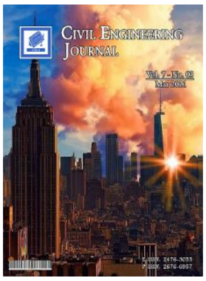
Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 7, No. 03, March, 2021



Numerical Modelling of One-Way Reinforced Concrete Slab in FireTaking Into Account of Spalling

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Received 19 October 2020; Revised 09 February 2021; Accepted 18 February 2021; Published 01 March 2021

Abstract

This paper presents a study of the behaviour of Reinforced Concrete (RC) slabs subjected to severe hydrocarbon fire exposure. In which the spalling phenomena of concrete is to be considered. The hydrocarbon curve is applicable where small petroleum fires might occur, i.e. car fuel tanks, petrol or oil tankers, certain petro-chemical facilities, tunnels, parking structures, etc. Spalling is included using a simplified approach where elements with temperatures higher than 400 °C are assumed to occur and the corresponding thermo-mechanical response of RC slabs is evaluated. The nonlinear finite element software SAFIR has been used to perform a numerical analysis of the spalling risk, by removing layers of concrete covering when a set of spalling criteria is checked. The numerical results obtained by finite element analysis of the temperature distribution within the slab and mid-span deflection were compared with published experimental data. Predictions from the numerical model show a good agreement with the experimental data throughout the entire fire exposure to the hydrocarbon fire. This shows that this approach (layering procedure) is very useful in predicting the behaviour of concrete spalling cases.

Keywords: Numerical Modelling; SAFIR; Fire; Spalling; Concrete Slabs.

1. Introduction

Most of the experimental and numerical research studies over the last few decades focused predominately on the behaviour of structural (RC) elements (beams, columns, walls and slabs) under fire exposure [1-3], but a very small number of numerical research studies have involved the spalling phenomenon [4-6]. Nevertheless, using present design practice, the effect of concrete spalling is ignored in the greater part of the computer software developed [7]. The concrete design against fire is often based on experimental approaches and basis methods developed from standard fire tests. Furthermore, the appearance of this phenomenon was first observed long ago but still not well understood in the calculation [6]. This is mainly due to the complexity of the phenomenon. Previous studies have shown that the mechanisms involved are very complex. According to several authors including [8-10], the degree and magnitude of spalling is affected by a number of inter-dependent factors such as, heating rate, heating exposure, size of the of reinforced concrete element section, dimensions and shape of concrete element section, moisture content, permeability of reinforced concrete element, age of reinforced concrete member, concrete cover to reinforcement.

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http://dx.doi.org/10.28991/cej-2021-03091667

Most concrete spalling cases of concrete seem to be due to a combination of pore pressure generated by boiling of the free water content and thermal stresses due to extreme temperature gradients.

In addition, some research suggests that the presence of the reinforcement steel in concrete impedes moisture movement and creates quasi-saturated moisture clog-zones that could lead to the development of significant pore pressure [11]. These zones change the flow of heat in the structure and tend to attenuate the rise of internal temperature. Consequently thermal stresses induced in concrete are not related only to the external thermal loading but also to the moisture flow, reinforcing steel placement, and thermal processes such as evaporation.

The main interest of this study is that it focuses on the prediction of the behaviour of one-way RC Slabs, when exposed to hydrocarbon fire (HC) conditions, in which the spalling phenomenon is considered.

In order to investigate this phenomenon, a layering procedure was used, by removing layers of concrete covering when the temperature of the element reaches 400 °C, and affecting zero value to the thermo- mechanical properties of these layers. However, this analysis will not attempt to predict or evaluate probable levels of concrete spalling, but will examine the effect of the spalling phenomenon on the global performance of concrete structures, while assuming that its appearance is certain. As a part of a research program carried out at Civil Engineering & Hydraulics Laboratory (LGCH) at Guelma University (Algeria), a study is undertaken where modeling the spalling phenomena of reinforced concrete beams was developed [6].

The analysis is carried out according to the following steps:

- Creation of the model by discretizing the RC slab using four-node quadrilateral elements and modelled by rectangular finite elements;
- Determination of temperature fields at every moment and at every point of the beam, which is done by solving the transient equations of heat transfer using the finite element method. It follows the temperature time-depending, used in the second stage for the mechanical study;
- After conducting the thermal analysis, the second step is to make a mechanical analysis in which the temperature history of the structure, due to fire, is read from the data files created during the thermal analysis;
- The numerical results obtained from the structural analysis are also compared with experimental data on RC slab subjected to severe fire (hydrocarbon fire) [23].

