Assessment of current crack width and crack spacing in enormous covered concrete constructions matter to exterior restrictions exploiting RBSM

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ABSTRACT

This study aimed to develop a numerical method to evaluate thermal cracking, in terms of parameters such as thermal crack width and crack spacing, on massive reinforced concrete (RC) wall structures externally restrained by a base structure. The existing experimental study was investigated using the rigid body–spring model (RBSM) with new constitutive laws developed for this objective. Thermal cracks, which localized and propagated throughout the wall thickness, were successfully reproduced, and the good agreement with the experiment indicated the capability of the proposed numerical method. The time-dependent cracking behavior and the impacts of fac- tors affecting thermal cracking, which are dif cult to investigate experimentally, are discussed.

KEYWORDS: Fracture Mechanics, Structural Integrity, Hydrogen Embrittlement, Nondestructive Evaluation

1.0 INTRODUCTION

Ice The structural performance and durability of concrete structures have been studied for the last few decades to prolong their lifetime. Several studies have focused on the impact of cracks on the structural performance and durability of reinforced concrete (RC) structures. Studies have reported that cracks cause a significant reduction in the mechanical properties of concrete [1-17]. The stiffness and natural frequency of RC structures are significantly degraded with the drying-induced crack openings [18–35]. The degradation of natural frequency was con rmed with recent investigations by damage monitoring with acoustic emission technique [36-48] and improved cohesive fracture approach [49-58]. Cracks also strongly affect the shear resistance of the RC beam which might lead to a change of the failure mode from shear brittle to exural yielding [50–63]. Furthermore, the existence of cracks (e.g., localized through cracks from thermal stress at an early age and surface cracks from drying shrinkage during the service period) in concrete might induce the ingress of harmful substances that dramatically accelerate the deterioration process. For instance, water uptake occurs when an RC structure is submerged in water [64–74], and water convection induces the penetration of the carbon dioxide and chlorite ions [75-84]. Thus, the evaluation of cracking is essential to ensuring good structural performance and durability over the structure's lifetime. Throughout the lifetime of the structure, cracking on concrete inevitably occurs for several reasons [1-19]. In this study, thermal cracks on massive RC members at an early age were investigated because they occur at the beginning, and some of the cracks remain throughout the lifetime. For decades, the knowledge of the early-age behavior and thermal-crack characteristics of massive RC members has been investigated through experiments. Countermeasures for thermal cracks have been suggested [20–34] based on experimental studies. However, experimental investigation cannot be directly used for performance-based design, the numerical methods that adequately evaluate the crack width and spacing of massive RC structures subjected to external restraint conditions are able to determine the details of RC members, mixture proportion of concrete, and the construction process. In this study, a rigid body–spring network model (RBSM) with new constitutive laws was developed for this objective, and its performance was evaluated by comparing it with existing experimental data. Regarding the cracking behavior at an early age, special considerations must be examined [35-49] such as the imposed deformation of the restrained structure from hydration heat inside massive concrete, the development of physical properties during the hardening process, early-age creep behavior, and autogenously shrinkage. For the design procedure, most numerical studies were conducted to evaluate early stress and predict cracking risk [50–67] based on the thermal cracking index (a ratio of tensile stress to tensile strength). In addition to the occurrence of cracks, the determination of crack width is also important, particularly with respect to durability. However, research on crack width calculations is scarce. Utilizing the smeared crack model based on continuum approaches such as the nite element method (FEM), thermo-mechanical analysis [44-58] and thermo-hydro-mechanical (THM) analysis [68–75] were conducted to predict thermal cracking at an early age. The distributed crack along RC members can be simulated with an average approach like a smeared crack model, however, strongly localized behavior, as well as multiple cracks in the element, could not be reproduced by using a crack band model [21-36]. Moreover, crack width assessment from the strain localization within the finite element method requires an adequate interpretation of data. Thus, it seems difficult to evaluate the crack width and its impact on durability. A cohesive fracture model, which is a continuum approach that introduces an inter-element cohesive fracture approach to allow crack-induced nonlinear processes to be easily predicted, was proposed to predict crack width [76-84]. The crack width was evaluated based on a displacement jump occurring between the elements. However, this approach has a limitation in that the used constitutive laws are dependent on mesh type and mesh size. Besides the continuum approach, discrete approaches were proposed and developed. Owing to the discontinuity of cracks, using discrete models could be easily adopted compared to a continuum. A lattice model, which discretized concrete into a network of beam elements, was employed to simulate cracking behavior [1-17]. Cracks were simulated by considering the damage degree or removing of truss element; thus cracks were explicitly reproduced. A discrete approach such as a rigid body–spring network was proposed and developed [18-32]. A concrete was discretized as an assemblage of rigid particles interconnected with the spring along its boundary. A 2D rigid body-spring network was utilized to investigate the thermal stress in RC wall structure at an early age [44]; however, the prediction of crack width was not accentuated. In this study, thermal cracks in massive walls restrained by the base structure were numerically evaluated using a three- dimensional (3D) RBSM which was developed by a rigid body-spring network. The reference experiment reported in the guidelines published by the Japan Concrete Institute (JCI) was a part of the parametric experimental study on the cracking of massive concrete structures affected by factors such as unit cement content, reinforcement ratio, environment temperature, and reinforcement bar diameter [33-48]. The RBSM is a discrete model that addresses cracking behavior in an RC structure. The numerical results will be discussed to elucidate the behavior of thermal cracks (e.g., crack width and spacing) and the impact of several factors that could not be investigated or were difficult to investigate experimentally in previous studies [49-57].

