INVESTIGATION AND EVALUATION OF THERMAL ANALYSIS FOR DIFFERENT WALL STRUCTURES WITH FINITE ELEMENT METHOD, SIMULATION OF TEMPERATURE DISTRIBUTION AND REACTION IN THE WALL TYPES

FARKLI DUVAR YAPILARI İÇİN TERMAL ANALİZİN SONLU ELEMENALR YÖNTEMİ İLE İNCELENMESİ VE DEĞERLENDİRİLMESİ, DUVAR TİPLERİNDE SICAKLIK DAĞILIMI VE TEPKİMESİNİN SİMÜLASYONU

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ABSTRACT

When the literature is examined it is figured out that crack/stress occurrence and temperature change in walls are closely related. Therefore, the study of the thermal reaction of the temperature changes in the wall structures is beneficial to understand and to acquire information on the crack /stress behavior and dynamic changes in the wall and the surroundings. It is considered that information and gained knowledge on the subject can lead to developing a methodology for checking building structure security and for detecting a body under debris. The calculation methods for the temperature field distribution of the concrete structures are investigated in this study. This is done by applying the Finite Element (FE) numerical model for the computation of the wall heat flux and thermal distribution under the reaction of a step temperature change at a wall side with given default and barrier conditions. The temperature variations due to the change in the structure of the wall are examined. Thermal properties and crack/stress, expansion situations are visualized, simulated, and analysed for typical walls by displaying temperature distribution and heat flow with the specified baseline and barrier conditions. This study presents a multi-aspect thermal analysis method that can allow the researchers to compare the thermal response of typical walls under different ambient conditions by showing simulated results for typical walls. Thermal stress analysis on the wall types should be performed to arrange a ground to reduce and control the existence of thermal cracking. The results of the study will be considered an asset to support further studies and investigations.

Keywords: Thermal Distribution, Numerical Model, Finite Element Method, Cracked & Typical Walls.

ÖZET

Literatür incelendiğinde, duvarlarda çatlak/gerilme oluşumu ile sıcaklık değişiminin yakından ilişkili olduğu anlaşılmaktadır. Bu nedenle, duvar yapılarındaki sıcaklık değişimlerinin termal reaksiyonunun incelenmesi, duvardaki ve çevredeki çatlak/gerilme davranışını ve dinamik değişiklikleri anlamak, bunlarla ilgili bilgi edinmek için faydalıdır. Konuyla ilgili edinilen bilgilerin, bina yapısı güvenliğini kontrol etmek ve enkaz altındaki cisimleri tespit etmek için bir metodoloji geliştirmeye yol açabileceği düşünülmektedir. Bu çalışmada beton yapılarında sıcaklık dağılımına ilişkin hesaplama yöntemleri ve duvarın yapısındaki değişikliğe bağlı sıcaklık değişimleri incelenmiştir. Bu hesaplamalar, varsayılan ve bariyer koşulları ile bir duvar tarafındaki kademeli sıcaklık değişiminin reaksiyonu altında duvar ısı akısının ve termal dağılımın hesaplanması Sonlu Eleman (FE) sayısal modeli uygulanarak yapılmıştır. Isıl özellikler ve çatlak/gerilme, genleşme durumları, belirtilen temel bariyer koşulları ile sıcaklık dağılımı ve ısı akışı gösterilerek tipik duvarlar için görselleştirilerek, simüle ve analiz edilmiştir. Bu çalışma, tipik duvarlar için simüle edilmiş sonuçları göstererek, farklı ortam koşullarında tipik duvarların ısıl tepkilerini karşılaştırmalarına olanak tanıyan çok yönlü bir termal analiz yöntemi sunmaktadır. Termal çatlamayı ve kırılmayı azaltmaya ve kontrol etmeye bir zemin hazırlamak için, duvar tipleri üzerinde termal gerilme analizi yapılmıştır. Çalışmanın sonuçları, ileri çalışmaları ve araştırmaları desteklemek için bir varlık olarak kabul edilecektir.

Anahtar Kelimeler: Isıl Dağılım, Sayısal Model, Sonlu Elemanlar Yöntemi, Çatlak ve Tipik Duvar.

1. INTRODUCTION

A Wall is a common component of a building structure in the world. Some factors and parameters such as orientation according to the sun and wind predominance, size of the doors and windows, etc. are to be taken into consideration during the design of a building. The thermal characteristics of the wall largely influence the energy performance of constructions. [1]. Therefore, in addition to the mechanical and structural parameters, heat transmission, heat flow, thermal conductivity, etc. should be considered remarkably. Moreover, the temperature parameter has a major role in analyzing and finding the solutions to thermal stress and crack problems of the wall types like a block of concrete, brick, etc. [2-9]. Numerical analysis techniques can give the possibility for a detailed research study. The purpose of numerical analyses based on the finite element method in the field of structural engineering has increased undoubtedly as the dominant discretization technique [10]. FE-analyses is a strong tool to design and assessment of walls and allows for more detailed analyses compared to traditional methods. In the design and analysis of the large concrete structures, non-linear analysis is mainly used to verify the structural behavior of the final design [11]. In this paper, numerical FE applications are used to collect thermal analyses, evaluation, and gain knowledge on the subject.

