standard EN 1991-1-2 called Eurocode 1 uses the parametric temperature-time curve to describe the mechanical and thermal actions for the structural design when buildings are exposed to fire. In the Eurocode 1, the parametric curve is explained: "*determined on the basis of fire models and the specific physical parameters defining the conditions in the fire compartment"*. There are limitations where parametric curve can be used for example the Eurocode has its own limitations. As it is written to Eurocode 1:" The following temperature-time curves are valid for fire compartments up to 500 m^2 of floor area, without openings in the roof and for a maximum compartment height of 4 m. It is assumed that the fire load of the compartment is completely burnt out." (EN 1991-1-2, 2002).

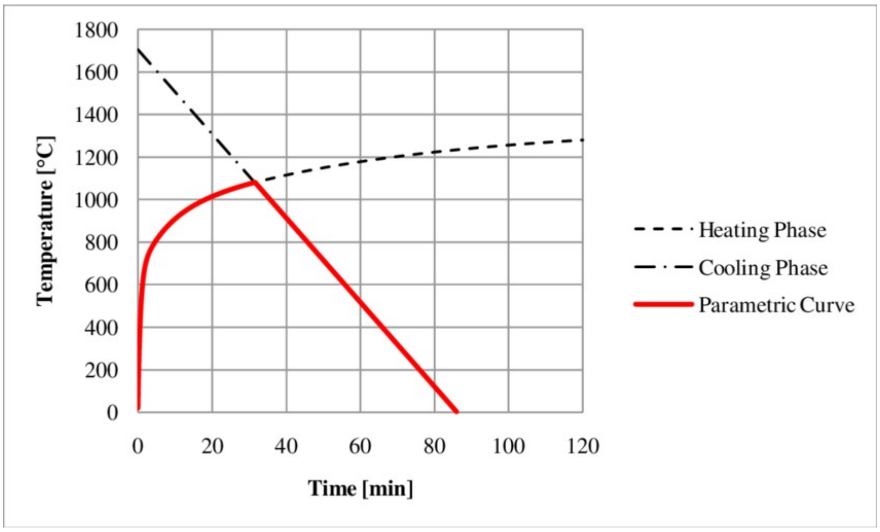

Figure 2. Example of a parametric temperature-time curve (Ljubinkovic 2016)

3.3 Local fire

In a local fire the fire develops two temperature zones, a hot zone on the top and a cool zone on the bottom of the compartment. The two-zone model is used in compartment fires to count the gas temperatures and estimate the spread of smoke. The assumption is that the heat is divided evenly in the heat zones. The programs based on numerical calculations are called zone models. These models use the information of the geometry, the building, the thermal feature of the surface and information from the fire like temperature and fire power. With this information and with the fire location the fire and smoke spreading can be calculated and modelled inside an apartment or compartment. Also, the results show the temperature of both gas layers, the air flow of the openings and the temperatures of the surfaces. (Outinen, 496-497 2006.)

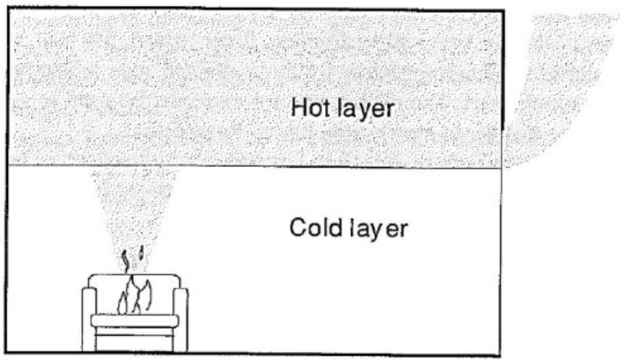

Figure 3. Two zone model in a compartment

Two fire models to estimate the local fire load on horizontal structures above the fire have been developed and these are called the Heskestad and the Hasemi methods. The Heskestad method is used to count the heat load in a local fire. Differences in the temperatures of the structures come from the ratio of the height of the flame and the height of the compartment. The Hasemi method is a simple tool to count the effect of the local fire on the structures above the flames. It bases on burning tests made in Japan. For application, Hasemi method uses the heat release rate of the fire, the height of the interior, the distance between floor surfaces and fire sources, and the effective diameter of the fire. (Outinen, 497-498 2006.)

3.4 Travelling Fire Methodology

The standard and parametric curves require uniform burning and homogenous temperatures in a full compartment involvement when a local fire look at a part of the structure which is in impact of the fire. None of these fires involve fire spreading in a large compartment and increased smoke temperatures farther away from the local fire. For this reason, a new design concept was originated in the University of Edinburgh 2007 called the travelling fire methodology by J. Stern-Gottfried and G. Rein. (Fire Safety Journal 54 2012, 78-79.)

Many large-scale building fires around the world like the World Trade Center Towers 1, 2 and 7 in New York 2011, the Faculty of Architecture building at TU Delft in the Netherlands in 2008 and the Windsor Tower in Madrid, Spain in 2005 brought up the need of a new methodology. In these buildings the fire was observed to travel inside the building across the floor plates which caused multiple fires and nonuniform burning. The same observation has been made in nonuniformly ventilated compartments. One similarity of these buildings is that they are all open space office style buildings where the fire has room to travel inside the smoke farther away. This has been observed to cause structural failure mechanisms and part collapses. (Fire Safety Journal 54 2012, 76-77.)

Stern-Gottfried J and Rein G explains the term travelling fire the next:
"Close inspection of accidental fires in large, open-plan compartments reveals that they do not burn simultaneously throughout the entire enclosure. Instead, these fires tend to move across floor plates as flames spread, burning over a limited area at any one time. These fires have been labelled "travelling fires".

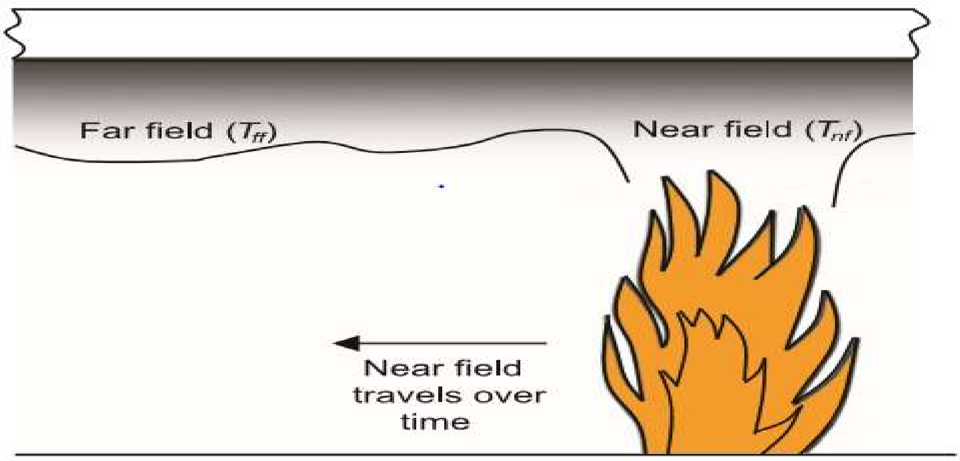

Figure 4. Travelling fire methodology's far field and near field (Fire Safety Journal 54 2012, 78).

In the travelling fire methodology, the burning area and the effect of the fire and heat is divided to two separate fields. Figure 4. of the travelling fire fields shows the difference between the far field and the near field. The near field consists of the area right beside the flames where the structure and surface are directly affected by the fire. The near field is the flaming region. The far field consists of the hot smoke gases that are remote from the flames. In the far field the structure and surface are affected by the hot combustion gases in the smoke layer. The near field experiences more intense heating than the far field. Structures will be affected by the far field conditions for most of the fire time and near field conditions when the fire is local. For this reason, the temperature of each field must be quantified. To represent the worst-case scenario the travelling fire method assumes that the temperature in the near field is about 1200 C. In compartment fires this is the temperature observed in the upper bound of flames. The temperature in the far field decreases with the distance of the fire. The hottest part affected by the gases is in the ceiling, so the ceiling temperature is used in the travelling fire methodology. In the travelling fire methodology, a calculation method for the far field can be used that takes geometry and fire size as inputs and produces temperature as a function of distance from the fire. It can be any engineering tool to count the temperatures in the far field. Travelling fire methodology is modular to these tools. (Fire Safety Journal 2012, 107.)

3.4.1 Further research of the original Travelling Fire Methodology

Stern-Gottfried's and Rein's original Travelling Fire Methodology has been studied more afterwards and there are different studies and tests done to develop and refine the original travelling fire methodology.

A study called Improved Travelling Fire Methodology done in 2015 refines the original Travelling Fire Methodology. In this study three improvements were done to the original methodology. The study examines the limitations to the fires through available fuel load, burning rate and fire spread. The study reduces analytical correlations for gas time-temperature curves to count the realistic far-field temperatures after founding out errors up to 12,7% and 20% for total burning durations respectively depending on the grid size chosen and peak bay temperatures through parameter sensitivity study. The earlier Travelling Fire Methodology assumed the compartment to be divided into discrete nodes where the use of compartment floor discretization adds unnecessary complexity to the problem and reduces accuracy.