2. Spalling Phenomenon

When reinforced concrete structural element is subjected to fire, it is possible that spalling of concrete takes place, and concrete cover which protects reinforcement will be removed [12, 13]. The violent removal of concrete layers and shrapnel from the compounds surface of concrete due to spalling can cause a severe reduction in the cross section of structural elements and can lead to early catastrophic failure [14]. The manifestation of this phenomenon can start during the first few minutes, exposing the reinforcement nearest of the front face to fire, and leading to decrease ultimate load carrying capacity of the reinforced concrete member.

As previously noted, the spalling is dependent on a number of factors (heating exposure, size of the section of reinforced concrete element, moisture content , type of fire exposure, properties of concrete, etc. Many of these factors are interdependent and can vary significantly in different scenarios.

Nevertheless, three main factors which cause essentially the spalling of concrete when exposed to fire were investigated by many researches, including Kodur and Phan (2007), So (2016) and Sun et al. (2018) [15-17]: (a) the build-up of pore pressure, (b) thermal stresses, and (c) combined high pore pressure and thermal stress in the concrete member when it is exposed to high and rapidly rising temperatures. According to several studies, this phenomenon is patent in many forms i.e: (a) aggregate spalling, (b) surface spalling, (c) explosive spalling and corner spalling. Even though different types of spalling vary by their severity, causing critical damage of material and deterioration of concrete structures in fires conditions [18-20].

Explosive spalling is a particularly dangerous type of failure and its consequences can be catastrophic. Figure 1 suggested by So (2016) [16] shows the aggregate spalling, surface spalling, and explosive spalling which usually occurred within 7-30 minutes after fire attack, accompanied by popping sounds (aggregate spalling) or violent explosions (surface and explosive spalling) [6, 18].

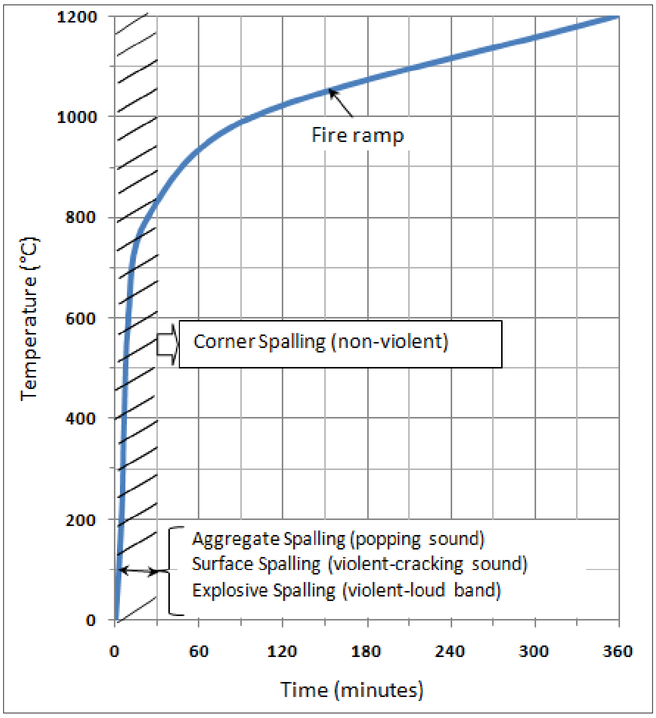

Figure 1. Time occurrence of different types of spalling under fire exposure

Through experimental tests carried out on concrete beams subjected to Hydrocarbon fire HC, [21] have shown that the spalling can occur in the first minutes (between 50 and 59 s), when the temperature is increased rapidly and exceeds 300 °C. In this study the authors consider a temperature of 400 °C (temperature to be sufficient to cause the spalling concrete) [6, 22].

3. Research Background

Very little scientific information about the performance and fire resistance of RC slabs when subjected to severe hydrocarbon fires, and few studies have been devoted to it, in which the spalling phenomenon is taken into account. In order to cover this gap in the literature, this paper aims to study the impact of the spalling concrete on the mechanical properties of RC slab under fire conditions. Within this context, a numerical simulation of the spalling of reinforced concrete one-way slab under hydrocarbon temperature exposure has been undertaken. The numerical results obtained by the finite element analysis are validated by comparing temperature and deflection prediction with the experimental tests carried out by So (2016) study [23].