One main problem among others for a wall is thermal crack and stress that occurs over time. Cracking is caused by the thermal expansion and contraction of the wall when heated or cooled. Seasonal temperature changes, landslides, earthquakes, and geographical conditions can cause large concrete structures to crack, wear, or break. How to crack temperature reaction on the walls and how the temperature distribution over these regions has been studied for a long time but this reaction is not studied to see effects in the environmental dynamics yet. Thus, the data to be extracted from this study can enlighten further studies for building safety and human body saving from debris in the future.

This study consists of mainly four sections. The first section is the background in which items 2 and 3 covers. In the background section, analysis methods of the wall structures are shown. Theoretical and scientific backgrounds are explained. The second section is the analysis and modeling section, item 4 and 5 explain the analysis temperature distribution, displacement, and the modeling crack propagation of the walls, etc. The applications are made on temperature distribution using FE engineering software for typical walls and cracked walls are modeled. The third section in item 6, shows the results obtained from the analyzes, gives the evaluations and discussions. The final section gives the conclusion the inferences reported.

2. LITERATURE REVIEW AND NOVELTY

When the literature review is made, it is seen that most published articles are focused on analyzing only one aspect or one specific problem such as the contractions of concrete, brick, composite walls, temperature distribution, and thermal analysis in the concrete wall [12-14], composite wall [15-16] and brick wall [17] heat transfer, heat conduction, heat flow and heat flux [18-22] thermal-temperature stress and thermal cracking [23-27] and thermal properties [28-29] separately. Multiple analyses combining these aspects and comparisons of the wall crack, stress, and fracture issues with the thermal-energy characters are almost non-existent. Crack and stress problems in the walls are interrelated and have a direct relationship with temperature and heat energy. Therefore, to obtain more realistic and effective results, it is necessary to perform all these analyses together, to determine the effects of the problems on each other, and to find solutions to the problems by comparing them. This approach will also help to develop new methods for further studies.

Looking at the issues from multiple perspectives, the interactions of the problems such as fracture, cracking and stress in the wall types, as well as the analysis of interactions with temperature distribution, thermal flux, heat flow, and heat energy, will have much more useful results in preventing these problems or in determining thermal characters and behaviors. Therefore, the novelty of this article is to multiple-analyze the crack and stress of the wall types with the thermal characters and behaviors. The relationship between these mentioned issues and their interactions is tried to determine and the effects of thermal characters and energy behaviors on these issues are tried to be revealed in this study. In this aspect, this article is intended to present a new approach to these fields.

3. BACKGROUND AND NUMERICAL MODELING

The general discretization equation in the FE analysis is derived from the integration of control volume and time interval $[t\ to\ (t + \Delta t)]$. The general equation is given by (1) and it is called a fully explicit scheme. This schema is used for problems with FE. Once the scheme is used, the solution for the succeeding time step will depend on the preceding time step's solution.

$$pc \int_w^e \int_t^{t+\Delta t} \frac{\partial \mathrm{T}}{\partial \mathrm{t}} \mathrm{dtdx} = \int_t^{t+\Delta t} \int_w^e \frac{\partial}{\partial \mathrm{x}}\left(K \frac{\partial \mathrm{T}}{\partial \mathrm{y}}\right) \mathrm{dx\ dt} + \int_t^{t+\Delta t} \int_s^n \frac{\partial}{\partial \mathrm{y}}\left(K \frac{\partial \mathrm{T}}{\partial \mathrm{y}}\right) dy\ dt \quad (1)$$

Where ρ is the material density, c is the heat capacity, K is the thermal conductivities of the concrete varying with temperature.

To have a weighting factor (f) zero in the finite volume method’s discretization equation, the problem is solved fully explicitly by changing the f factor from 0 to 1 and it is reached fully scheme separately [30-31]. The thermal analysis finds and calculates the distribution and other thermal quantities under conditions that vary over time. Typical thermal quantities of interest are temperature distributions, amount of heat lost or gained, thermal gradients, thermal fluxes. The mathematical solution for the element’s conduction heat transfer is based on the thermodynamics and energy conservation law [32-34]. The general unsteady heat conduction equation is given by (2).

$$(\mathrm{K_x} \frac{\partial^2 \mathrm{T}}{\partial \mathrm{x}^2}) + (\mathrm{K_y} \frac{\partial^2 \mathrm{T}}{\partial \mathrm{y}^2}) + (\mathrm{K_z} \frac{\partial^2 \mathrm{T}}{\partial \mathrm{z}^2}) = \rho \mathrm{c} \frac{\partial \mathrm{T}}{\partial \mathrm{t}} \quad (2)$$

Where ρ is the material density, c is the heat capacity, K is the thermal conductivities of the concrete varying with temperature. The above conduction equations (1) and (2) are general, and it is used for most materials.

