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DO RAKED JOINTS AFFECT THE FIRE RESISTANCE OF CONCRETE MASONRY? - NUMERICAL STUDY

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ABSTRACT

Prescriptive fire codes have been used to allow simple designs, but they come with many restrictions. Performance based codes on the other hand, attempt to provide clearer guidance than the prescriptive codes, taking into consideration all possible functional objectives that will affect the fire safety of a structure. These are usually guided by set objectives and are accordingly met by the designer. A full-scale fire test is usually required in the quest to provide these defined criteria for guidance in the use of performance based codes. However, a full-scale fire test is not always a practical solution as it is very expensive and needs a state-of-the art furnace with an appropriate fire capability. A computer simulation serves as an alternate option, for researchers to account for the effect of heat transfer on an element, assembly or a structure. The use of finite element (FE) modelling aids in the study of heat transfer and can be used to study the fire behaviour of a structure. This study focuses on modelling concrete masonry walls composed of normal weight concrete blocks and Type S Mortar with the aid of Abaqus/Standard 6.13. Results obtained from the fire model is compared with the experimental fire resistance tests, which has been conducted as part of an ongoing project. Mortar joints bond the masonry units of a wall together, and therefore play a significant role in affecting the overall appearance of these units. Raked joints are commonly specified for aesthetic purposes; however, they have been thought to reduce the fire resistance of masonry. One reason being that part of the mortar is scraped away from the joint at a consistent depth, which could cause joints to fail and allow for thermal bridging. Raked joints were modelled 0.5 cm deep on both sides of the wall. The typical concave mortar joint was used as a control in the analysis. Based on numerical results, and as confirmed by experimental results conducted earlier, both raked and full mortar joints produced similar fire resistance behaviour.

KEYWORDS: *Abaqus, fire, heat transfer, masonry, mortar, raked joints*

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INTRODUCTION

Building materials such as concrete/clay blocks/bricks, mortar, grout and reinforcement bars serve as the basic components for constructing masonry walls. The choice of these listed materials in constructing masonry walls is dependent on the function of the wall. In terms of their function, masonry walls are either loadbearing or non-loadbearing walls. A loadbearing wall is part of the structure of the building; it holds the building up. A non-loadbearing wall can serve as a partition.

Non-loadbearing masonry walls have considerable capacity, from a fire perspective, to isolate parts of the building's interior from fire flames, heat, and the effect of smoke. For this reason, the fire behaviour of masonry elements has promoted a great deal of interest in building construction [1]. Thermal properties such as thermal conductivity, specific heat capacity, and thermal deformation of concrete masonry have demonstrated excellent behaviour under elevated temperatures. Also, concrete masonry is quite resistant to weakening with increasing temperatures [1].

It is known that ungrouted and unreinforced masonry, for instance non-loadbearing walls, have less thermal mass and potential lines of weakness at the mortar joints. Although this remains a fact, these walls have demonstrated excellent fire resistance provided that the foundations and the supporting structures can keep the wall in place during the anticipated fire [2].

Non-loadbearing walls consists of hollow concrete blocks mortared together. The concrete blocks and the mortar have different mix designs, additives, and moisture contents. It is expected that there will be variations in their thermal behaviour when exposed to elevated temperatures. The mortar joints play a significant role in the walls as they primarily hold the units together in both reinforced and unreinforced walls and therefore transfer structural and/or thermal loads. Concave, flush, raked, beaded, struck, weathered, etc. are different forms of mortar joints that can be used in the construction of masonry walls. The main reasons for adopting a particular mortar joint is based on aesthetic as well as water-penetration or durability reasons. For instance, raked joints are commonly used for aesthetic purposes; however, they have been thought to reduce the fire resistance of masonry [3]. Creating raked mortar joints, part of the mortar is scraped away from the joint at a consistent depth, which creates potential points of failure and allows for thermal bridging. Similarly, in concrete block construction interior walls often have joints that are struck flush with a surface. In some instances, where a wall is going to covered, in say gypsum board, these struck joints may have small perforations and imperfections which would function similarly to a raked joint and create unintended points of thermal bridging. Thermal bridging of mortar is a phenomenon where the area around the mortar has the possibility of having a significant higher heat transfer than the surrounding materials (concrete block) resulting in an overall reduction of the thermal insulation of the wall.