4. Description of the Numerical Analysis

For the purpose of the present study, the finite element software, SAFIR [24] is used to perform the thermal and structural fire analysis, which is capable of handling a thermo-mechanical coupling simulation. The spalling risk is taken into consideration by the elimination one layer of concrete covering each time when a set of appearance of this phenomenon criteria is checked (temperature reaches 400°C), and affecting zero value to the thermo- mechanical properties of these layers. It can be noticed that the thickness of the layers removed will be a function of the element thickness used in the finite element analysis.

5. Slab Properties

Seen that the results of the three slabs studied by So (2016) [23] are almost identical, a one-way, simply supported slab, denoted as S5 was selected for the current study. The span length, total length, width, and thickness of the tested slab specimen are 300, 330, 120, and 20 cm, respectively. Concerning the thermal and mechanical properties of concrete and steel were taken into account are based on those proposed in the [25], where different behaviour is considered under heating and cooling phases. For these purposes, the slab was made of normal weight concrete using siliceous aggregates with a density of 24 kN/m^3, an average concrete strength of 42MPa and water content of 4.30 %. The elastic modulus at ambient temperature was taken as 25.20 GPa.

The slab is reinforced with 6 steel bars, embedded longitudinally along the slab at a spacing of 22 cm from centre to centre, having a diameter and yield strength of 12 mm and 460 MPa, respectively, as shown in Figure 3. The concrete cover from the longitudinal steel to the nearest concrete slab surface was 40 mm. 13 steel bars with a diameter of 10 mm were placed perpendicular to the main reinforcement with a spacing of 30 cm. The following tables summarize the mechanical properties of concrete and steel adopted in this study.

Table 1. Mechanical properties of concrete

Property of concrete (C40/50)		
Compressive strength	f_{c28}	42 MPa
Tensile strength	F_{t28}	0.0
Poisson's ratio	υ	0.2
Type of aggregates		Siliceous
Water content	w	4.3 %
Cover	C	40 cm
Density of concrete	ρ	2400 kg/m^3

Table 2. Mechanical properties of steel

Property of steel		
Modulus of Elasticity	E_a	210 GPa
Tensile strength	F_e	460 MPa
Poisson's ratio	υ	0.3
Reinforcement bars embedded longitudinally		6Ø12
Reinforcement bars placed perpendicular		13Ø10

The bottom surface of the slab was subjected to the hydrocarbon fire curve action, which represent a possible scenario in petrochemical installations or oil and gas production facilities when hydrocarbon chemicals and fuels ignite. The top side was not subjected to fire as it can be assumed that the top side would be protected by the concrete slab. There are numerous types of fire associated with petrochemical fuels. The hydrocarbon curve (HC) is based on a standardized type of fire. The temperature development of the hydrocarbon fire curve is described by equation [26]:

$$\theta_g = 20 + 1080(1 - 0.325.e^{-0.167t} - 0.675.e^{-2.5t}) \quad (1)$$

Where: θ_g is the gas temperature in the fire compartment (°C), t is the time (min).

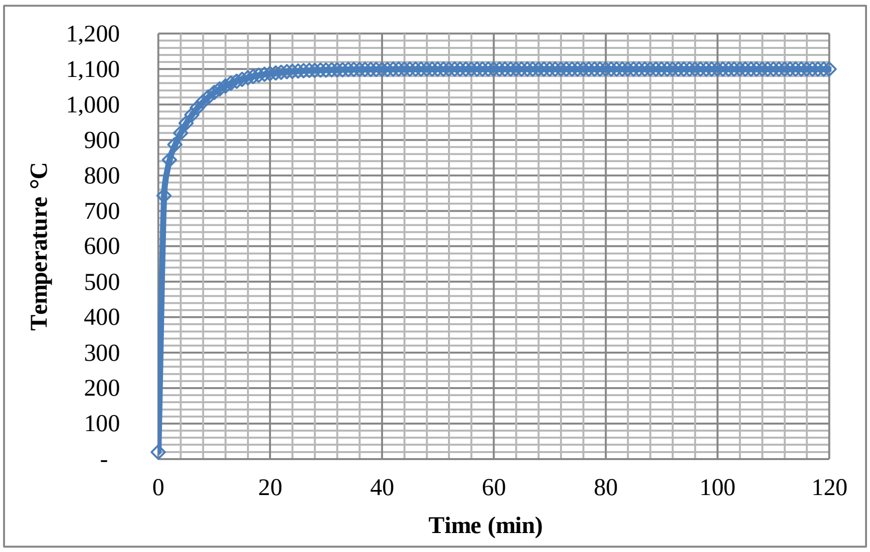

Figure 2. Hydrocarbon fire curve (HC) used in the analysis

The coefficients of convection at the exposed and unexposed surfaces of the slab were taken as 25 W/m^{2}K and 9 W/m^{2}K respectively. The emissivity of the concrete was assumed as 0.8. The moisture content was taken as 4.3% (according to the value reported by So (2016) [23]. The effective span of slab was exposed to the temperature curve over a length of 300 cm. The self-weight of considered slab is assumed to be concentrated at mid span of 27 kN, as illustrated in Figure 3.