Refines are done also to the near-field temperatures for smaller size fires. In the original Travelling Fire Methodology, the near field temperature was set on 1200 ˚C, but the concept of flapping of the flames and mixing of cooler air makes the temperature to reduce and the cover range is refined to 800–1200˚C. This covers more the real fire scenarios and temperatures observed in real fire scenarios. (Rackauskaitea; Hamela; Rein, 2015)

Another study called" A Conceptual Framework for a Design Travelling Fire for Large Compartments with Fire Resistant Islands" done 2016 includes the structural response and fire resistance of structure during travelling fire and is used for measuring the fire resistance for structural design. The other models do not include accumulation of hot smoke layers and the global structural response while they are both developed for application of structural designs. This new method uses the mobilised Hasemi localized fire model for near field and simple smoke layer calculation for far field and these two are combined to calculate the temperature on structure on the plume location and away from the burning region. Also, the structural analysis as the final object is applicated with a fire-resistant core in the middle of an open plan office floorplate. This method uses the concept of regulatory minimum fuel depth (RMFD) that is linked with fire spread rate and fuel load density. The RFMD refers to the fuel layer on the floor plate that contributes to the total heat flux calculation. (Dai; Jiang; Maclean; Welch; Usmani, 2016.)

The travelling fire speed of the Hasemi localized fire and the heat release rate of the travelling fires are the two most important patterns in this method where travelling fire speed determines how long the structure element is affected by the localized burning of the Hasemi model and the heat release rate determines the thermal energy per time release. The burning area of fuel and burn-out time are used to calculate the total travel speed and the heat release rate of the fire.

The limitations to this model are that the fire is fuel-controlled, and it is a 1-D trajectory-model of travelling fire. On the Hasemi local fire model limitations are that the fire diameter has to be less than 10 meters and the heat release rate maximum is 50 MW. (Dai; Jiang; Maclean; Welch; Usmani, 2016.)

4. ASPECT OF AIR

When fire travels across the floor pattern and farther away from the so-called near field to the far field, air movement and airflow is always included. Burning needs air for the combustion reaction and it needs to release the hot gases and smokes to be able to keep burning. As it shows in the travelling fire phenomenon the fire can travel in the hot smokes and gases and burn when affected by fresh air in an outlet or opening where fresh air is attached to the hot gases. Fires can be controlled when the air movement is controlled the right way and when not, the fire can spread rapidly, and the fire conditions can change rapidly.

To understand more about the aspect of air, two different phenomena will be introduced. These both are hardly noticed and studied in Finland but rather in England and North America. These phenomena are called the flow path and wind driven fires.

4.1 Flow path

” The flow path is the space through which fire, heat and smoke progress, moving from an inlet and the high-pressure fire area to were the fire wants to go – forward lower pressure oxygen sources, outlet areas such as door and window openings” (UL-NIST 2012)

The flow path thinking is from the 1980s when two different firefighting strategies were compared to each other. In the USA ventilation and opening making was main part of the firefighting tactics and in the United Kingdom isolating the fire into the burning room was the tactic. These two tactics were compared to each other and a thought of something between occurred. This brought the thinking of using smoke ventilation and opening making the right way as part of firefighting tactics to extinguish the fire. Flow path thinking is used especially in smaller building and compartments where the fresh air flow to the fire can be limited or even cut off. (Grimwood 2017, 356.)

Figure 5. Cool zone and hot zone in flow path. (Grimwood 2017, 375)

Flow path thinking divides the airflow inside the burning house into two different zones. The cool zone is the zone where cool air floats into the fire and burning area. The hot zone is the zone where hot air floats out towards an opening away from the fire and burning area. For firefighters it is important to control this flow and so making the firefighting safer inside the building. When the flow path is controlled the right way with openings and smoke ventilation, the firefighters can attack and approach the fire through the cool zone. With wrong timed and based openings and ventilation the conditions inside the building can change rapidly and so cause danger situations and pressure changes inside the burning building. The danger is that the firefighters must approach the fire through the hot zone. (Grimwood 2017, 374-375)

The flow path is formed through basic air dynamics. Fires always form changes in the air pressure and air, fire gases, heat and smoke are driven by the differences in pressure changes in the outlets and inlets. The heat of the fire causes excess pressure which is the biggest pressure change when the hot air and gases expand and flows towards any outlets to escape the fire. The fresh air flowing into the fire is caused by a vacuum that the fire creates. This pressure division can be seen in the two-zone model where the upper part of the hot layer has the excess pressure of the hot gases and air that expand and escapes the fire. The lower part has a vacuum where fresh air flows into the fire. The rapid changes of pressure in the building during a fire can change the direction of the flow path and make the conditions dangerous inside the building. (Grimwood 2017, 376.)

An example of a flow path that occurred in Finland can be found in the Turku eight floor apartment house fire in 2014. A fire occurred in an apartment on the second floor where the occupant of the apartment left the apartment but died at the apartment door blocking the door to the stairwell so it could not be closed. The cool zone was formed when the windows broke causing the air to flow into the fire though the windows. The hot zone was formed into the stairway when the automatic smoke extraction hatches of the stairway opened, and the plastic skylight windows melted causing the air to move into the stairway and up to the openings. This caused a so-called flue phenomenon or a flow path into the stairway that strengthened when firefighters opened the front door. The temperatures increased rapidly and investigations showed that the 30-minute fire doors of the apartments burned in 22 minutes. (Tutkintaselostus Y2014-02.)

4.2 Wind driven fires

NFCC Hazard Uncontrolled Ventilation article describes the wind-driven fire: “'wind-driven fire' has no formal definition under ISO or in UK fire and rescue service manuals. It is, however, becoming the standard generic term for fires that may also be referred to as force draught, wind-assisted, force vented or blowtorched.” Wind driven fires are not a special type of fires, but it includes lots of different phenomena that can happen during wind, high velocity air movements and pressure changes. Wind driven fires in building fires occur mostly in high-rise building fires were external wind affects the speed and direction of fire, for example, through window failure. (Hazard - Uncontrolled ventilation.)

Four main points can be separated to understand wind driven fires. These are wind and wind patterns, wind pressure, wind loading and high energy fires.

Wind and wind pattern explain the natural phenomenon of wind movement that is caused by temperature and pressure differentials and the effect of the rotation of the planet.

Wind pressure explains the physical characteristics of air movements through fluid dynamics science. This explains the positive and negative pressures when wind is hitting an object and going over and around it. Also, the difference in air pressure makes the air flow to balance the difference.

Wind loading explains the force exert created by pressurization. This is a critical part of building design because of the effect of strong winds against the structure.

High energy fires explain the fires that liberate a notably high amount of energy and can be caused by an oxygen source or characters of the fuel. It is important to notice that high energy fires is not an official term. Wind driven fires are the most common high energy fires in high rise building fires. This is due to the straight effect of wind to the fire. Wind causes oversupply of oxygen that causes the fuel to burn at a higher temperature, the fuel will burn more quickly, and the fuel releases energy at a higher rate. (Wind driven fires 2013.)

Two tests were carried out to study more about wind driven fires in the USA, Governor Island New York. These experiments provided more information about wind driven fires and possible tactics. The results provided several notes about the wind driven fires. Small changes in ventilation and inlets of air can change the conditions rapidly and even a window opening can cause the fire to increase. Important is to notice that smoke is also fuel and ventilation does not always equal cooling. Also, the flow path and air flow during a fire are important aspects, when facing wind driven fires. The air flow and the flow path can change the conditions rapidly and push the rich smoke towards fresh air causing flashes. From a tactical view wind and flow path control and pressure control are important ways to control the fire during wind driven conditions. Also, a right type and correctly aimed water streams can slow down the fire. (NIST Technical note 1629 2009.)

As the experiments and articles show wind driven fires are not a special type of fires but the term is used to understand more about the air movement and rapid changes of air flow and flow path during fires. Mostly in building fires wind driven fires occur in high-rise buildings because the building is more affected by wind. In open spaces the air movement during a fire can cause the fire travel and so wind driven fires can be studied alongside with the travelling fire phenomenon.

5 FDS SIMULATIONS

5.1 Training area test

Two phases of experimental tests were made at the practice area of the Emergency Service Academy Finland in the end of November 2019. In these experiments the objective was to get a water-monitor spray characterization and an experiment of a rapid cooling of fire exposed steel beams. The information gathered in these experiments were transferred into FDS simulations. These experiments were carried out by Aalto University researchers Rahul Kallada and Saani Sakim as part of their study of the travelling fire phenomenon. The Emergency Service Academy Finland collaborated by spraying the water from one of the Academy's fire truck and organizing the location and temperature recording thermal couples to perform the burning tests at the Academy's training area.