The thermal analysis purpose is to calculate the thermal distribution in the concrete wall. The result outs of the thermal analyses are used as an input to calculate stresses, displacements, and crack propagation caused by the temperature variation. Thermal stresses appear because of the restrictions in motion while the material enlarges due to a temperature change. The thermal stress and crack can be calculated by equation (3).

$$\Delta \sigma = \epsilon_{\mathrm{th}} \mathrm{E} = \alpha (\mathrm{T} - \mathrm{T_0}) \mathrm{E} \quad (3)$$

Where E is the elastic modulus, ϵ_{th} is the strain due to temperature variation, α is the thermal expansion coefficient, T is the current temperature, T_0 is the initial temperature.

Using equation (2), how thermal energy is distributed, and heat transfer are reacted. Equation (3) calculates thermal cracks and thermal stresses caused by temperature. In this study, these mentioned thermal analysis equations are used and the results are presented with graphs.

Boundary conditions describe behavior at the boundaries of the domain. Boundary conditions are needed for a system of equations to find the correct result. For the calculation and simulation to be successful, boundary conditions must be well defined, boundary conditions are real-life initial values. Boundary conditions can be assigned as essential or natural. Essential conditions affect the degree of freedom and are imposed on the node displacement vector, whereas the natural conditions are imposed on the force vector. Temperature and humidity affect the heat dissipation of concrete walls and cause cracks and breaks. Temperature and relative humidity enforce on the inner and the exterior layers of the flat concrete block. Therefore, in FE analysis, these boundary conditions must be known in advance. Moreover, the default temperature of the whole concrete block is considered, also total time length is assumed. Based on the differential equations with considering the spatial-temporal boundary conditions, the heat balance for the structural nodes at the time $(t + \Delta t)$ is given by (4).

$$[\mathrm{C}]\{\mathrm{T}\} + [\mathrm{K}]\{\mathrm{T}\} = \{\mathrm{F}\} \tag{4}$$

Where $[\mathrm{C}]$ is the heat capacity matrix $[K]$ is the conductance matrix containing thermal conductivity terms (k) and heat exchange coefficients (α), $\{T\}$ is the nodal temperature rate vector $\partial T/\partial t$, $\{F\}$ is the thermal load vector.

4. THERMAL ANALYSIS OF THE TYPICAL WALLS

In this section, thermal analyzes of typical wall types such as slab wall, composite wall, furnace wall, and concrete wall are made, and the results are shown graphically to compare and to understand the thermal characteristics of these wall types. The slab wall's thermal distribution in a rectangular plate is illustrated in fig.1.(c). In this analysis, an optimum-logical temperature value is determined as 200 ^{0}C and the temperature distribution is examined to see the distribution in temperature. The interesting point is that the heat is dispersed from the middle to the bottom and the temperature is concentrated in the middle regions. The possibility of cracks forming is considered to be in the middle area of the wall structure.