Fire resistance of walls can be determined by performing full-scale fire tests. There are varying parameters within a single test such as moisture contents, mix designs, types of mortar joints, types of blocks, etc. The use of full-scale fire test is not always a practical solution as it is very expensive, time consuming, and requires the use of a state-of-the-art furnace with an appropriate fire capability. Therefore, the use of a FE modelling software to analyze these typical scenarios offers a more practical solution. In this paper, the objective is to evaluate the fire resistance of non-loadbearing masonry walls constructed with normal weight concrete blocks mortared either as raked or full using a numerical approach which, has been compared to actual fire tests to verify validity of the model.

Choice of FE Software Package

FE analysis has been packaged in many commercial computer programs such as Abaqus [4], ANSYS [5], LS-DYNA [6], and many others. The availability of different element types, analysis procedures, material models, interfaces, load types, platform usage are the basic standard capabilities of these programs. The choice of the FE software for any analysis is an important factor in determining the quality and scope of analysis that can be performed.

Abaqus offers a user-friendly interface and therefore allows the user to easily adapt to the tools in modelling and analyzing complex three dimensional problems. It is an equation based FE software that has two main solvers; Standard and Explicit and has the capability to run a variety of simulations. Such Multiphysics simulations include coupled acoustic-structural, piezoelectric, and structural-pore capabilities, making it attractive for production-level simulations where multiple fields need to be coupled. Abaqus has no modules or packages for machining simulations and therefore the user is capable of performing very thorough analysis right from the start without using any pre-set controls and assumptions. This provides the user with control over the entire simulation process. Joints, connections and other discontinuities can be also modelled into the program. Though Abaqus has no support for any specific materials, it gives the user the ability to configure the materials using a variety of parameters. In addition, it has a very fine and precise control over the meshing in the model [7]. Meshing in any FE analysis is very important as this determines the computational time and accuracy of the output. Abaqus provides the user with a very fine and precise control in meshing models. For instance, in refining a mesh, the user is provided with a wide variety of options; seeding, partitioning and virtual topology. The user can optimize the mesh chosen and verify the mesh concerning the quality of the elements used in the mesh [4]. Abaqus is command-line accessible and therefore supports scripting functionality [7].

PARAMETERS, PROPERTIES AND NUMERICAL PROCEDURES

In any numerical study, consideration is given to the parameters, properties and numerical procedures that would effectively imitate the experimental study. In identifying these factors, Nguyen and Meftah [8] analyzed the fire behaviour of non-loadbearing and loadbearing clay hollow-block masonry walls, with regard to the risk of spalling. This analysis included a detailed investigation of the temperature, deformation and local mechanical degradation phenomena in the tested walls. Results showed that the two main modes of heat transfer identified during a fire are radiation and convection. Also, heat conduction, phase changes, and heat advection due to steam release were identified as major dissipation mechanisms that control the thermal resistance and unit geometry. Integrity and insulation were the failure criteria of interest. The non-loadbearing walls were not susceptible to excessive spalling; therefore, the governing failure criterion for non-loadbearing walls is temperature rise. The temperature rise criterion calls for the temperature on the unexposed side of the test specimen not to exceed an average increase of 140ºC and a maximum increase of 180ºC at a single point [2]. Based on these criteria, these parameters were incorporated into the presented numerical model.

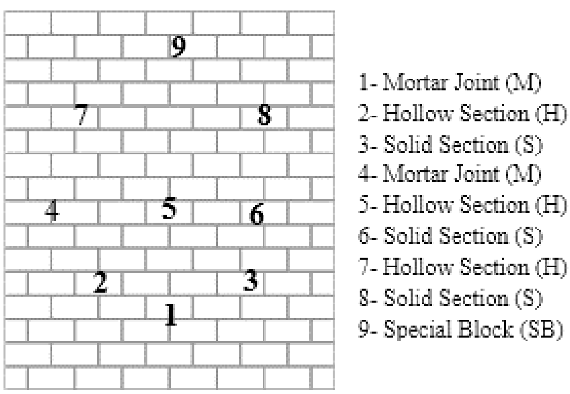
Al-Sibahy and Edwards [9] evaluated the thermal behaviour of novel lightweight concrete at ambient and elevated temperatures by conducting experimental, modelling and parametric studies. Concrete samples were modelled using Abaqus in a pure heat transfer analysis. Parameters such as the mesh size, coefficient of convection and surface emissivity were studied extensively in a series of iterative procedures to calibrate the model. Different mesh sizes had a minimal effect on the output because of the uniformity of the heating action on the exposed surface, as well as the isotropic behaviour of the thermal conductivity feature. This was also observed in a numerical study by Chow and Chan [10]. However, in the presented numerical model, the walls are anisotropic in the thermal properties and therefore required keen consideration to mesh sizes.