The water-monitor spray characterization was made with the bucket test where two different kind of water sprays, one-meter wide and three-meter wide, were characterized by spraying water with a water cannon into different kind of bucket patterns. A total of eight different test were made. After each water spray tests the buckets were weight and the data collected and transferred into FDS simulations. With the bucket test the spray width and length of the spray were measured so a real spray model could be transferred into simulations (Doctoral student Rahul Kallada Janardhan, lecture 8.18.2020.)

In the burning test a steel beam was exposed to fire for a total of 15 minutes and eight different burn tests were made to calculate the heat transfer in the metal beam. The temperature of the beam was measured with a total of eleven thermocouples which were attached into the metal beam. After surgent time of the fire exposure the steel beam was cooled with the one-meter and three-meter width water spray for 15 seconds depending on the test setup. This experiment was done because the FDS did not have a water-cooling metal model. With these experiments the FDS code now includes water cooling for metal. The gained information is used in simulations that are made in the Ruukki express building later when simulating the travelling fire phenomenon (Doctoral student Shakil Saani, lecture 8.18.2020)

With these experiments and collected data more simulations were done by Aalto researchers to study the travelling fire phenomenon. The data from the bucket tests and burning tests are used to study the travelling fire inside the Ruukki building. The bucket tests data is used to build a simulated water spray so during the simulations the fire can be extinguished with the spray and cool the structures. The burning test data is used to understand and simulate the cooling effect of the water sprays to the metal beams and the metal frame of the simulated building.

5.2 Ruukki building

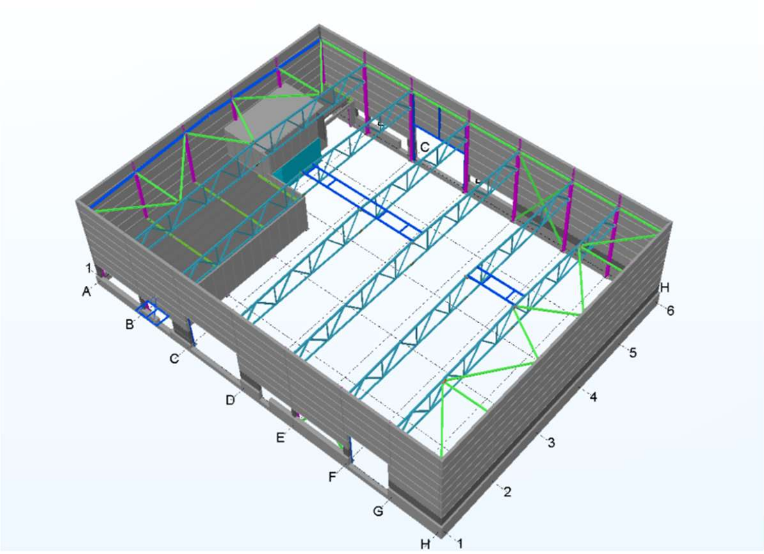

Figure 6. Layout of the Ruukki Express building (Doctoral student Rahul Kallada Janardhan, email 8.3.2020).

The so called Ruukki building shown in figure 6. which the simulations are based on is a real building and its location is in Tampere and it is owned by Ruukki Express. The building is metal framed, and the dimensions of the building are 38 m x 31 m x 9,6 m and the surface area is 1140m^2. The building has a warehouse area and a separated office area inside the warehouse in the other end of the building. The offices are separate fire sections, and the walls are made of concrete. There are several doors and openings on both sides of the longer walls.

Materials of the warehouse frame are next:

Columns - STEEL/S355J2H

Beams - STEEL/S420MH

Walls – Sandwich structure (Steel sheet + Mineral wool)

Roof - STEEL/S350GD+Z (This is corrugated steel)

The building has a total of six long span trusses made from steel. These trusses support the ceiling and the roof (Doctoral student Rahul Kallada Janardhan, email 8.3.2020)

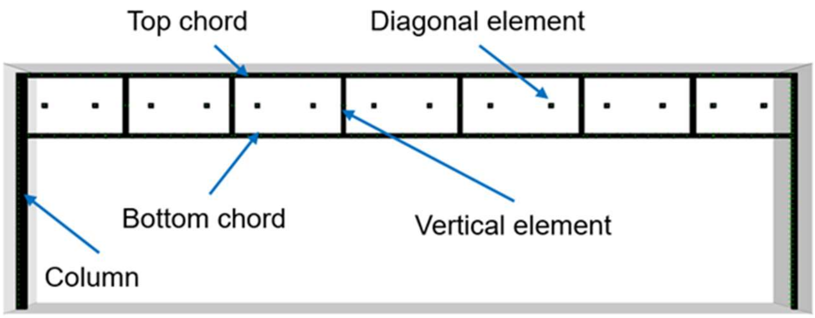

Figure 7. FDS model of the frame showing the simplified diagonal elements (Doctoral student Rahul Kallada Janardhan, document 3.16.2021).

The columns are 9.2 m high and are modelled as 200 mm thick hollow rectangular elements. The lower beam and upper beam in the model are 30.4 m and 30.8 m long respectively. The vertical elements are 2.2 m long and were placed at the same locations as in the actual truss. The diagonals are modelled as a simplified one grid cell thick cubical elements, placed along the centre of the truss. This is done as the FDS currently does not support such geometries. (Doctoral student Rahul Kallada Janardhan, document 3.16.2021.)

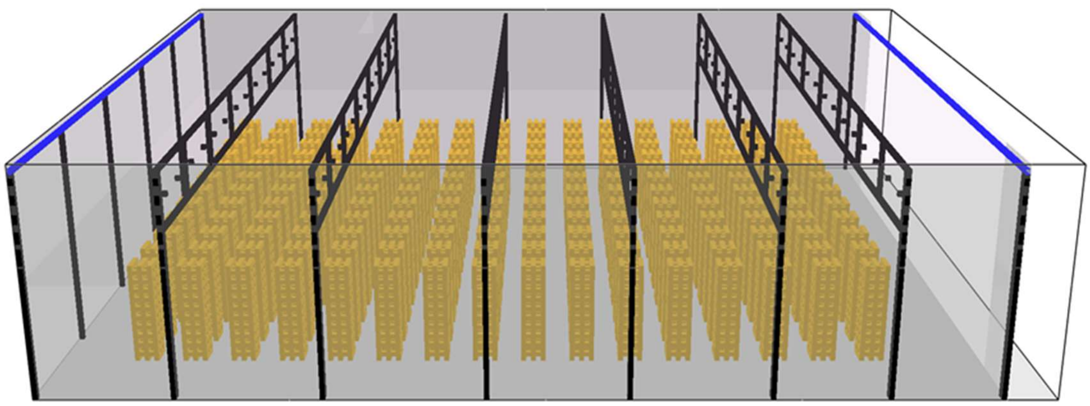

Figure 8. The simplified FDS model of Ruukki warehouse building used in the simulations. (Doctoral student Rahul Kallada Janardhan, email 8.3.2020.)

Figure 8. shows that inside the warehouse there are a total of 12 rows of shelves that are used to storage different kinds of items. The height of the shelves are over four meters. These shelves are used as fire load in Aalto University's simulations with FDS. Figure 7. also shows the side and layout of the separated offices inside the building.

5.2.1 Building code

The Ruukki building is considered as a warehouse building that has an office space in one end of the building. The assumption is that the warehouse belongs to fire hazard class 1 according to Finland's national building code 958/2017, which is the basic class for warehouses that do not storage a large number of hazardous materials inside the building but rather are used for normal item storage. The building code 958/2017 also demands that the office space must be separated as a separate fire section and it needs a fire-resistant wall between the office and the warehouse space. When the surface area is total of a 1140m^2 and the height of the building is under nine meters, the warehouse counts as fire class P3, which is the minimum level of fire safety in the building. This means that inside the warehouse the weight bearing framework does not have any requirements of how long the structure can stand fire without collapsing. In this building the bearing framework consist of the metal span trusses (Figure 7.). When the office and the warehouse spaces count as different fire sections, the code 958/2017 gives requirements that the framework and the wall between these two spaces must resist fire for 30 minutes. The office area has its own building safety and fire resistance requirements that can also be found of Finland's national building code 958/2017. (Finland's national building code 958/2017)

5.2.2 Safety of the firefighters related on aspect of Ruukki building

When choosing a tactic for a warehouse fire and a larger volume fire, fire fighters' safety is an important aspect. The warehouse environment has many kinds of challenges and risks that smaller compartment fires do not have. In this research the risks and dangers are studied from the Finland's building code, Finland's building stocks and the Ruukki Express buildings viewpoint.

The first thing to notice when arriving to the fire scene is the buildings fire class, which in the Ruukki type of building commonly is P3 and is a so called small industrial hall. This fire class has the weakest fire safety standards and requirements of fire resistance ability and there are no standards for the roof bearing structures to stand fire for a certain time so it can collapse suddenly. The weight bearing materials are usually made of wood or steel. The smoke extraction can be designed from the windows that need to be broken and the doors are used as exits. There might not be any fire sections inside the building and if there is, its class in EI30 that should resist fire for 30 minutes. In the Ruukki building between the offices and the warehouse there is a fire-resistant wall. (Teollisuushallien rakenteellinen paloturvallisuus pelastustoiminnassa 2020.)