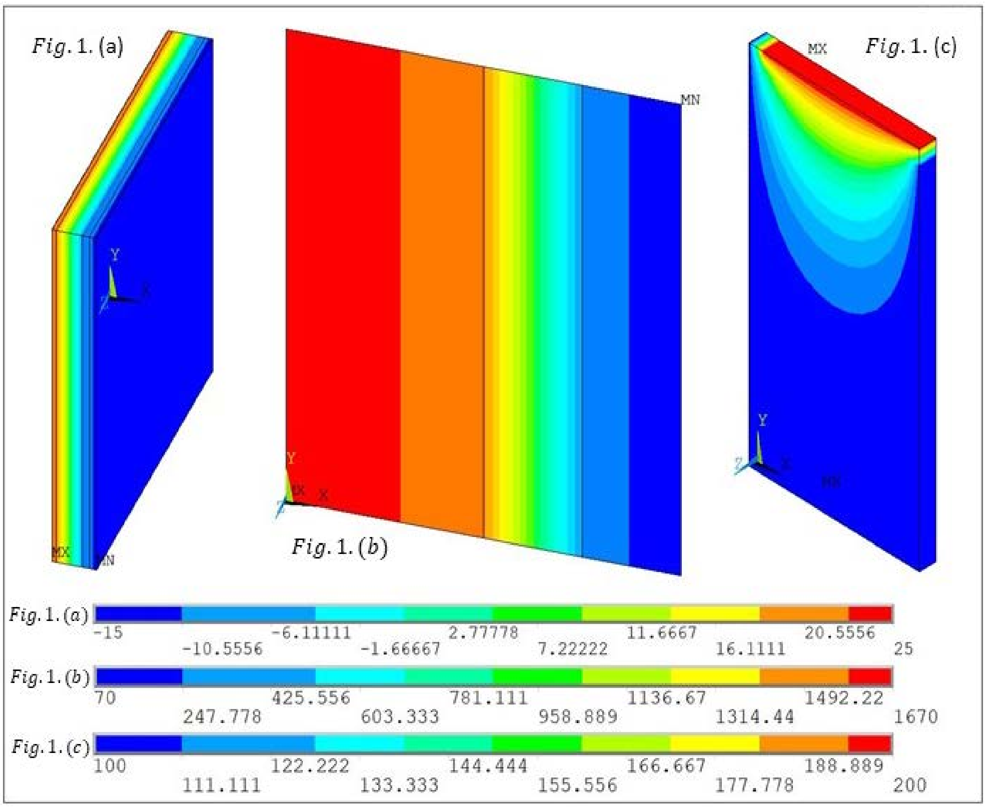

Fig. 1. Temperature distribution of the walls. (a). Composite, (b) Furnace, (c). Slab

Multilayer materials are complex structures composed of many layers and construction using multilayer elements because of the extra benefit of fusing different mechanical, physical, and thermal features [35-36]. The thermal analysis of the composite wall is done to find solution methods to define the thermal features of the composite wall materials. As seen in fig.1.(a), the composite wall is constructed of four materials and convective heat transfer coefficients on the inner and outer surfaces of the composite wall are different values. It is observed from this analysis that if the temperature is not so higher (such as room temperature or the exterior temperature is less), the materials that make up the wall do not need to be resistant to high temperature or to keep the heat in it, the elements can be determined accordingly. This may lead to the detection of insulation materials or may lead to the selection of low-cost elements when determining the building materials of the wall.

The thermal analysis of the furnace wall, which is one type of composite wall is studied to find solution techniques to determine the thermal distribution features. The rate of temperature distribution per unit area through a furnace wall consisting of 3 layers of bricks is calculated and results are shown in fig.1.(b). From this analysis, it is understood that for a structure like a furnace, the material type chosen can function to withstand temperature, up to 1670 ^{0}C. These wall types can be used to prevent the heat from spreading to the exterior and interior as well.

In the 3D composite wall, fibre and matrix materials are chosen for the model to see thermal expansion and stress. Using the modeling of a fibre embedded in an epoxy/matrix, similar to what would be found in composite materials, a 158℃-temperature change is applied, simulating cooldown after composite laminate manufacture in an autoclave. Fig.2.(a) shows the stress concentrations at the boundaries between the different materials as a result of the mismatch between the expansion coefficients. As seen in this analysis, the thermal stress levels of the materials are different when using composite material. The stress levels of fiber and matrix materials show how it is here at 158℃. The differences in temperature and heat transfer in the materials used on the walls and obvious differences can be seen here as well.

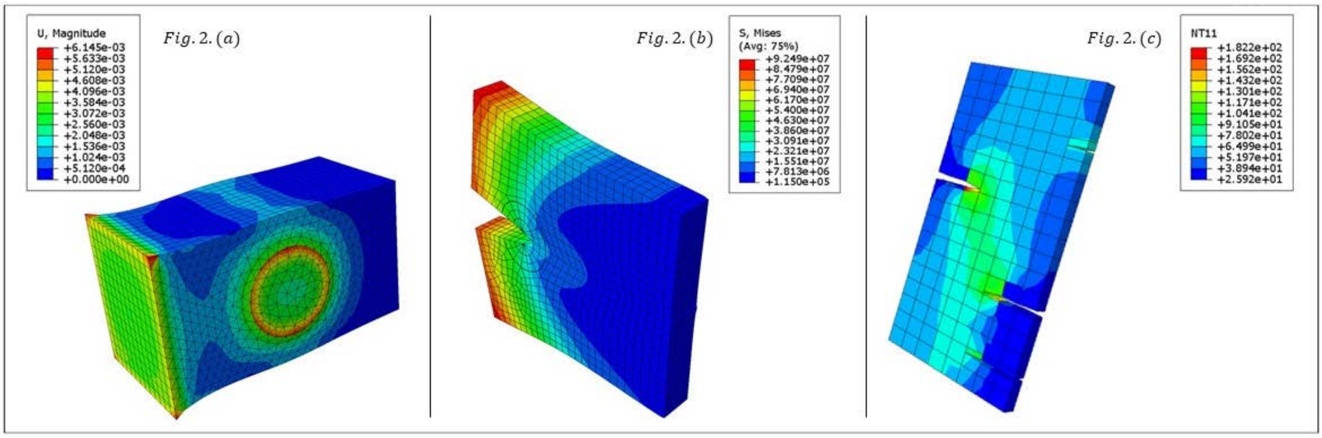

Fig. 2. Thermal Stress of the typical walls

(a) Composite wall with matrix layers, (b) Cracked concrete wall, (c) Cracked brick wall