Further details of this analysis in terms of element types, material properties, geometry, loading and boundary conditions are provided in the following subsections.

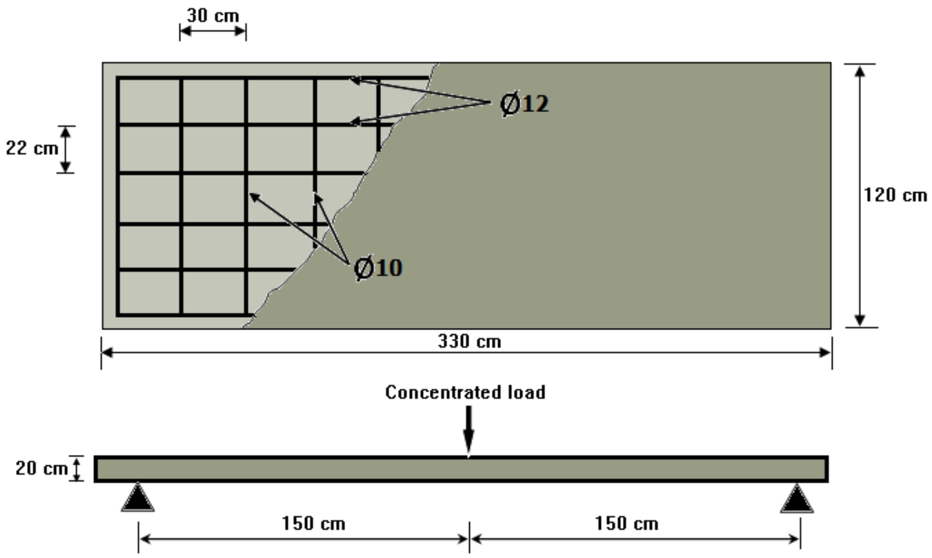

Figure 3. Details of concrete slabs

6. Numerical Analysis Validation

The numerical model is validated against measured data from fire tests on RC slab. Experimentally measured mid-span deflection, temperatures distribution at various locations, in which the spalling phenomenon of concrete is taken into account.

6.1. The Finite Elements Software SAFIR Assumptions

Some of the assumptions of the SAFIR thermal and structural analysis are, as follows:

- Shear failure of the beam and shell elements cannot be determined.
- SAFIR cannot model moisture migration in its thermal analysis but the effect of moisture on the temperature distributions is accounted for by using appropriate thermal properties.
- A full composite action between the concrete and the reinforcing steel is assumed, with no slip between these two materials.
- Spalling of concrete cannot be modelled by SAFIR, hence a layering procedure was used in this paper.

7. Thermal Analysis

7.1. Temperature Field

According to the principle of energy conservation and Fourier's law, the transient temperature field is given by the following equation:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+\emptyset=c\rho\frac{\partial T}{\partial t} \quad (2)$$

Where T, λ, *c*, ρ and Ø are the temperature, the thermal conductivity, the specific heat, the mass density and the internal heat source, respectively. Knowing these parameters, the temperature field in the solid body under specified boundary conditions can be determined by solving the governing equation with the finite element method.

According to be physical definition, the heat transfer is mainly classified into three mechanisms including thermal conduction, thermal convection and thermal radiation. However, the software SAFIR used for this analysis considers that the heat is distributed in the structure essentially by conduction since most construction elements are made of solid materials. Radiation and convection are the heat transfer modes in internal cavities such as those present, for example, in hollow core slabs [27].

7.2. Thermal Model

The temperature distribution in the shell element is obtained from a SAFIR thermal analysis that has to be performed before the structural analysis.