Fire and rescue work during a fire in a class P3 warehouse requires its own aspects to consider. The most important aspect is the weight bearing structure and its stability during a fire. There are no guarantees when the structure can collapse. Also, the fire spreading is an important aspect. The insulation in the walls and roof can be combustible and the fire can spread rapidly inside the structures in the insulation. The warehouses and workshops can have lots of fire load inside the building and have flammable liquids and gases stored and used in them. The fire load and materials inside can produce significant amounts of smoke that makes the fire and rescue work harder and so ventilation should be considered at the beginning. Shelves, the maze-like spaces and long distances make the extinguishing hard and the fire should be limited with several water sprays. (Teollisuushallien rakenteellinen paloturvallisuus pelastustoiminnassa 2020.)

The figure 7 shows the layout of the Ruukki building from inside. There are several rows of tall shelves that make the fire and rescue work challenging. The shelves might not stand the fire long and can collapse during the rescue work. The shelves make it hard to aim the water sprays straight to the fire. The metal beam span trusses (Figure 7) that are the weight bearing structures in the Ruukki building are long stretch metal beams and there is lot of space between the metal trusses. The structures between the weight bearing structures are so called secondary structures that have no fire safety requirements. These secondary structures can collapse whenever during the fire.

5.3 Fire resistance of steel structure

Steel structures during fire and high temperatures loses it weight bearing capacity due to losing strength and resilience. With fire design the fire resistance of the structure can be studied and trough the design it can be ensured that the steel structure lasts the required time of fire resistance. For this reason, the highest temperature for the steel structure must be determined and during a fire the stress is counted with the prevailing load. Also, the critical temperature is counted during fire deign. Steel structure fire resistance is improved by fire protection (Vallioniemi 2019, 28).

The steel structures used in constructions are basic steels, climate corrosion resistant and rustproof steel. The strength of the steel makes it different compared, for example. to concrete, brick, and wood. Steel and metal structures usually conducts electricity and heat well and they are nonflammable. Steel can lose it wight bearing capacity in the early phase of heat rise even in 10-20 minutes after ignition. Also, a long time in a high temperature over 400 °C leads into steel structure to creep. The metal structure loses all its strength in 1000 °C temperature (Liimatta 2020, 46).

The structures used in the Aalto University's research are steel structures. In the travelling fire studies the pulsive temperature changes in the structure are studied to understand the behavior of the steel structure during travelling fire conditions when temperature changes are the important factor when studying the fire resistance of the structure.

5.4 Suppression simulations

The simulation results shown below were performed by Aalto University's researcher Rahul Kallada Janardhan. The simulations were carried out with the FDS version 6.7.5 (Fire Dynamics Simulator) and were performed to test suppression tactics for large fire scenarios and the effectiveness of the tactical approach of structural cooling. These simulations were a major part of the Aalto University's research.

The fire load distribution within the structure was modelled to represent a crude version of rack storage systems in warehouses. A total of 204 wood piles with a height of 4.2 m were arranged in the structure with a spacing of 1.0 m in between each pile. Each wood stick in the pile was 0.2 m thick and 1.0 m long. Each layer of the pile consists of 3 sticks and each pile consisted of 21 layers of sticks. According to the Finnish Building codes, warehouses have a fire load density above 1200 MJ/m^2 and in this study, a value of 1300 MJ/m^2 is taken as the fire load density within the structure. (Doctoral student Rahul Kallada Janardhan, document 3.16.2021.)

The temporal development of the fire can be divided into three phases – 1. growth phase 2. rapid spread to the opening and burning at the opening and 3. backward spread phase.

In the simulations the fire starts to develop around seven minutes creating a hot plume above the wood pile. The maximum gas temperature experienced by the truss above the plume is around 700 °C. By 10 minutes the wood pile above the initial fire begins to burn producing a classical ceiling jet and a clear hot gas layer is observed near the ceiling. The gas temperature is around 1000 °C above the plume centreline. By 11 minutes, the fire starts to spread to the adjacent wood pile. This is accompanied by a reduction in oxygen around the burning region. By 16 minutes, the flashover phase is reached, and fire has spread to the third pile. During this phase the gas temperature experienced by the trusses in the entire compartment ranges from 700 – 1000 °C. By 21 minutes, the burning is observed only at the opening and the trusses near the opening are exposed to a temperature close to 1000 °C. The other trusses in the compartment experience a temperature around 600 °C. Around 25 minutes from ignition, the fire starts to travel back into the compartment as it completely consumes the fire load at the opening. (Doctoral student Rahul Kallada Janardhan, document 16.3.2021.)

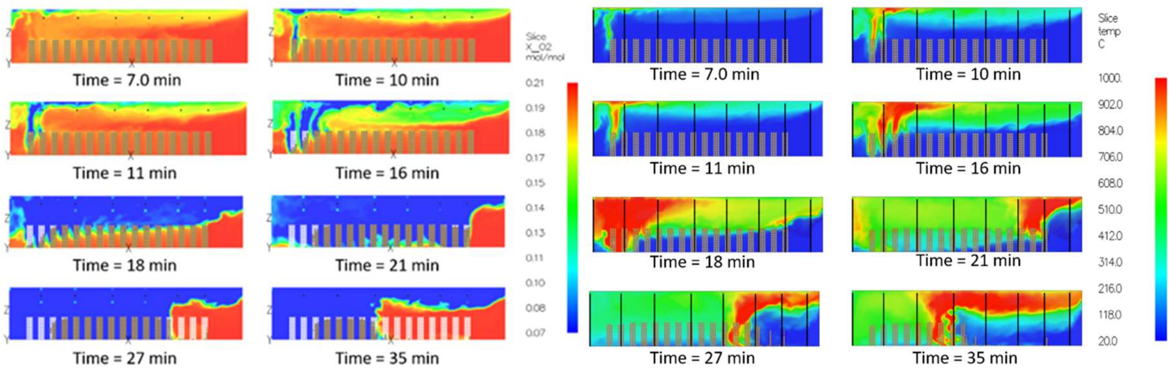

Figure 9. Predicted oxygen concentrations and temperature (vectors) along Y=15 m at different times from the scenario 1: fire path perpendicular to the trusses. (Doctoral student Rahul Kallada Janardhan, document 3.16.2021).

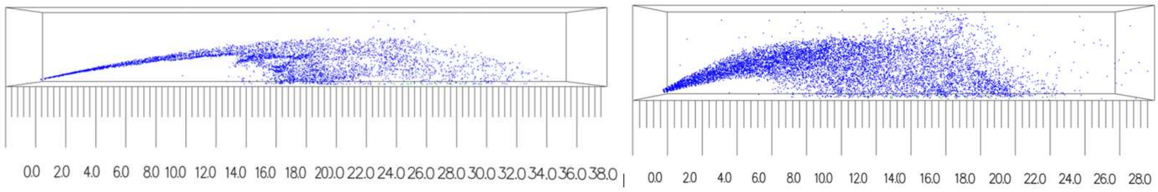

Figure 10. the charachterized 1 m wide and 3 m wide water sprays. (Doctoral student Rahul Kallada Janardhan, document 3.16.2021).

The bucket tests performed at the training area were used to characterize the one-meter and three-meter-wide water-monitor sprays. Figure 10. shows the FDS simulated water sprays used in the suppression simulations in the Ruukki warehouse building. The 1-meter-wide spray with a throw of -38 meters was used in the suppression simulations. The nozzle pressure of the sprays was 10 bar. The flow rate at the nozzle was 650 L/min and 1750 L/min for the 1.0 m and 3.0 m sprays, respectively.

The simulation parameters that were varied are listed below:

1. Water sprays: The number of water sprays used for the suppression action.
2. Residence time: The residence time is the duration for which a spray stays at one position.
3. Sweep angle: Sweep angle is the angle between the nozzle positions after every 30 seconds.

(Doctoral student Rahul Kallada Janardhan, document 16.3.2021.)

Set 1: Intervention time = 900 seconds, Duration= 180 seconds

In the first set of simulations the suppression starts at 9000 second or 15 minutes from ignition. This is based on the UK statistics of the fire brigade's response times for suburban fires. This includes the time required detection, time for the call and other miscellaneous actions such as setup of the hoses at the location. This is also the last possible intervention time before the fire transitions from a localized fire to spreading fire around 1000 seconds. This means that the fire brigade would have 1.5 minutes to prevent the spreading. The duration of the suppression is 180 seconds, and it assumes that the first smaller fire truck reaches the fire scenario first. (Doctoral student Rahul Kallada Janardhan, document 16.3.2021.)