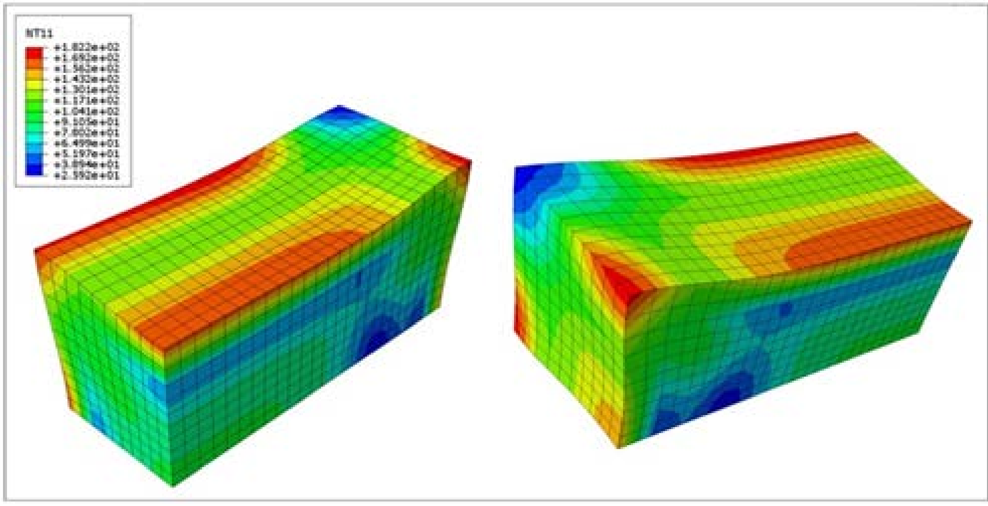

Fig.3. Thermal expansion and heat transfer of the wall

Thermal stress is shown in fig. 2. (b) of the 3D concrete wall having a single material to see thermal stress effect on the one material of the concrete. This analysis shows a maximum of 10 cm fracture growth and temperature distribution when pressure is applied from the back of the wall and a temperature of 100°C from the front. Also, thermal stress is shown in fig. 2. (c) of the 3D brick wall having composite materials. The progress of the temperature towards the inner regions and concentration in the cracked regions are modeled in this simulation with 158°C. It is observed that the temperature creates thermal stress and causes a crack in the middle regions of the concrete wall. Thermal expansion and heat transfer analyzes of the concrete wall are shown in fig.3. The simulation shows the reactions and behaviors of a concrete wall to temperature under certain temperature values. It is a useful simulation in terms of the realization of heat transfer and thermal diffusion in the concrete wall. It is understood from the simulation graph; it seems that the concrete wall changes its shape at 190°C and its geometry is impaired. Problems such as distortion and change may occur in hot climates or on the surfaces of factory walls operating at high temperatures.

5. NUMERICAL MODELING AND DESIGN PROCESS

During heating, cracks start on the inner wall and during quenching, cracks start on the outer wall. Cracks start at the cooler side of the wall and move towards the hotter wall. In regions with hot climates, wall cracks and stresses are very common due to the temperature change over time. Because temperature can be turned into heat energy in time and cause the walls to be stretched and then cracked. Certainly, many factors cause a crack on the walls such as material properties of concrete, environmental conditions, structural properties, function, and efficiency of heating and cooling equipment, etc. Therefore, the conditions caused by temperature and heat energy are modeled. Structural analysis with the FE method is done for concrete walls to determine how the temperature in the cracked wall changes. In this section, several scenarios are modeled, simulated and the results are shown in a graphical form.

The extended finite element method (XFEM) is a numeric method for the solution of problems that involve singularities and high gradient changes. In the fracture mechanics context, it can be used to model cracks and XFEM is more suitable where meshing is more complex such as problems associated with crack propagation. To perform thermal stress/crack analysis, it is necessary to model a structural analysis first. Thus, the crack concrete wall is modeled using XFEM as seen in fig.4. Subsequent thermal analyzes are carried out in this modeled part of the wall structure.

Another cracked 3D concrete wall is modeled, and the thermal stress is illustrated as shown in fig.5. This structure consists of a solid main material and a shell cracked to make it as reliable a simulation as possible. Due to the concrete wall dimensions and structure used in this simulation, it can be compared to a beam, modeling a broken wall. Pressure and energy were used in certain proportions. Under normal conditions, the wall overlaps the beam as a load and creates pressure, this pressure creates heat energy over time and causes breaks and cracks in the beam together with the temperature. These criteria have been modeled by taking them into consideration, and the crack wall is shown in the simulation in fig.5. The left side shows the wall piece with two cracks right sight shows the wall piece with three-crack. Simulation results show that when thermal energy is applied to the concrete wall cracked from several points, the thermal stresses on the wall change according to the depth, number, and size of the fractures. However, when calculations are made, it is seen that thermal stress formation occurs faster in broken walls. There are differences in the heat distribution of two-cracked, three-cracked walls.