Various approaches were used to study the combined effect of convection and radiation action during exposure to elevated temperatures [10, 11]. Based on the results from the ongoing experimental project, applying the effects of both convection and radiation to the exposed surface, while the unexposed surface is subjected only to the convection effect was adopted in the presented numerical model. To evaluate the effect of radiation, the surface emissivity of concrete was investigated. A range of values were investigated, however, this produced similar results to the experimental work and therefore did not affect the overall thermal behaviour of the samples, this was also confirmed through previous research [9, 12, 13].

Mariyana et al. [14] implemented the capability of a three-dimensional heat transfer analysis in Abaqus for a single storey of reinforced concrete frames, and non-loadbearing walls. The temperature dependent materials followed EC2 [15] for heat transfer analysis. Convection and radiation were the main two modes of heat transfer. Results showed high temperature distribution in the numerical modelling of the frame elements as compared to the experimental work. This could be attributed to the inability to properly define the moisture content of concrete in the numerical modelling. In the presented study, the moisture content was considered an important feature due to the anisotropic behaviour exhibited by the masonry wall. Therefore, this feature was linked to the specific heat capacity. High specific heat capacity values were used for the mortar as compared to the blocks in the range of 80ºC to about 140ºC. This is because the mortar contains more moisture as compared to the block units [3]. This was done in several iterative procedures.

EXPERIMENTAL SET UP

Building elements and assemblies are normally tested and rated based on their ability to perform intended functions under exposure to standard fires, commonly referred to as “fire resistance ratings”. This is mostly quantified as the time for that element or assembly to perform its “fire barrier and separation" and /or loadbearing function in the building [2]. The experimental work, that is being modelled, is part of an ongoing fire-masonry research at Carleton University. A series of walls were constructed and tested as per the CAN/ULC S101-14 [16]. Walls were 2.8 m wide and 3.2 m tall (7 blocks wide, 16 courses high). Each of the walls were built within a frame of reinforced concrete masonry columns and beams comprised of 20 cm normal weight concrete (NWC) hollow block mortared with Type S mortar. Type S mortar is suitable for general and below-grade uses and particularly when high lateral strength is required [3]. Grout and reinforcement bars were not used and therefore the cells were left hollow. Eighteen thermocouples were used to measure the temperature of the exposed and unexposed sides of the wall (nine on each side) (Fig. 1a). Masonry walls are anisotropic in geometry and moisture content, therefore three different unique locations for placing thermocouples were used. The different locations include the mortar joint (M1-M3), solid section (S1-S3) and hollow cells (H1-H5) (Fig. 1b). At the 9th position, the temperatures at different locations within a block; known as the special block was further evaluated. The tested walls were constructed with raked mortar joints and full mortar joints (control). Raked joints were 0.5 cm deep on both sides of the wall. Recorded temperatures varied based on these locations. Therefore, these locations and sections were taken into consideration for the numerical study.



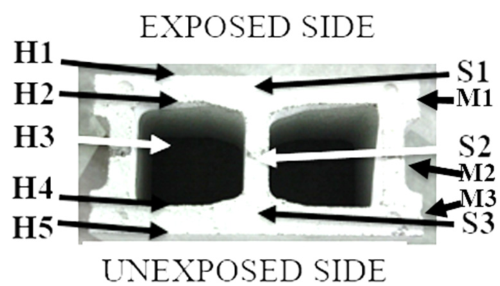


Fig. 1a **Fig. 1b**

Figure 1: Thermocouple locations on exposed and unexposed sides of the wall (Fig. 1a) and within special block (Fig. 1b)

NUMERICAL STUDY

In comparing the experimental fire resistance of the masonry walls constructed with raked joints and that of full mortar joints, a robust and reliable three-dimensional (3D) FE model was developed using Abaqus. The model considers a pure heat transfer analysis, the development of a non-linear thermal behaviour of the model and procedure for the FE solution.

Pure heat analysis

A pure thermal analysis is incorporated, where the temperature profile within the wall is determined and therefore no mechanical behaviour is accounted for. This form of exposure is governed by equation 1 [2].

$$Cp\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2}\right) \tag{1}$$

Where Cp = specific heat capacity (J/kg.K), T = temperature (K), t = time (s), k = thermal conductivity (W/m.K), and x = thickness of the wall (m)

Numerical simulation procedure

The main components of a FE model in analyzing a pure heat transfer problem are the element discretization and meshing, material model, thermal load and boundary conditions in addition to the selected solution procedure.