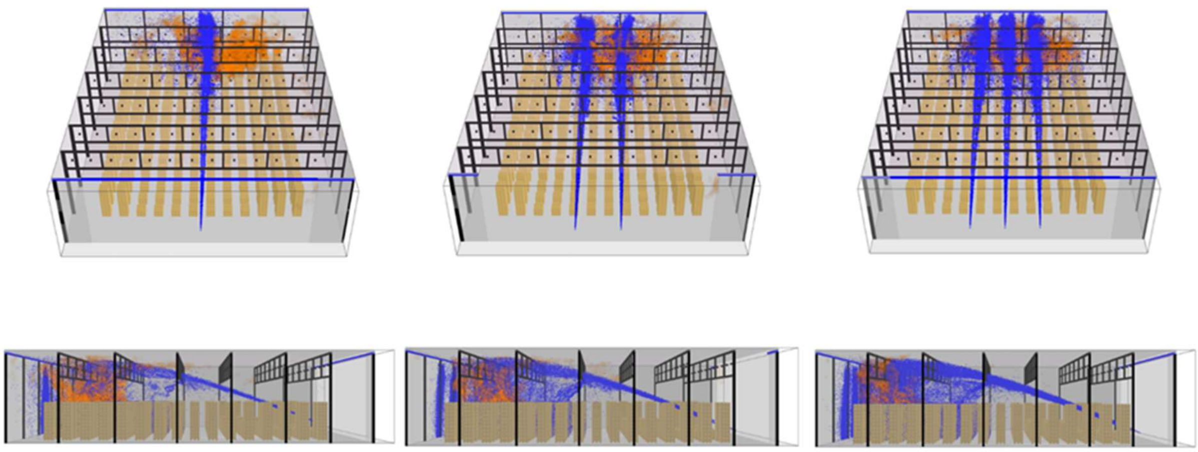

Figure 51. Illustration of the different spray scenarios, their arrangment and region of impact. (Doctoral student Rahul Kallada Janardhan, document 16.3.2021).

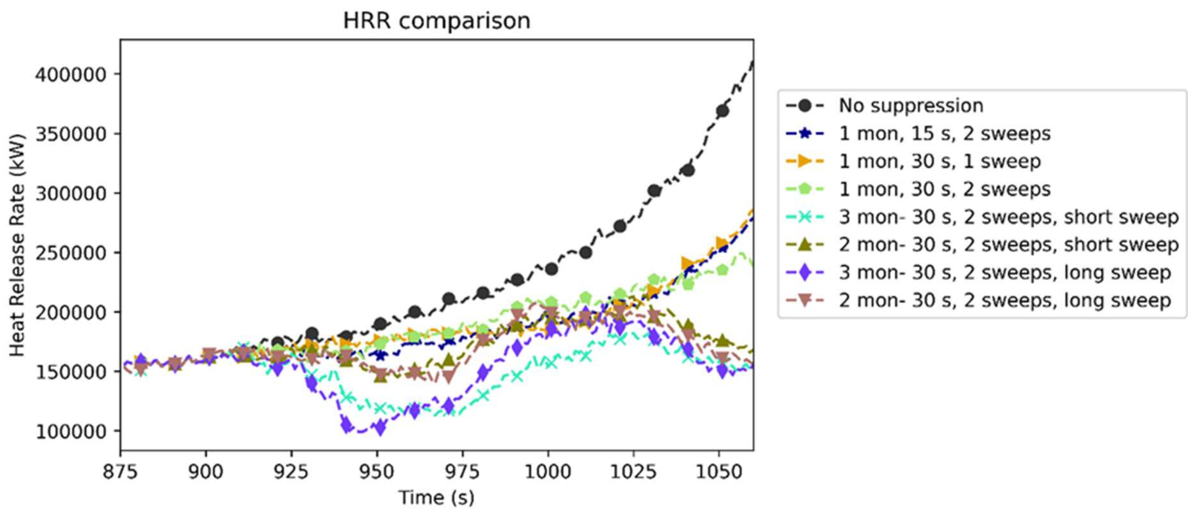

Figure 62. Comparison of the influence of suppression on the heat release rate curves for the different spray configurations. (Doctoral student Rahul Kallada Janardhan, document 3.16.2021).

From the perspective of cooling power, a single spray delivers 650 L/min

$$\dot{m}_f = 650\frac{L}{min} = 650\frac{kg}{min} = 10.8\frac{kg}{s}$$

$$Latent\ heat\ of\ vaporization\ of\ water, L_v^{H_2O} = 2300\frac{kJ}{kg}$$

$$\dot{W}_{absorbed} = \frac{2300\ \times 650}{60} \approx 25000\ kW$$

$$\dot{Q}_{t=\ 900\ s} = \ \ 165000\ kW$$

$$\frac{\dot{Q}}{\dot{W}} = \frac{165000}{25000} = 6.6$$

Figure 12. shows that the suppression with 3 monitors is the most effective to control the fire over 180 seconds. The simulations and calculations performed by Kallada Janardhan of Heat Release Rate and cooling power of the 650 L per minute sprays show that when using one monitor for suppression the energy abstraction rate is 6.6 times lower than the energy produced by the fire meaning that using low flow rates of water instead of decreasing the fire it might accelerate the fire spread. (Doctoral student Rahul Kallada Janardhan, document 3.16.2021.)

Set 2: Intervention time = 900 seconds, Duration= 360 seconds

Another set of simulations were done with a suppression period of 360 seconds. The suppression period chosen by Kallada Janardhan (document, 16.3.2021) referring Särdqvists report where a minimum suppression period of 360 seconds required for extinguishing during a large-scale suppression experiment conducted in Sweden. (Doctoral student Rahul Kallada Janardhan, document 16.3.2021.)

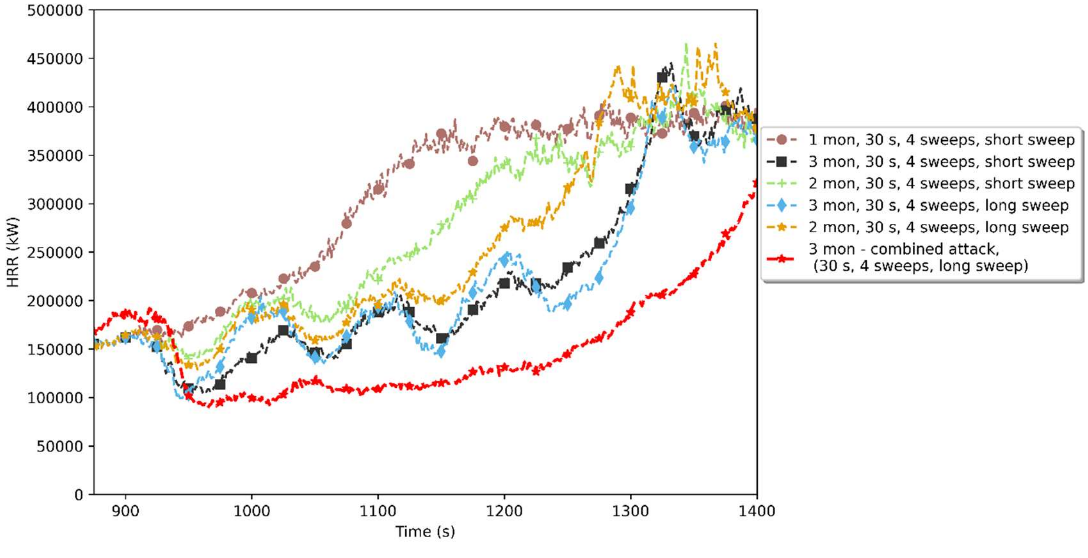

Figure 73. Comparison of the influence of suppression duration of 360 seconds on the heat releasse rate curves for the different spray configurations. (Doctoral student Rahul Kallada Janardhan, document 16.3.2021).

These results show that even with a 360 second suppression period the flames are not fully controlled, and they spread away from the region affected by cooling. These simulations do not include the actions of the firefighters when the fire starts spreading on the sides. The water sprays are aimed to cool the same region even though the fire starts to spread on the sides. This would not happen when the firefighters are suppressing the fire but rather the fire fighters would aim the spray towards the burning region. (Doctoral student Rahul Kallada Janardhan, lecture 16.3.2021.)

Set 3: Intervention time = 600 seconds, Duration= 180 seconds

The third sets of simulation were done to answer the question about earlier suppression time and the suppression started at 600 seconds or 10 minutes after the fire started. The suppression time was chosen to be 180 seconds assuming the first fire truck arriving to the scene would be with a smaller water capacity. (Doctoral student Rahul Kallada Janardhan, document 16.3.2021.)