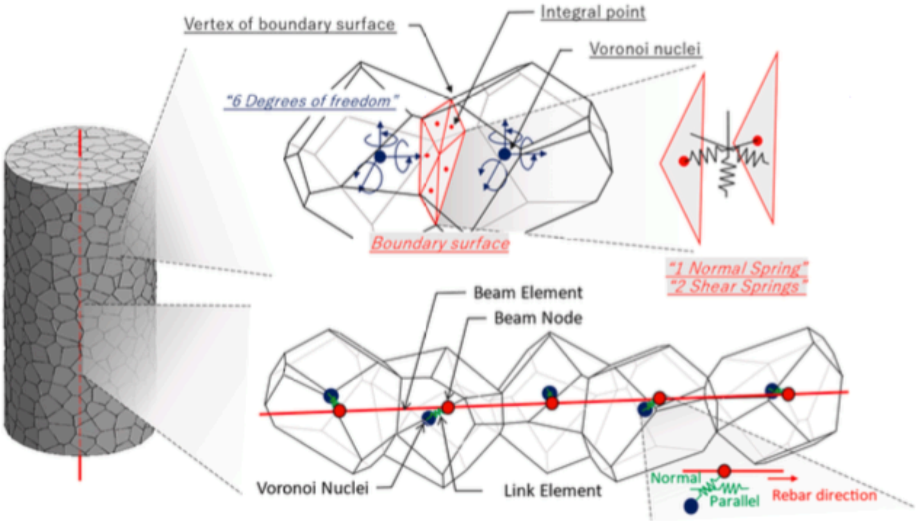

Fig. 1. Schematic diagram of the rigid body–spring model

2.0 METHODOLOGY

In this study, the coupled numerical method, RBSM, and the truss network model (TNM), which have the potential for the thermo- chemo-mechanical modeling of massive concrete structures, were implemented. Additionally, they can explicitly reproduce the fracture behavior and heat transfer process and consider the impact of cracks on RC members [12–35]. The RBSM is a discrete model that discretizes concrete into an assemblage of rigid particles based on the Voronoi diagram. Each particle is connected to zero-size springs, one normal spring, and two shear springs at the integral point of the Voronoi surface. Each zero-size spring has the stiffness which was determined by the mechanical properties of concrete (Young's Modulus) and the geometry of the Voronoi element. With an assemblage of several Voronoi elements, the global stiffness was constructed and able to perform structural analysis. The deformation and crack width were interpreted from the strain of zero-size spring and the distance between adjacent Voronoi nuclei. Because this study focused on massive RC structures, the reinforced bar (rebar) was explicitly modeled using the discrete approach proposed by Saito et al. [36-51].