Under the element discretization and meshing, parts were initially created and assembled under the assembly field. The use of extrusion and cut features were adopted to model all these parts; standard 20 cm masonry block, a half masonry block and a 10 mm mortar joint. The choice of the mesh sizes was controlled by the geometry, discontinuities and contact interactions of the assembly [4]. Different mesh sizes were adopted to fit the curvature geometry of each of the components. Based on the element type, an eight-node linear interpolation diffusion heat transfer brick (DC3D8) element was used to simulate the heat flow through the component's assembly for the heat transfer model. The degree of freedom exhibited by using this element is the scalar temperature (nodal temperature (NT11)) [4]. A solid homogenous section was assigned to the element's entire geometry to simulate the non-linear behaviour of the material properties.

The material model required defining properties for heat transfer calculations in solid materials. These include; density (ρ), specific heat capacity (C_p) and thermal conductivity (k). Abaqus therefore provides an option to define these temperature-dependent properties. A temperature range of 20ºC to 800ºC was used as this serves as a critical temperature range for concrete [17]. The density of most concrete masonry will be reduced by up to 100 kg/m^3 when heated to a temperature of about 100ºC (free water evaporation). However, this has a minor effect on the thermal response. Other than these moisture changes, there is no significant changes in the density at elevated temperatures [2]. The specific heat capacity of NWC decreases while the thermal conductivity increases with temperature increase [2]. Therefore, different values were tabulated in the material model as functions of temperature changes.

Based on the thermal load and boundary conditions, the various modes of heat transfer were effectively incorporated into the heat transfer analysis, and defined in the interaction model. The heat source was a uniform net heat flux ($\dot{q}''$) (W/m^2), Equation 2. The geometry of the masonry wall was divided into exposed surface (hot), unexposed surface (cold), and the side surfaces were considered unexposed as they were insulated.

$$\dot{q}'' = h_c\left(T_f - T_s\right) + \phi\varepsilon_{ff}\sigma\left(T_f^4 - T_s^4\right) \tag{2}$$

where; h_c = convection coefficient; T_f = furnace temperature (K), T_s = surface temperature (K), ϕ = configuration factor, ε_{ff} = effective emissivity, σ = Stefan-Boltzmann constant (5.67x10^8 W/m^{2}K^4). The estimated heat flux was incorporated as a boundary condition to the modelled assembly through an edited user Distributed Flux (DFLUX) subroutine [18] . This is a set of computer programming instructions, which is used for simulation of applying thermal loads on a model assembly. This heat flux can be applied non-uniformly during the heat transfer analysis as a function of element number, integration point of the assembly, position, time and temperature.

Procedure of the FE solution

Non-linear numerical simulation was considered due to the non-linearity of the material properties with temperature. To incorporate this into the FE solution, an uncoupled heat transfer analysis was conducted on the entire assembly. This form of analysis requires primarily inputting an ambient temperature to the entire assembly at the start of the test. A "predefined field" serves as the input for this temperature in Abaqus. Heat flux was applied to the exposed surfaces on the assembly and the heat penetrated the modelled test assembly over a period. The full Newton method was adopted for the transient heat analysis. This method is an iterative scheme, which can resolve potential non-linearities during the heat transfer analysis. The sources of these non-linearities include the non-linear temperature-dependent properties of the materials and radiation heat flux effects [4]. A nodal temperature-time history at all points in the assembly during the duration of the fire exposure was the output obtained from this analysis. The element mesh size, surface emissivity, and the coefficient of convection were parameters that had main influences on the results. Number of iterative procedures were considered until the numerical results converged to the experimental results, and to validate the model (material properties, analysis procedure, modelling approach).

RESULTS, DISUSSIONS AND LIMITATIONS

In both numerical (Num) and experimental (Exp) studies, for both cases raked wall (RW) and control wall (CW); top block courses recorded highest temperatures as compared to bottom courses, (Figs. 2a and 2b). This is independent of whether the position was within the mortar, solid or hollow sections. This could be attributed to the movement of buoyant hot gases, which rise rapidly to the topmost part of the wall during the burning stage thereby making the wall hotter at the top than at the bottom. This was achieved in the numerical study using the DFLUX subroutine, adopted in the heat transfer analysis, which provided a non-uniform heat flux on the surface of the wall.