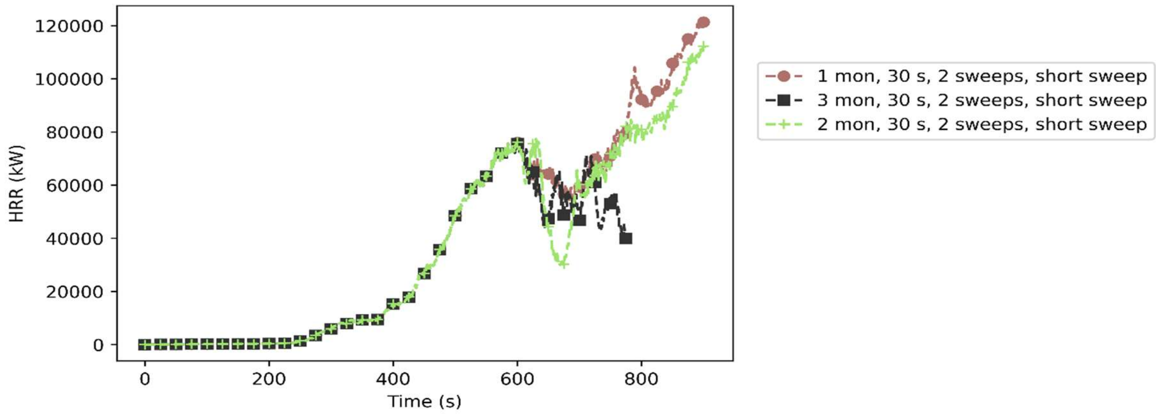

Figure 84. Comparison of the influence of suppression at 600 seconds on the heat release rate for the different spray configurations. (Doctoral student Rahul Kallada Janardhan, document 16.3.2021).

These simulations show that even at an earlier suppression time the fire is difficult extinguish completely. A longer suppression time could yield better results at extinguishing the fire and thereby reducing the temperatures experienced by the structures.

Kallada Janardhan sums up the simulations that adopting a single approach is not useful, there is a danger of fire spreading and becoming uncontrollable. He mentioned that "attempting to cool the load bearing elements within the structure reduces the thermal exposure on these elements". Also, as it is known that the load bearing capacity of the structure can significantly reduce during a fire and structural cooling might help prevent drastic loss of the load bearing capacity. The actual impact of this structural cooling on the strength reduction or post-fire performance of the structural elements is not known.

6 STUDY

As it is mentioned in paragraph 2, the Emergency Service Academy Finland’s part of this Aalto University’s research of travelling fire was to study different kind of firefighting tactics from different countries. The focus was to find different tactics and approaches in a warehouse type building fire used around the world. The objective was to find differences and similarities from the tactics to gain an understanding and thought process behind the tactics. The tactics were based on the Ruukki building which is the building the researchers of Aalto University FDS simulations are based on.

To get an understanding about the used tactics a qualitative approach was chosen. Several emails were sent to different contact person from all around the world. These contact persons were chosen by Senior Research Scientist Marko Hassinen who belongs to an international group which discusses tactics and research in the firefighting field. Hassinen sent a heads-up message to the contact persons and then an email was sent for each person who answered the heads-up message. All the contact persons have a long experience working in the firefighting field. The objective of the emails was to gain an understanding of the tactics used in the countries wherefrom the person answered.

The questions asked were:

What is the main strategy in the country?

Is it gas cooling, structural cooling or something else?

How does the firefighter’s safety show in the strategies to fight fires in a warehouse and industrial building similar to our building (Ruukki building) in this research?

Figures 5 and figure 7 about the Ruukki building were attached to the email to give an understanding about the building that the questions were based on.

A total of four persons answered the email and one skype meeting was arranged through this topic and the questions to talk about firefighting tactics. The answers were got from Sweden, Honk Kong China, USA Maryland, and Ottawa Canada. These emails included answers for the questions and several articles of this topic were received. These received answers were used to get a general idea of different kind of tactics and actions at the fire scene in a warehouse type of fire. The Skype meeting was analyzed, and all the answers were studied by the contents of the answers. These common parts of different tactics were used on the simulations to have as authentic fire event and firefighting method as possible in the Ruukki warehouse.

The simulations done by Aalto University's researcher Rahul Kallada was also used to analyze the impact of structural cooling. The results of the simulations were analyzed and learned information transferred and used on the compilation of the study with the learned tactics from around the world.

7. FIRE FIGHTING TACTICS FROM DIFFERENT COUNTRIES

7.1 Finland

The tactical approach from Finland were gained through education of the Emergency Service Academy Finland's. The tactical approach is taught during classes for fire fighters, group leaders, and fire officers. I also attended a course of warehouse fires that was a training package put-up for firefighters.

Warehouse fires require a different kind of approach than an ordinary compartment fire. In a warehouse when the fire is hard to locate and the building is full of smoke and gases, the firefighting begins from the entrance of the building. Firefighters chose a large entrance where they can start extinguishing the fire from and slowly enter the building if possible. It is important to have enough resources and adequate waterflow at the scene before attempting to extinguish the fire. (Teollisuushallien ja suurten tilojen sammuttaminen 2020.)

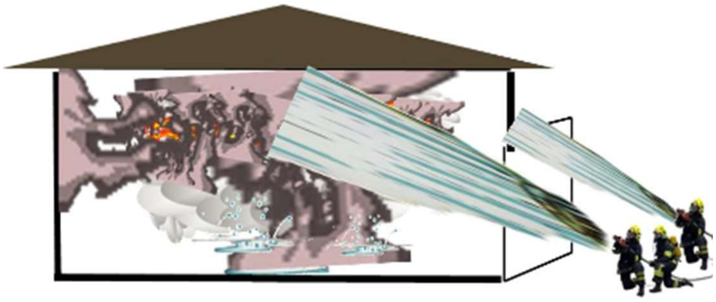

Figure 95. Indirect extinguishing and gas cooling

When starting the fire attack the setup is to have one main 75mm mainstream hose line water spray and a 42mm work hose line spray ready. The 75mm mainstream includes three fire-fighters to work on it and the 42mm stream includes two firefighters to work on it. Also, there must be adequate water flow ensure the minimum for extinguish the fire. The first step to extinguish is to get the smoke ventilation going and so get more visibility and hot gases out of the building. Smoke ventilation is done by opening the smoke extraction hatches or making openings into the roof or windows. The next step is to open a door or entrance and from the smoke boundary start spraying with the 75mm mainstream up to the hottest area in the gases with a sweeping motion from far corner to the other far corner. It is important to remember that the ventilation should be started when the hose lines are ready, and the spray-ing can be started right away after the ventilation is started. The 42mm spray is used to extinguish visible fire and support the 75mm spray. The idea of the 75mm stream is to cool gases and make steam that takes out the space from oxygen and gases from the fire and cools the hot smoke and gas layer. Same time the spray can affect the flames and the fire. When the smoke boundary moves inwards the building, firefighters move in with the edge of the smoke boundary. (Teollisuushallien ja suurten tilojen sammuttaminen 2020.)

Water droplet size is an important factor when cooling gases. With the right size of a droplet the cooling is effective, and it mixes into the hot gasses better. The too small droplet size can be lost with the gas flow and too big droplets do not vaporize, but they fly farther in and so can affect the flames directly. An optimal water droplet size vaporizes into the gases and they fly deep enough. (Teollisuushallien ja suurten tilojen sammuttaminen 2020.)

If the building is on full fire, firefighters will not enter inside of the building but rather spray water inside from openings and keep the fire inside the fire section. Also roof work and openings to the roof are possibly made and a ladder unit is used to extinguish the fire from atop. Also, the roof can be removed off with a special truck that has a grapple attached to it or even use a logging truck for this purpose.

7.2 Sweden

Lars Axelsson "Firenerd" from Sweden who works with fire fighter education and is a former firefighter, captain and battalion chief answered the email and he a had couple of thoughts about the tactics in a warehouse fire like in Ruukki building. His thought was that effectiveness of" gas cooling" is very small, this due to the fact that the mixing of hot gases and the smoke is too small to be effective. By this he refers to the gas cooling technique where short pulses with a fog nozzle is used for the spray pattern commonly used in small compartment fires.

Lars Axelsson mentioned that ventilation is the main part of the tactic and vertical ventilation is superior to horizontal ventilation. When the smoke is below 100-150 degrees the ventilation should be done" the more the better" as Axelsson says. To get the temperature from the smoke thermal camera is an useful tool or if possible, it can be checked with" exposed skin". When the smoke is too hot (above 100-150) it needs to be cooled before starting ventilation. Axelsson mentioned two ways when cooling large volumes of smoke

" *Option 1 is high pressure water systems like the Coldcut Cobra. It can mix smoke with water much better than normal nozzles. And it can be done from the outside*".

” *Option 2 is smoke cooling with straight streams with high volume. It can mix smoke with water more effective compared to gas cooling with sprays in large volumes. The methods can be combined depending on the situation*”.

Like others, Axelsson also reminds that when there is an option to put water straight into the fire that should be a priority. (Lars Axelsson, email, 227.2020.)

A Lund University PhD thesis ‘*An Engineering Approach to Fire-Fighting Tactics*’ by Stefan Särdqvist studies firefighting tactics in a environment of a chemical warehouses in Sweden. The extinguishing is divided into three separate ways, water, expansion foams and dry powder.
The extinguishing effect of water comes when water is heated and vaporized and so the heat is absorbed. There are commonly three ways to apply water into fire.