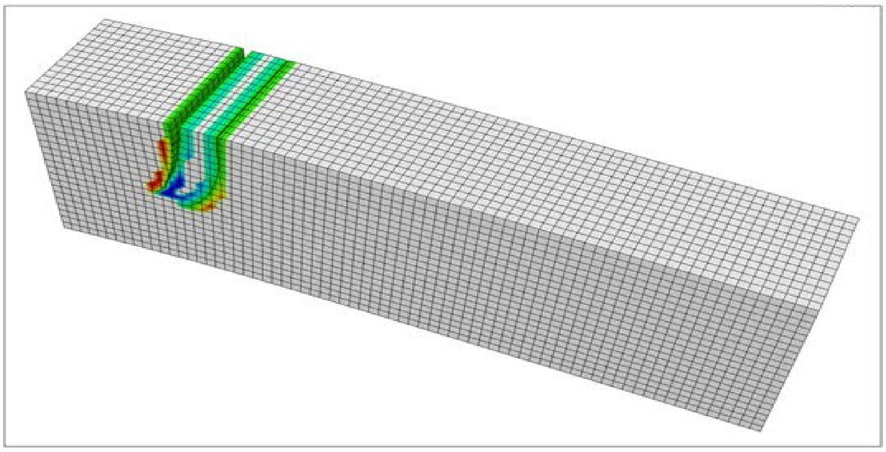

Fig. 4. Structural modeling of the crack wall

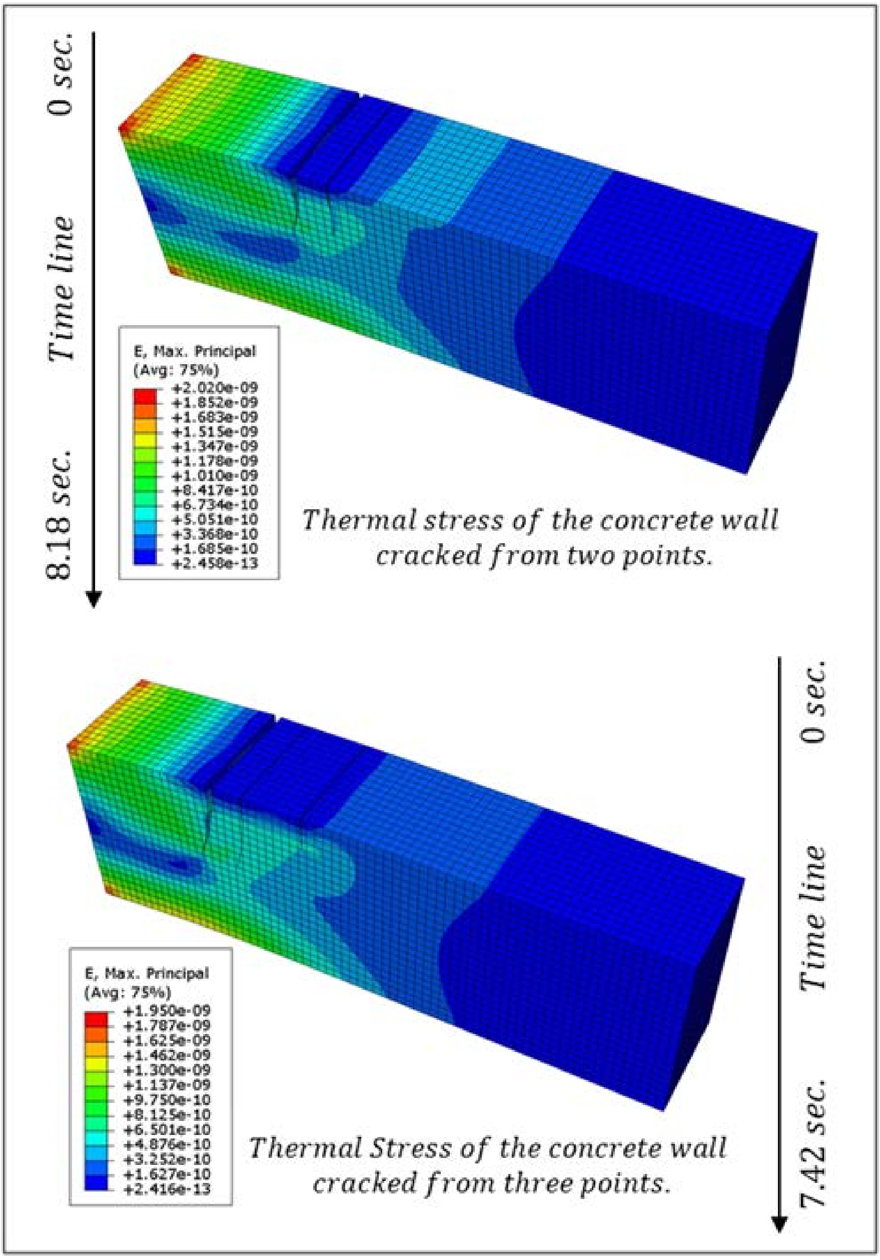

Fig.5. Thermal stress comparison of the crack walls, (a) Two-cracked wall, (b) three-cracked wall

The thermal energy distribution of a concrete wall with the same dimensions and features are simulated. It is seen that the thermal energy spread in 8.18 seconds in two-cracked walls occurred in 7.42 seconds in a three-cracked wall for the same size. It is observed the thermal heat energy is absorbed and dissipated faster in the cracked walls. This indicates that thermal spreading is 9.2% faster than thermal spreading in three-cracked walls.