To predict the thermal behaviour of the different sections, a special block was chosen and various nodal temperatures were taken for the M, H and S section, (Figs. 3a and 3b). In the special block, the locations of interest were M3, H5 and S3, these were sections on the unexposed side of the wall. H5 recorded highest temperatures right from the start of the analysis. This could be attributed to the air cavities within this section and the rapid transfer of heat by convection and radiation. Also, S3 records a higher temperature as compared to M3 as it conducts heat rapidly through the web. Comparatively, the main modes of heat transfer are through convection and radiation and this affirms the higher temperatures recorded by H5. However, just around 90ºC, M3 records a much higher temperature as compared to the H5 and S3 for both cases. This could be attributed to the moisture content (MC) within M3; M3 contains the highest MC and therefore would require a higher temperature to evaporate the moisture. This process lags on until all the MC is evaporated; this explains why it takes a relatively lengthy duration while maintaining the same temperature. The results are similar to the experimental study for both walls.

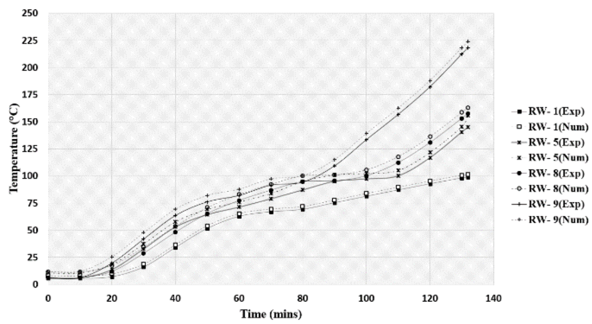


Fig. 2a

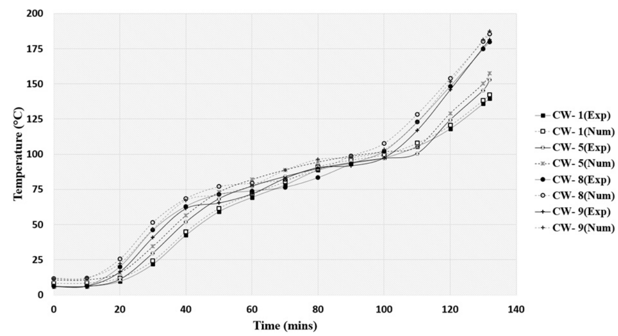


Fig. 2b

Figure 2: Temp. profile for locations 1, 5, 8 and 9; Raked wall (Fig. 2a) and Control wall (Fig. 2b)

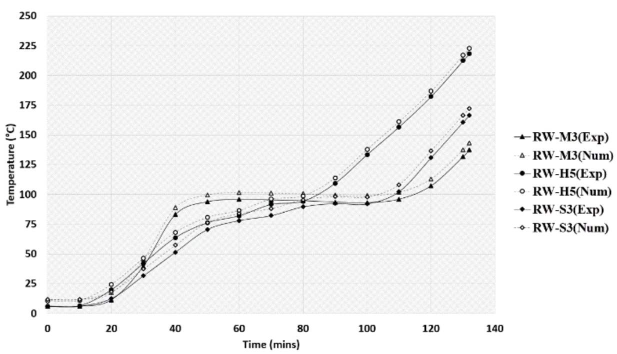


Fig. 3a

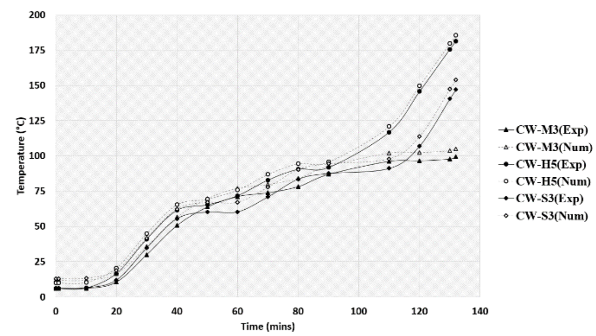


Fig 3b.

Figure 3: Temp. profile for special block; Raked wall (Fig. 3a) and Control wall (Fig. 3b)

In comparing the average temperature (AT) for both walls, the temperatures were closely in line with the recorded temperatures from the experimental work (Fig.4).