1. Small size water droplets (1.0mm) are added into the flames during the gas phase of the fire. The flame is cooled through heat absorption and so putting out the flame. An example of this kind of extinguishing is when water is sprayed through a fog nozzle into the burning smoke and gas layer. Another example can be when water is sprayed into the burning compartment through the wall or ceiling with a fog nozzle.
2. The water is added into the burning surface to reduce the pyrolysis rate of the fire and through the lack of fuel the flame goes out. Usually done when the flashover is knocked out and so can extinguish the fire. Also, during exterior extinguishing when a bigger water droplet size (2.0mm or 3.00mm) are used. Then the flames do not affect the water droplets.
3. The not burning surface is cooled so the fuel does not ignite when the pyrolysis rate does not increase. This is used during the defensive operation to wet the structures to protect ignition.

(Särdqvist 1996, 52)

7.3 USA, Maryland, Columbia

Stephen Gerber from the USA, who is a Vice President and Research Director at UL Firefighter Safety Research Institute, answered the email answering the questions and sending articles and a research article about the topic. He reminded that there are over 30 000 independent fire departments in the US and so there is no clear consensus of how to fight fires.

Quick answers to the tactical approach were that the common tactic is to deploy a 63mm hoseline and ventilate as part of a direct attack and if there was a ventilation limited fire there would be several 63mm hoselines deployed and multiple doors/windows ventilated and holes cut in the roof depending on conditions and assessment of structural stability.

Gerber also answered to extra questions that were asked. About structural cooling during a fire attack the answer was that structural cooling as an effective manner would be an interesting research. Gerber also presented a thought that cooling the steel structural members in certain circumstances could cause structural collapse depending on what contraction or deformation it may cause. In their experiments in the strip mall fires they had a clear elongation of the steel trusses that began to push the front and rear walls out that caused serious concerns of structural collapse. To question that if the water spray is aimed towards the walls and ceiling at any point during a fire the answer was that wetting walls and ceiling could be included when the fire is not visible, and the water would be directed to the direction where the fire is believed to be. (Vice President, Research Director, UL Firefighter Safety Research Institute, Stephen Gerber, email, 8.3.2020.)

Gerber mentioned the strip mall experiments where the steel trusses elongated causing concerns of structural collapse. These experiments were part of the project examining coordinated fire tactics utilizing acquired structures. The strip malls that were used were 12-unit shopping plazas and the test were done to explore the impact of ventilation in a large open volume commercial structures and the fire dynamics in them. (Exploratory Analysis of the Impact of Ventilation on Strip Mall Fires 2016.)

The goals of these experiments were:

1. Expand the body of knowledge relating to fire dynamics in larger compartment fires.
2. Evaluate the impact of horizontal ventilation in strip malls.
3. Evaluate the impact of vertical ventilation in strip malls.

These goals were set to understand more about the ventilation done by the fire service in a strip mall fires. A total of seven experiments were done that included no ventilation, three sets of horizontal ventilation and three sets of horizontal and vertical ventilation. (Exploratory Analysis of the Impact of Ventilation on Strip Mall Fires 2016.).

The experiments showed that even though the strip malls are large from size and can fit more air inside them the fire became ventilation-limited like in the smaller compartment fire experiments. When openings were done, the additional ventilation area increased the exhaust of combustion products, but also additional air entered the fire. This made the temperatures increase when the additional air added oxygen to the fire. Experiment 1-4, 6, and 7 showed that ventilation increased the heat release rate of the fire without coordinated suppression. The experiment 5 with coordinated fire suppression and vertical ventilation showed reduction in resultant fire heat release rate and in temperatures. (Exploratory Analysis of the Impact of Ventilation on Strip Mall Fires 2016.)

The strip malls have more oxygen available than smaller compartments for combustion before needing more air and oxygen to draw from ventilation openings. When more oxygen is added to the fire the heat release rate increases and so the temperature increases corresponding to gas expansion and so creating pressure. The air and gases always flow from higher pressure are to lower pressure area. The experiment showed unidirectional exhaust movement from the differences of the interior and exterior pressures. (Exploratory Analysis of the Impact of Ventilation on Strip Mall Fires 2016.)

Nick Salameh from Arlington County, Washington writes in his article" Warehouse Size Structure Fire" about warehouse fires. The main points are to notice that residential structure tactics may not be enough when fighting a warehouse fire. Warehouse fires need more and stronger water streams because of increased square footage, high ceilings, open space floor plans, and the increased fire loading and so more ventilation. Also unprotected steel and light weight structural elements can collapse during the fire. (Salameh 2019.)

Ventilation is an important aspect, and a wrong kind of ventilation can increase fire intensity, rapidly spread fire and backdraft or smoke to light off. Ventilation can also create exhaust points, create air intakes, and establish a flow path. With the right decisions and timing with ventilation the increased energy of the fire can be released safely and so make the firefighter job easier. This can be done with large usage of water with ventilation. (Salameh 2019.)

The tactical view is to make a full assault on the fire as fast as possible with high volume fire and hit the seat of the fire and cool walls and ceilings. An offensive fire attack should start as soon as possible because the conditions and extent of the fire can change rapidly and so make the approach to be defensive. When firefighters are in control of the fire, ventilation should be a major action. Uncontrolled ventilation can cause backdrafts. A thermal camera should be used to identify the seat and extent of the fire, to identify known location trapped occupants, to observe heat signatures, to observe structural instability of unprotected steel components, and to aid in maintaining orientation under smoke conditions and situational awareness. (Salameh 2019.)

Article of the firefighter nation content directors' "Warehouse Fire Attack Strategy" brings up ten topics when fighting warehouse fires. Usually, the material stored in the warehouses make the fire grow exponentially. High volume of material and hazardous materials makes the fires grow rapidly and so require heavy fire attack. The heavy fire attack requires a big water supply to accomplish the tactics. It is important to know where to get water and how to sustain adequare water supply. During a fire, the article mentions that all openings and doors should be opened. (Warehouse Fire Attack Strategy 2013.)

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Ventilation is a key point during a fire and a roof is a good place to start ventilation. PPV (positive pressure ventilation) is recommended but it should be used early at the point when firefighters are stretching initial lines into the building, but it is not recommended to use when the location of the fire is unknown and in concealed space fires. (Warehouse Fire Attack Strategy 2013.)

7.4 Canada, Ottawa

Peter McBride who is a retired incident safety officer (ISO) with the Ottawa (Canada) Fire Services and a Project Manager for FKTP (From Knowledge to Practice) curriculum, answered the email. McBride sent many useful articles, and a Skype meeting was arranged to discuss the tactical approach in a warehouse fire.

In the skype meeting with McBride the topics of firefighting tactics and decision making, buildings frameworks, air and fire dynamics and the use of thermal camera where discussed. In Ottawa, Canada structural cooling and roof work to stop the fire spreading is an used tactic especially in so called noncombustible buildings. McBride mentioned gas cooling as an ineffective approach in some situation, and he had experience when buildings were lost through this approach. He mentioned that during gas cooling the main task of extinguishing the fire can be forgotten when cooling the combustible gas layer down. Also, it does not affect the insulation inside the structures of the roof and between the walls and the fire can spread in the combustible insulation of the building. (Peter McBride, interview 7.27.2020)

In McBride's opinion the fire dynamics and the aspect of air is not considered enough in smaller and larger building fires. A thermal camera used with the water stream is a useful way to observe the flow and movement of fresh air and hot gases. McBride mentioned that a thermal camera could be used in a lot more ways than just observe the structural temperatures inside the building. The air movement and understanding air is an important aspect also. In Ontario ventilation is part of the main tactics and when understanding the air flow and air as an aspect it is easier to make the right decisions when choosing ventilation tactics. This is valid in all kinds of fires. (Peter McBride, interview 7.27.2020)

In Canada there are lot of so-called noncombustible buildings including warehouses. Mostly these are constructed that both wall-bearing and skeletal frame structures use bar joists in a parallel array (size, spacing, and bracing) designed to carry the roof and anticipated loads. The structure itself and the frame itself do not burn but in a rapid spreading fire it can bent or even collapse. The roof system is finished with insulation and a waterproof cover that may or may not be surfaced with stone or granular ballast or roll-on coating. When the fire spreads from the floor base into the insulation of the roof, problems are caused, and water sprays cannot affect the fire inside the roof structures. This requires different kind of approaches to tactics when fighting the fire burning in the insulation inside the roof (Firefighting Tactics for Noncombustible Buildings 2009.)

There are experiences from so called noncombustible building when hot gases and smoke have caused a full roof fire. The tactic is to cool the structures from below and cut the gases out of the metal frame and trusses. In these situations, ventilation should not be done from the roof because of serious danger of collapse of the structures. (Know Your Enemy #34 2003.)

Structure cooling is a standard practice for the firefighters in Ottawa and the goal is to cool structures so keep them stable during a fire and with this action prevent it from collapsing. Master streams or a 2½ inch hand line are aimed towards the ceiling ad underside of the deck to cool the steel structures. The problem can be when the underside of the deck is hard or impossible to reach with water streams, then other tactics should be considered. A thermal camera is an important tool when observing structures while cooling them. One person with the thermal camera should observe the structures and guide the firefighters where to aim the water spray and when to change to another part of the structure. (Firefighting Tactics for Noncombustible Buildings 2009.)