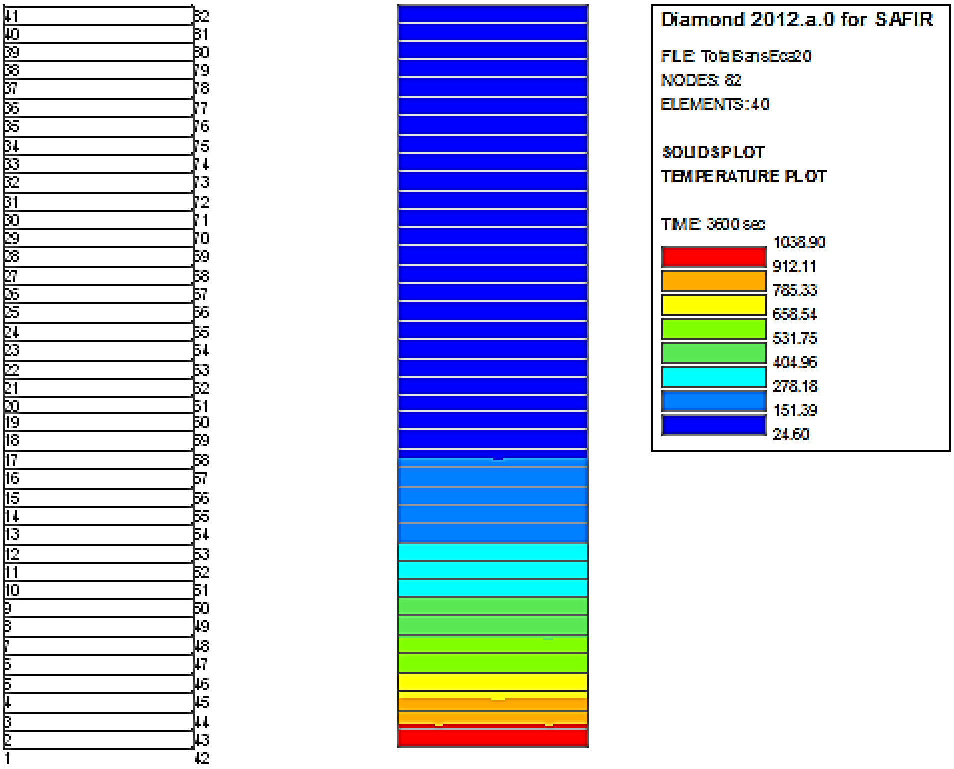

Figure 4. Temperature distribution through the shell cross-section at 60 min

Thermal analysis can be performed in order to evaluate the temperature distribution in the shell elements, by a slicing the slab, which has to be performed before the structural analysis. For this purpose, the cross section is discretized using four-node quadrilateral elements and is modeled by rectangular finite elements, having same width as the discretized section width (Figure 4-a). Figure 4-b shows the variations of the temperature profile in the 200mm slab when subjected to uniaxial heat flux from the bottom. The temperature is assumed to be non-uniform on the thickness of the shell and uniform across the plane of the slab. The reinforcing bars present in the slab, were not considered in the thermal analysis, because they do not significantly influence the temperature distribution, but will be added in the mechanical analysis [28]. Thus, the temperature of the reinforcing bars was considered to be equal to the concrete temperature at the location of the steel reinforcement bars [29].

7.3. Slab Temperatures

Figure 5 shows the development of the temperatures with time across the depth of the slab at three points, when taking into account the effect of concrete spalling, i.e. at exposed surface (node 1), mid height (node 21) and the unheated surface (node 41) of the slab.