Simulation of the single-cracked wall, multi-cracked wall, and non-cracked wall temperature distribution for a defined duration results are shown in fig.6. In this figure, the blocks of 10cm x 3cm x 2cm dimensions, the left column shows the wall piece without crack, the middle column shows the wall piece with a single-crack and right column shows the wall piece with multi-crack and the figures in the same line matches heat distribution for the same time for the duration of 1.2 seconds. This simulation is very useful for studying the close relationship between temperature distribution and the number of cracks. The results of these simulations show that there are differences in the heat distribution of single-cracked, multi-cracked, and non-cracked walls. It is observed that heat is absorbed and dissipated faster in the cracked walls. It is seen that a difference of 4% of degrees of heat distribution between the non-cracked wall and single-cracked wall in 1.2 seconds time period.

Also, a difference of 7% is observed in the heat distribution in the same period between the non-cracked and the multi-cracked wall types.

6. RESULTS AND DISCUSSIONS

After analyzing the typical walls with multiple perspectives such as concrete, composite, and brick the interactions of the cracking and stress, as well as the interactions with the thermal characters and the behaviors, final results, evaluations, and the determinations are described here.

The thermal distribution and heat transfer of the typical walls are given in fig.1.(a), fig.1.(b), fig.1.(c), and fig.3. It can be said that due to the unstable temperature change and different physical properties of the layers, thermal stress and deformation can be observed which can be negatively influenced by volume stability and structure. Moreover, in the walls exposed to high heat, heat transfer occurs quite quickly, causing disruptions and changes in the surface and geometry of the wall. Also, it is seen that the temperature difference of the structure distribution is not linear. The key to studying the temperature effect on a concrete wall is to determine the most unfavorable temperature distribution.

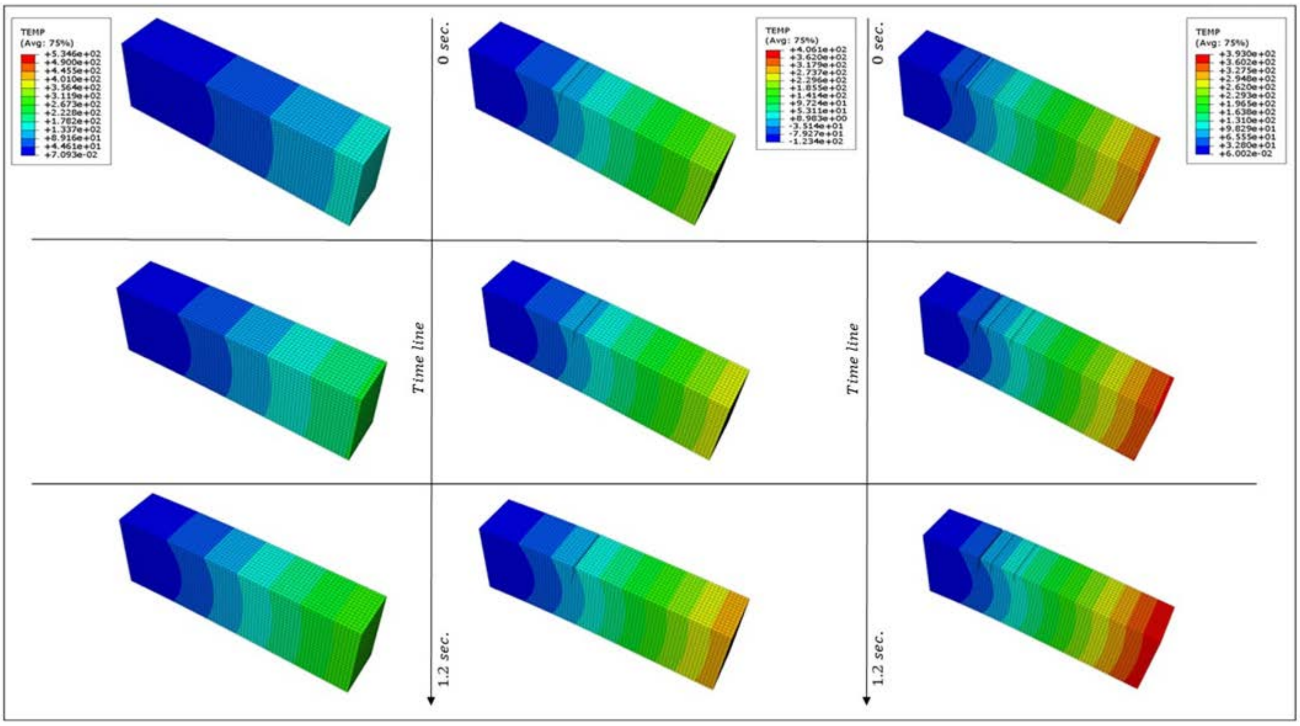

Fig. 6. Temperature distribution and comparison of a non-crack, single-crack, and multi-crack.