The main things to focus on are ventilation, roof work and structure cooling. There are two different opinion of top-vent or no-top-vent when deciding to ventilate the building. No-top-vent opinions in discussion have accrued after collapses and accidents have happened while firefighters have been doing roof work during a fire. Ventilation can be done horizontally or vertically, and that decision must be made when starting to attack the fire. Air movement and air flow should be recognized as one part of the matters so right kind of a ventilation can be started at the right time. Ventilation is important to perform the right way, so the fire-fighter work stays safe, and the fire conditions do not change rapidly. (Firefighting Tactics for Noncombustible Buildings 2009.)

Depending on the pace and location of the fire, if it is safe, roof work is an important part of the tactics with ventilation. Most of the time there is insulation that can cause a roof fire so with roof work the goal is to stop the fire spreading inside the roof in the insulation when it is impossible to extinguish it with the water spray from below. Also, ventilation can be worked from roof doing holes to get the gases and smoke out of the building. It is important to know the pace of the fire to know if it is safe to have firefighters work at the roof. During a fire roof work is considered one of the hardest and challenging tasks for the firefighters. (Firefighting Tactics for Noncombustible Buildings 2009.)

One important thing to notice is the wall structure and insulation between the metal sheets. The Ruukki building also has a sandwich type of wall that has insulation between the metal sheets on both sides. If there is urethane or some other flammable insulation used, it can vaporize when in contact with hot air/structure. This can cause serious danger of explosion. The gas cooling does not affect the walls, and this can lead into flash fire or even an explosion inside the structures in the insulation. The insulation of the Ruukki buildings is mineral wool which does not burn or vaporize.

7.5 Honk Kong, China

Raymond YU, who works as a Divisional Officer in Hong Kong Fire Services Department answered the email. He mentioned that in Honk Kong they use more or less the same tactics as in Finland adopting offensive tactics as far as possible coupled with gas cooling techniques. The difference is that in large volume fires like warehouse fires they use narrower cone angle or even jet to achieve a longer throw instead of using gas cooling solely. (Raymond YU, email, 28.8.2020.)

Ventilation is main part of fighting the fire in Hong Kong. Raymond mentioned that they rarely use the vertical strategy like cutting off the roof. This comes from the fact that they normally build their building with R.C.C. (reinforced concrete) and they are so densely populated area that most of their buildings are high-rise, which makes it impractical to cut through the roof of the compartment since it might be the floor of the level above. Sprinklers and/or standpipe systems are used in Honk Kong and they have no problem of freezing as Raymond mentioned. (Raymond YU, email, 28.8.2020.)

7.6 Summary

A total of four answers were received through the emails. The answers were from Sweden, the USA city of Columbia from the state of Maryland, Canada Ottawa, and Hong Kong China. Finland's tactical approach was from the Emergency service Academy Finland's teaching and materials of warehouse fire course. The answers were received from all around the world and tactics were studied through the answers, articles and the Skype meeting. As the answers and tactical approaches showed there are lots of similar measures taken during fires, but also there are tactical differences. The goal of the tactics is always the same, to extinguish the fire.

When studying the tactics, it is important to notice three different affairs. First, the answers were received from persons working in the firefighting field and the tactics represent their tactical approach and way of thinking during a fire. The tactical approach can be different in other areas in the country, for example the USA where there are over 30000 independent fire departments. Second, before sending the emails a search was done through the Internet and it was challenging to find any articles or research from the used tactics around the world. Most of the received articles and answers were opinions and ways to do by the persons, that are received through long experience in the firefighting fields. Third, in the firefighting field there are not so many larger researches done but the tactics rather usually the tactics base on experience and from learned incidents. However, the answers give an a understanding about the different firefighting tactics used around the world and the persons answering the emails have a significant experience in the firefighting field.

All the tactics base on the same understanding that in warehouse fires there is more affairs to consider than in smaller compartment and building fires. The basis is that the fires are larger, and they take longer time to extinguish. There are more problems that make the fighting more challenging. The main points are that the fires are larger, there is more space for the fire to burn and more combustible material, hazardous materials make the work of the fire fighters more dangerous, the fires burn with higher energy and create more smoke and gases and the collapsing and bending of structures of the building make the extinguishing more challenging.

The basis for all tactical approaches is that there should be enough resources at the scene to the extinguishing to begin. Depending on the situation and resources, the tactic is chosen between defensive or attack. In all answers the adequate water flow and high volumes of water is a main affair when beginning the extinguishing. Large, high energy fires need a large amount of water and throughout the world the tactics all included that there should be enough water to extinguish the fire.

Ventilation was an important aspect in all countries and answers. With the ventilation the hot combustible gases are ventilated out of the building to decrease the temperature, make the visibility better and release the energy created by the fire. The ways and opinions of how to ventilate and what is the best way to do it differs, but an agreement is that ventilation is one of the most important aspects during warehouse fires. The used ventilation methods were vertical ventilation, horizontal ventilation, and positive pressure ventilation. Experience, building codes, building styles, and the operating model affect to how the ventilation is done. For example, in Hong Kong horizontal ventilation is the used method because of the building code and mostly of the high-risen buildings where vertical ventilation cannot be done. In Finland vertical ventilation is used and the building code of warehouses requires ventilation hatches to the roof of warehouses. The answers show that ventilation is studied, and technics of ventilation is researched and discussed around the world.

Differences in the tactical approaches occurred on the ways of extinguishing the fire. When the fire cannot be located or reached by the mainstream there were two different kinds of techniques how to use the water streams, gas cooling and structural cooling. In gas cooling the stream is aimed into the hot smoke and gas layer to cool it down and so indirectly extinguish the fire. The vaporized water displaces the oxygen from the air when expanding and cools the gases and so extinguish the fire. In structure cooling the structures are cooled to keep them stable and not let the fire spread inside the structures, for example, in the insulation. In Canada roof work is attached to the structure cooling technique. Gas cooling is used in Finland, Sweden and Hong Kong and structural cooling in Ottawa Canada and Columbia Maryland USA.

The simulations done by the Aalto University's researcher Kallada follows the same line with the tactics from around the world. Especially the amount of water and continuous water spray is an important factor during the fire. The right timed and right way used water sprays can reduce the Heat Release Rate and stop the fire spreading. Also, the temperature of the trusses can be reduced with the water spray and so structural cooling should be also considered during the firefighting. An interesting question came up through the simulations that can the fire spread through fire brigades' actions when there is not enough water sprayed to the fire. The results showed that with one monitor for suppression the energy abstraction rate is 6.6 times lower than the energy produced by the fire. This can make the fire spread rapidly when the vaporized water changes the pressure at the base of the fire and so makes it spread faster.

8. DISCUSSION

8.1 Results of the final project

The topic of this final project is comprehensive and there is lot of information from the subject of fire safety design to the subject of firefighting tactics. The Travelling Fire Methodology is a relatively new phenomenon and method to be used in fire safety design of buildings and structures. The Travelling Fire Methodology is used to understand and count the real dynamics of the fire and more the non-uniformly burning and how it affects the structures of the building. This methodology is useful when studying the fire resistance of the structures.

Fire spreading and fire dynamics are also studied in this final project. The aspect of the air and the air movement and pressure changes should be considered more during large-scale building fires. Especially the reasons of fire spreading and sudden changes of the phase of the fire should be considered more. This final project presents a small sample of the fire dynamics and air movement in it.

The most important results of this final project were on the firefighting tactics and on the approach during a large-scale fire. The tactics and simulations are based on the Ruukki Express warehouse building. The results show that there are many different approaches and tactical choices how to extinguish warehouse fires. An adequate water flow, enough recourses, ventilation and extinguishing of the fire are main steps all around the world. Differences in ventilation and tactical choices of gas cooling and structural cooling makes the approaches different. It shows that there is not only one way to extinguish a fire and there is a lot to learn from other countries and tactical approaches. All the tactics base on experience and researches and it is important to be open for changes in the tactics if some actions do not end up in the wanted results. ‘

The results of the simulations showed in this final project gives more questions to the tactics. Is it possible that using one monitor for extinguishing the fire spreads instead of extinguishing? Are there situations when firefighters have to wait more resources before starting the extinguishing? Would it be better to apply more water streams to the basic tactical approach when extinguishing a large-scale fire? More studying and research of the topic should be done to gain more understanding of the fire dynamics and pressure changes during extinguishing.

8.3 Own learning

This final project taught me about different kind of tactics used in a large-scale warehouse fires and the reasoning behind it. Tactical approaches differ in the world and there is not only one right way to approach a warehouse fire. This final project taught me that education of extinguishing a warehouse fire should also contain consideration of what could be done differently and why. This especially for the fire officers. During this final project I learned more about fire dynamics, pressure changes and air movement. These phenomena can play a major role of fire spreading and rapid changes of condition during a fire.

This final project was done as part of Aalto University's research and it taught me about how to make research and gain information. With the study and interview the expected results were achieved and I learned how to make a study and what can be done better later in a similar situation. When researching materials for this final project it showed how hard it is to find different tactics from around the world if there are no contact persons who to ask.

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