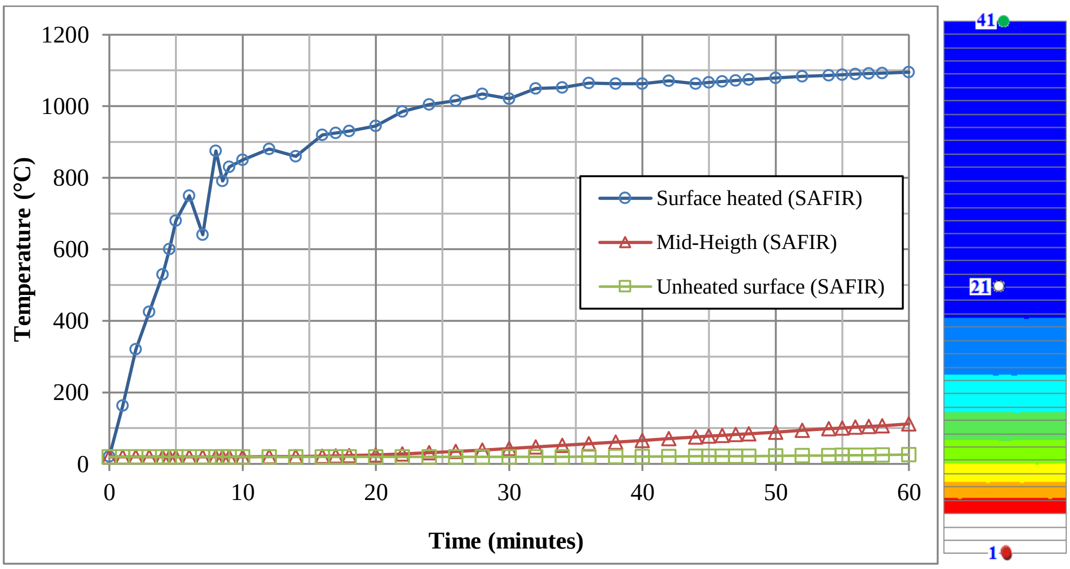

Figure 5. Evolution of temperature as a function of time for different depths within the slab cross-section (with spalling)

The graph representing the exposed surface show a very high temperature gradients across the slab during the first minutes. After that, the steepness of the temperature gradients decreased and approached a linear distribution. However, a disruption of heat flow during the first five minutes of the heated surface (node 1) is noted. This disturbance can be attributed to the fact that the spalling that happened in the early stages has disturbed the mechanism of heat flow the heated surface [14]. On the other hand, the two other curves (node 21 and node 41) show no disturbance because they are far from the heated face. The calculated temperature using this analysis was compared with the temperature obtained experimentally from the fire tests by So (2016) [23].

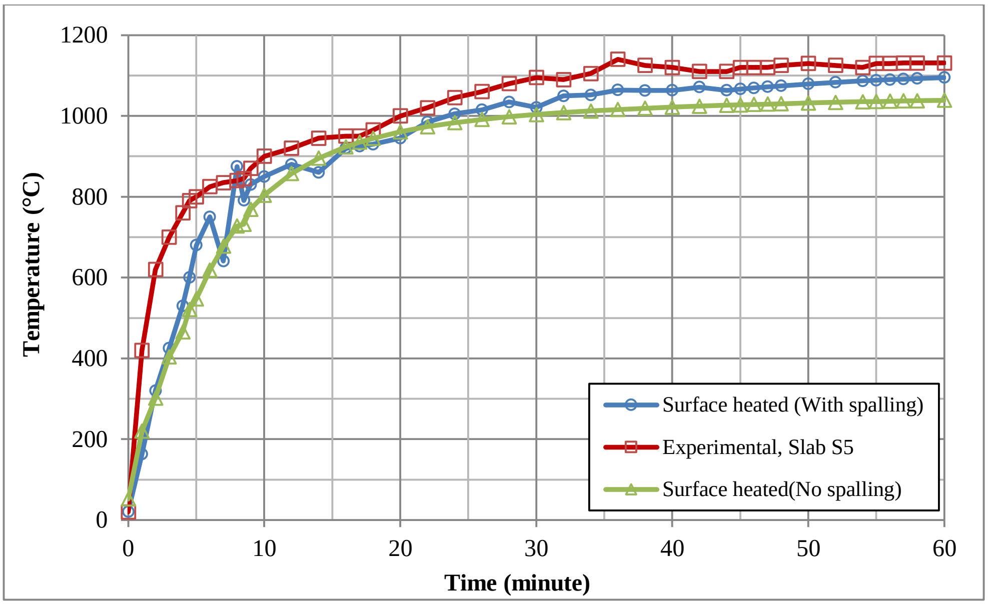

Figure 6. Comparison between experimental and numerical results of temperature at surface heated of slab under Hydrocarbon fire

Except the first 7 minutes, where a slight difference and a disturbance in the heat flow of the numerical model was noted. It is clear that there is an accurate correlation between the numerical analysis and experimental results of temperature measured at surface heated of the RC slab, in which spalling risk is taken into account. The temperature of the exposed surface of slab reach 1095 °C and 1131 °C at 30 minutes for the predicted and measured temperature respectively.