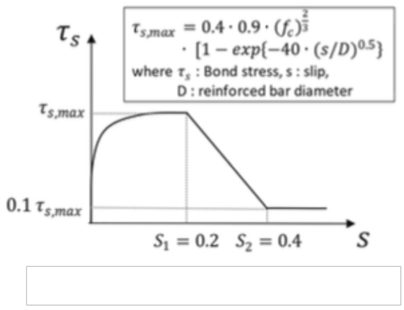

Fig. 2. Constitutive model of the springs in an RBSM

The rebar was discretized as a Truss element along its length. The position of the truss node must be consistent with the Voronoi nuclei that the rebar was embedded. The rebar–concrete bond was considered with a Nonlinearity was introduced into the springs through constitutive laws (Fig. 2) to reproduce the deformation and fracture behavior of the concrete material. The axial behavior of the reinforcing bar and bond stress–slip model was described using the formula pro- posed by Shima et al. and Suga et al. Under the volumetric change in the early stages of ageing, a massive RC member encounters hysteresis loading from expansion and shrinkage under a temperature increase and decrease, respectively. Therefore, the stress–strain hysteresis of each constitutive model was carefully implemented (Fig. 3). This hysteresis is important for evaluating the stress release and resultant deformation of elements other than the cracked region. The impact of mechanical development was also considered using the time-dependent constitutive (TDC) model to evaluate stress development after changes in stiffness and sustained load by adequately considering the plastic deformation due to loading history [52-68].

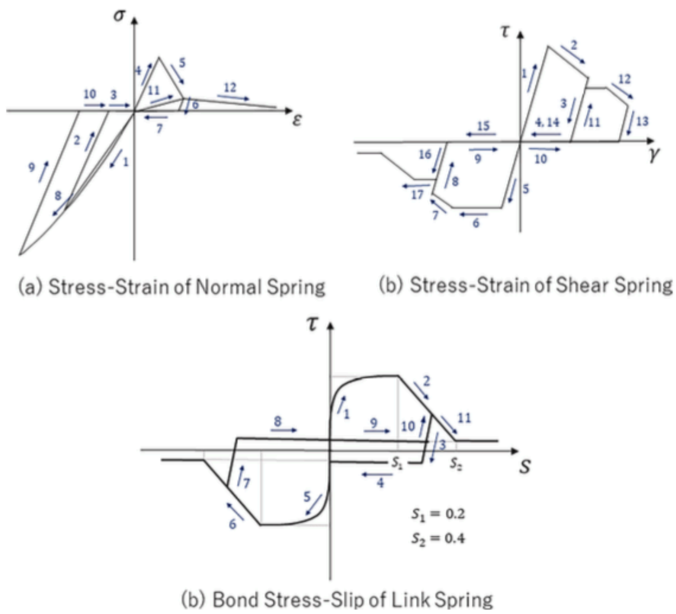

Fig. 3. Hysteresis of stress–strain of spring in constitutive models The numbering and arrows refer to direction of stress–strain path under hysteresis loading.

zero-size link element between the truss node and Voronoi nuclei. The bond-slip behavior was interpreted by the strain of a zero-size spring. A schematic of the RBSM is shown in Fig. 1. During the hydration process, known as the hardening process, the development of mechanical properties has a signifcant influence on the mechanical behavior of concrete. A TDC model, which was initially created by Maruyama et al. and further developed in later studies, was employed to assess the impact of changes in the mechanical properties. In this study, the TDC model was carefully re ned along with the hysteresis relationship (Fig. 3) to cover all stages of the stress–strain mapping. A schematic of the TDC is shown in Fig. 4. According to the hardening process, the evolving mechanical properties (e.g. concrete strength and Young's modulus) must be considered in constitutive models. The stress–strain path must be relied on the updated constitutive model to consider the early age behavior of concrete material [54-78].