(a) Non-crack wall, (b) Single-cracked wall, (c) Multi-cracked wall

The thermal stress analyzes of the typical cracked and non-cracked walls are given in fig.2.(a), fig.2.(b), and fig.2.(c). It is observed that the more cracks distributed over the concrete and brick walls, the faster heat propagates with the increasing temperature. A cracking accretion and breeding around the walls support the increase in the temperature which can be led to the structural disruptions of the walls. Also, from the analyses, it is seen that increasing the temperature causes thermal stress intensity because of the circulation of warmth in the walls. The unstable temperature changes generate a high-temperature gradient of the cracked-walls, this induces the appearance of high values of tensile stress that could worsen the static behavior of the concrete walls.

The thermal stresses on the wall changes with the depth, number, and size of the fractures. However, the thermal energy distribution of a concrete wall with the same dimensions and features are simulated, it is seen that thermal stress formation occurs faster and the thermal heat energy is absorbed and dissipated faster in the three-cracked walls. When the thermal energy is applied to the concrete wall cracked from several points as shown in fig.5. there is around a 4 to 7 % change in the heat distribution of two-cracked, three-cracked walls. It is seen that the thermal energy spread occurred in 8.18 seconds in two-cracked walls, it occurred in 7.42 seconds in a three-cracked wall. This indicates 9.2% faster thermal spreading in three-cracked walls.

By the simulation of non-crack wall, single crack wall, and multiple crack wall thermal analysis the thermal distribution of a wall due to the crack occurrence is displayed as shown in fig. 6. The 10cm length, 3cm height by 2cm width block with uneven cracks have temperature changes in the cracked walls when compared to the non-cracked wall structure. This supports the close relationship between the temperature on the wall and the cracked wall. It is seen that a difference of 4% temperature change is observed in the heat distribution in 1.2 seconds time period between the non-cracked wall and single-cracked wall. Also, a difference of 7% temperature change is observed in the heat distribution in the same period between the non-cracked and multi-cracked wall.

Results of the thermal analysis in this study also show the materials used in the manufacturing of concrete walls affect the heat dissipation considerably. Therefore, a suitable material can be used as a thermal sealer to achieve good thermal insulation. These materials can be used up to get the appropriate k value, so thermal sealing can be set on the concrete wall. The results show that heat exchange is determined by the wall thermal characteristics and so, materials of the wall should be selected appropriately to control the local climatic conditions.

7. CONCLUSIONS

The study presents the FE modeling results of several wall types. Simple and reliable models are established to analyze the temperature field, thermal stress, and crack of concrete and brick walls. This study deals with the peculiar aspects connected to the numerical modeling of thermal and structural analysis on the wall types to see the temperature effects of fractures and cracks in concrete walls. Thus, FE applications have been employed to perform temperature and structural analysis by considering the temperature-dependent features of the walls as thermal conductivity. It is believed that these results allow us to lead further studies to investigate thermal and structural subjects such as safety issues, greenhouses, etc., in the concrete, composite, and brick walls.

A practical calculation is done using the FE method to analyze the reasons for the temperature distributions, temperature stresses and cracks, heat flows, and heat fluxes. The temperature design parameters have a close relationship with the geographical position, direction, natural condition, material, etc. of a concrete wall or brick wall and are difficult to determine. The temperature loads of sunlight, a sudden drop in temperature, and annual temperature variation will produce a temperature effect on a concrete wall and these factors are considered in-wall construct designs. The simulation and modeling results can be a guide for the selection and design of several walls with several different properties considering energy conservation. Thermal cracking and thermal stress problems in the walls are interrelated and have a direct relationship with temperature and high-performance concrete can be used for increasing resistance and to decrease absorptivity.

Finally, this study presents a multi-aspect thermal analysis method that can allow the researchers to compare the thermal response of typical walls under different ambient conditions by showing simulated results for typical walls. If appropriate sensors can be developed to detect the thermal changes in the wall structures, the human body detection can be done under debris. This situation can be improved by using a network of sensors and installing these sensors around the debris. This type of monitoring can be used also for structural analysis of a building wall structure and the system can produce a warning signal to the living people. The results of the study are considered an asset to support further studies.

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