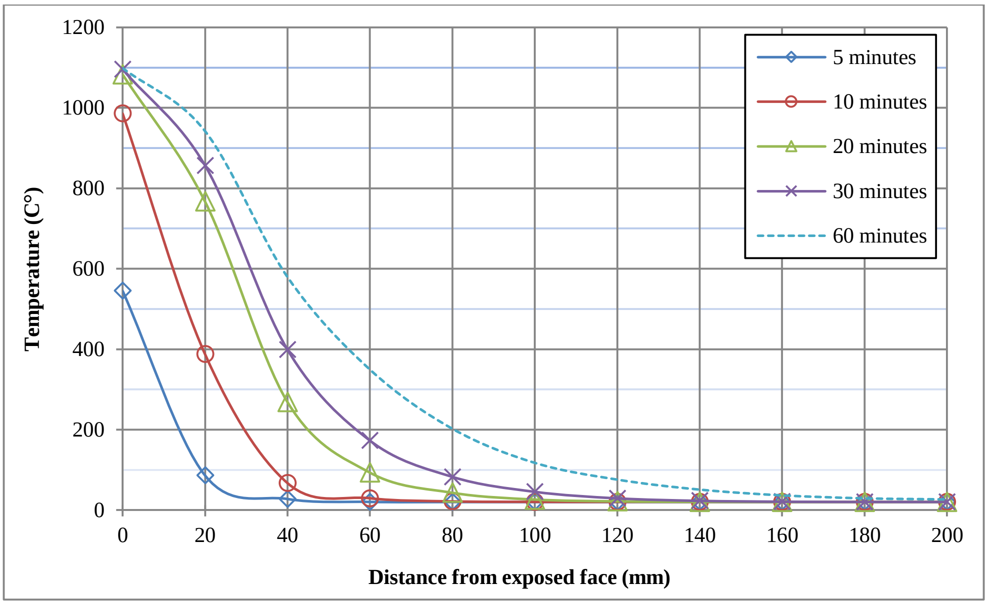

Figure 7. Temperature distributions across the 200 mm slab (with spalling)

Figure 7 shows the temperature distribution across the 200 mm thick slab at various times during the hydrocarbon fire exposure. The temperatures were determined using the SAFIR analysis.

The curves show very high temperature gradients within the first 40 mm of the exposed face of the slab. After that, the steepness of the temperature gradients decreased as a function of depth and approached the ambient temperature.

8. Structural Analysis

Due to the symmetry in the geometry, materials, thermal flow, boundary conditions of the specimen, and in order to reduce the computational time of the simulations, a quarter of the slab is considered, as illustrated in the Figure 8.

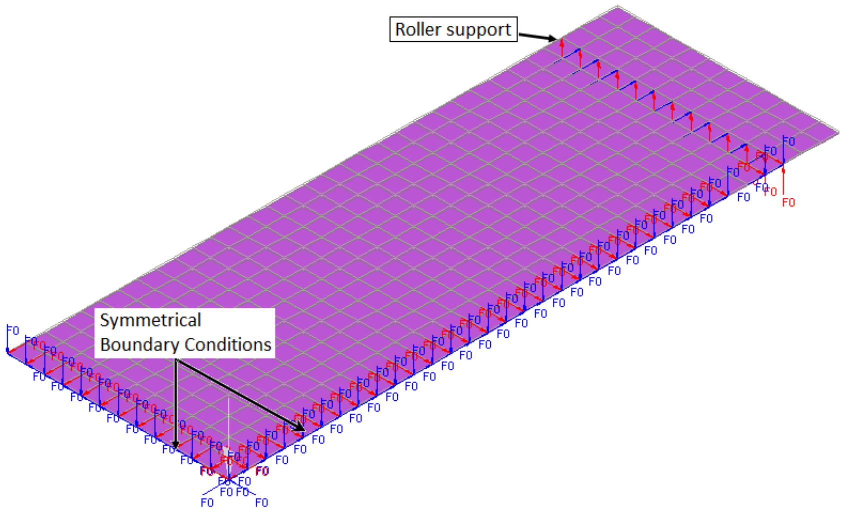

Figure 8. Isometric view of quarter of the discretized RC slab

After conducting the thermal analysis, the following step is to make a structural analysis in which the temperature history of the structure, due to fire, is read from the data files created during the temperature analysis. The slab is modeled using shell elements under the combined action of fire and structural load. The stress-strain material laws are assumed as nonlinear for concrete and linear-elliptic for steel. The predicted results obtained from the structural analysis are also compared with the measured experimental data obtained by So (2016) [23]. Figure 9 shows a comparison between the experimental and numerical results mid-span deflection response of the slab as a function of exposure time using SAFIR for zero MPa concrete tensile strength.