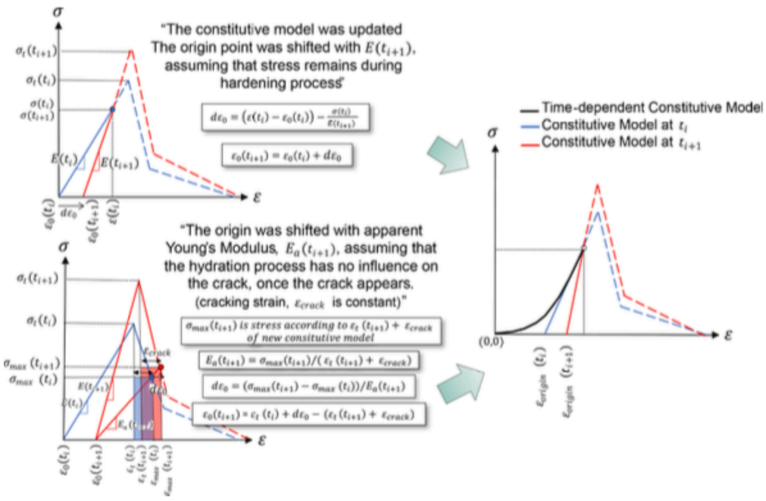

Fig. 4. Time-dependent constitutive (TDC) model

However, the drifting of the stress–strain path (e.g. sudden change of stress) was observed with the updated constitutive model. Thus, the origin shifting of the constitutive model is necessary to reasonably reproduce the stress–strain path under the hardening process. In the elastic range, the constitutive model was updated based on evolving concrete strength and Young's Modulus, then the origin of the constitutive model was shifted with the new Young's Modulus by assuming that the stress–strain state remained during the hardening process [71-84]. With this process, the stress–strain path will continue from the previous to the new constitutive model without any drifting. After cracking, the origin of the constitutive model after updating the constitutive model was different. The origin was shifted based on the apparent Young's Modulus (the slope between the origin and maximum strain) by assuming that the hydration process does not in uence existing cracks (cracking strain should remain during the hardening process). With this process, the stress–strain path will continue from the previous to the new constitutive model through the reloading path (apparent Young's Modulus) without any drifting [22-48].

Table 1
Experimental condition for experimental series 2

		Specimen			
		No. 2	No. 1–2	No. 3–2	No. 4
Cement Type	OPC	O	O	O	O
Unit cement content	$w_c = 320$ kg/m^3 (w/c = 0.50)		O		
	$w_c = 380$ kg/m^3 (w/c = 0.42)	O		O	O
Reinforcement ratio	$\rho_s = 0.27\%$	O	O		O
	$\rho_s = 0.65\%$			O	
Rebar diameter	D = 10 mm				O
	D = 19 mm	O	O	O	

zero-size link element between the truss node and Voronoi nuclei. The bond-slip behavior was interpreted by the strain of a zero-size spring. A schematic of the RBSM is shown in Fig. 1. During the hydration process, known as the hardening process, the development of mechanical properties has a signifcant infuence on the mechanical behavior of concrete. A TDC model, which was initially created by Maruyama et al. and further developed in later studies, was employed to assess the impact of changes in the mechanical properties [1-23]. In this study, the TDC model was carefully re ned along with the hysteresis relationship (Fig. 3) to cover all stages of the stress–strain mapping. A schematic of the TDC is shown in Fig. 4. Previous studies on ageing viscoelasticity suggested that basic creep signi cantly impacts the early-age stress development in concrete and must be considered to calculate the stress throughout the analysis. In this study, a basic creep model based on the recommendation of the Architectural Institute of Japan (AIJ), considering ageing viscoelasticity, was employed. Creep behavior was considered in the RBSM based on the superposition principle of creep strain stipulated at each time interval. The creep coef cient, which is the ratio of creep to elastic strain, was determined based on Young's modulus ratio during the loading period and during maturity, as expressed in Eqs. (1)–(4). where ∅(te , t0) is the creep coef cient considering the age at the loading time based on the 28-day Young's modulus, ∅0 is an ultimate value of the creep coef cient, βH is a coef cient that represents the ageing creep rate, te is the temperature-adjusted concrete age (days) determined using Eq. (13), t1 is a coef cient to standardize the material age (t1 = 1.0 days), cc is the coef cient that represent creep rate, fc,28 is the compressive strength (N/m2), and Ec(te) and Ec,28 are Young's modulus (N/m2) at the loading time and at 28 days, respectively [24-47]. In the early-age period, autogenous shrinkage in massive concrete structures should be considered when evaluating the risk of cracking. It was reported that the autogenous shrinkage of concrete (w/c = 0.55) in massive RC wall structures results in a 10% higher tensile stress at a later age. In this analysis, the autogenous shrinkage, which depends on the water-cement ratio and the maximum historical temperature, was determined based on the relations in Eqs. (5)–(9). A network of truss elements was constructed within the Voronoi elements and assumed as a linear conduit for the potential ow in concrete material [48-61]. The truss elements generated between the Voronoi nuclei, and the intermediate point of the boundary surface are internal truss elements (blue line). The internal truss element acts as the linear conduit with a cross-section area Voronoi surface. To avoid the redundancy of truss volume, the calibration factor, a ratio of all truss element volume to total volume of specimen, is introduced. The truss elements generated between the intermediate point, and the middle point of the line between the vertex are boundary truss elements (green line). The boundary truss element acts as the linear conduit with a cross-section area determined by the crack displacement at the integral point. Thus, the boundary truss elements are activated when cracks were generated [62-78]. However, the heat transfer through cracks was neglected for the simplicity of numerical study. The schematic diagram for Truss-Network Model is shown in Fig. 5. The heat transfer process in a concrete member is based on the classical thermal energy balance equation. Heat generation via the hydration process, heat conductivity within the massive concrete, and heat convection at the concrete surface were considered in the TNM. The governing equation based on Fourier's law and the boundary condition equation for the 1D heat transfer process are expressed as in Eqs. (10) and (11), respectively [68-84].