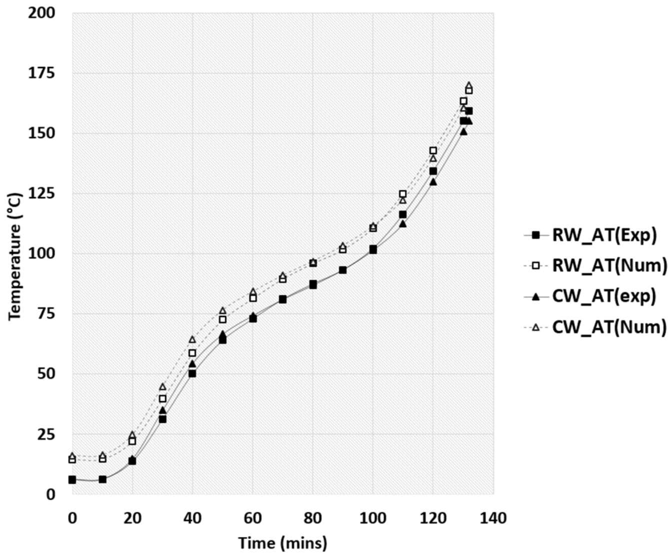


Figure 4: Average temperature profile on the full wall (Raked and Control wall)

Also, the temperature distribution on both walls were compared to the thermal images taken from the experimental study. The temperature contour is similar for both cases when compared to the numerical study (Fig. 5)

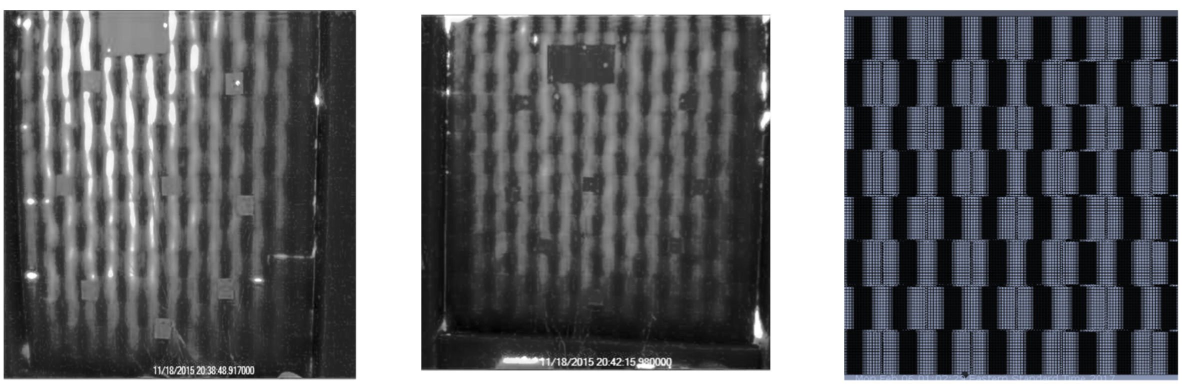


Fig. 5a **Fig. 5b** **Fig. 5c**

Figure 5: Thermal images (Fig 5a and 5b) compared with the heat flux distribution from a section of the wall (Fig 5c) from numerical study.

Conclusion

Based on the outputs from simulations the following conclusions can be drawn:

1. Numerical simulations can be used to assess the fire resistance of raked and full mortar joints in masonry walls, as an alternative to full scale fire resistance tests, following a successful model validation. An uncoupled (pure) heat transfer analysis procedure in FE model generally represents the thermal response of the masonry walls in fire conditions. The model's predictions for the fire resistance of both cases were closely within the temperatures recorded from the experimental study.

2. The material properties for normal weight concrete produced in EN 1993 provided the temperature dependent properties of the concrete material for the thermal analysis. The validation of the thermal model showed the reliability of these values in accounting for the thermal behaviour of concrete masonry.

3. Based on numerical results, and as confirmed by experimental results, raked and full mortar joints produced similar fire resistance behaviour.

4. The use of raked mortar joints has no thermal effects on fire behaviour of masonry walls.

Limitations

This study incorporated some limitations, which are either related to the sake of simplification considerations or to comply with the intended research objectives. These include;

1. The DFLUX subroutine file incorporated the CAN/ULC standard fire-curve. The coefficient of convection used was 25 W/m^2K.

2. Blocks modelled were of normal weight concrete and the mechanical properties were not considered since this is a pure heat transfer analysis.

3. Mortar was modelled with a higher specific heat value, for a temperature range of 80ºC to 140ºC, as compared to that of the concrete block to account for its higher moisture content.

4. Raked joints modelled were 0.5 cm deep on both sides of the wall. No deeper joints were considered due to computational time and verification of the validity of the experimental results.

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