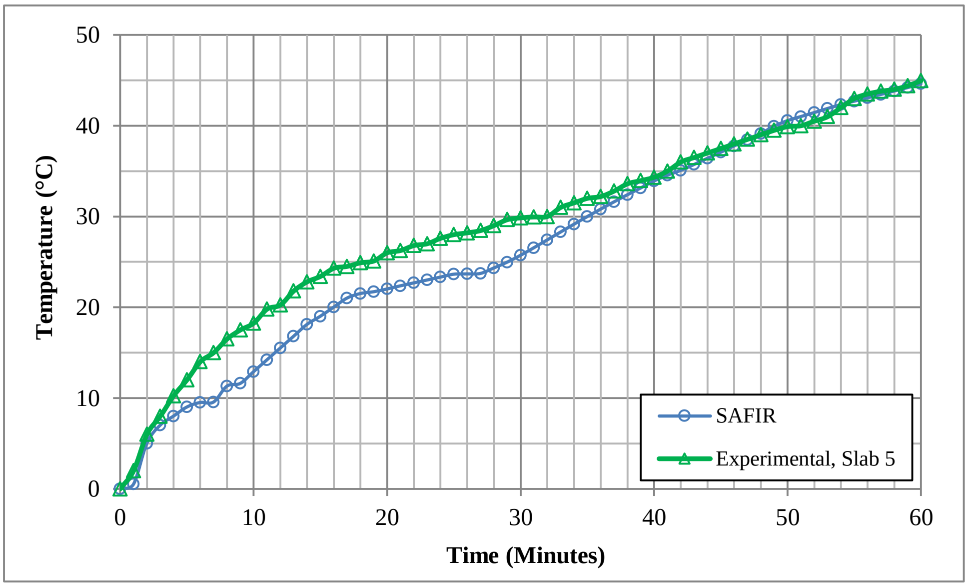

Figure 9. Comparison between the predicted and experimentally measured mid-span deflection

It is clear from Figure 9 that there is a good correlation between the predicted and measured mid-span deflections at all stages of fire loading of the RC slab.

9. Discussions

Modelling the spalling phenomenon is a very complex operation because it is influenced by a great number of inter-dependent factors such as, heating rate, heating exposure, size of the reinforced concrete element etc. Furthermore we have demonstrated that we can assess the risk of spalling phenomenon by using the hydrocarbon fire curve. In this context, SAFIR code was used to perform a numerical analysis of the spalling risk, by removing layers of concrete cover as a set of spalling criteria is checked (therefore this is not a classical modeling). Hence the gap lies in the modeling itself, because most of regulations codes are based on experimental approaches, therefore a very little predictive computation has been realized yet. The numerical results presented in this paper are a contribution to the analysis of the spalling risk of one-way RC slab when exposed to Hydrocarbon fire. So far, there is no model or method that can accurately predict the probability and risk of spalling. Although the prediction of the exposure fire has been largely based on experimental approaches [30], because it is very difficult to reproduce numerically the spalling of concrete. This is due to the lack of knowledge on the physical phenomena that can be at the origin of the phenomenon. It should be noted that, despite the difficulties encountered, we were able to model this complicated phenomenon.

10. Conclusions

Spalling of concrete remains one of the main issues to be addressed in the case of fire in buildings, parking structures and tunnels. The removal of the concrete in spall forms on the concrete surface could cause a severe reduction in cross section of the structural elements; in addition expose the steel reinforcement near the front face, to high temperatures. Based on the results obtained in the present study, the following observations and conclusions can be drawn:

- The impact of spalling consideration on the fire resistance calculation of concrete structures is important. The main difficulty of this problem is the large amount of parameters that influence the spalling phenomenon.
- According to the results obtained in the present study, the layering procedure allowed us to predict with acceptable accuracy the behaviour of one-way RC slabs in fire without recourse to expensive experimental tests.
- A satisfactory agreement between the deflection measured at mid-range and the numerical simulations at all stages of the RC slab has been recorded.
- The layer removal method proposed in this study is capable to predict, with high accuracy, the temperature distribution and mid-spam deflections of simply supported reinforced concrete one-way slab subjected to sustained gravity and fire loading.
- It should be noted that the numerical analysis of the slab specimen subjected to the ISO834 temperature-time curve is not reported in this work because of its poor agreement with the experimental data.
- The fire resistance of the tested slab specimen is not reported by So (2016) and thus could not be compared with the numerical simulations.
- Despite the difficulties encountered in modeling the spalling phenomenon, it was possible to investigate it, as shown in this paper.

11. Declarations

11.1. Data Availability Statement

The data presented in this study are available in article.

11.2. Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

11.3. Acknowledgements

The research presented in this article is in partnership between the University of Souk Ahras and the laboratory of Civil Engineering and Hydraulics of the 8th May 1945, University of Guelma.

11.4. Conflicts of Interest

The authors declare no conflict of interest.

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