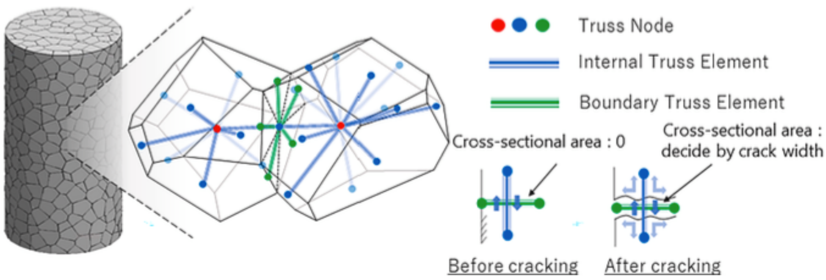

Fig. 5. Schematic diagram for the truss network model.

3.0 RESULT

In The hydration heat, resulting from the hydration reaction in cement, has been a source of concern in massive concrete because the heat is gradually transferred through the thickness before dissipating at the concrete surface. The temperature in the concrete increases and then decreases owing to heat accumulation and dissipation, respectively, before reaching equilibrium [1-27]. The temperature change results in a volume change that induces stress under restraint conditions. Figs. 1 to 5 show the temperature and stress history extracted from the center of the reference specimens. The analytical results exhibited consistency in the temperature history compared with the experiment. The horizontal stress from the volume change under restraint conditions can also be reproduced. The development of compressive stress during expansion was closely reproduced. However, the development rate of tensile stress after reaching the maximum temperature was higher, while the maximum tensile stress was lower than that in the experiment. For the experimental study, the stress history was measured using an effective stress meter that evaluated the concrete stress by converting the force acting on the load cell based on elastic strain. Studies have reported that the evaluated stress significantly depends on its rigidity, the length of the load cell part, and the stiffness of the surrounding concrete [28-51]. In addition, for the measurement at an early age, the rigidity of the load cell should be reduced to achieve realistic stress in concrete structures. Generally, the effective stress is often overestimated (approximately 1.1 times of the realistic concrete stress); thus, it should be calibrated. There is no report on the calibration in the reference experiment; hence, the measured concrete stress might have been overestimated. For the numerical study, the stress history from the analysis was averaged from the concrete element near the measured point because the element stress around the measuring point appeared to be sensitive after the occurrence of cracks. The scattering of the stress evaluated from the concrete elements was observed. Nevertheless, the scattering of stress history in the analysis exhibited the same tendency and appeared to cover the range of the experimental results. As suggested by the RILEM, several phenomena in uence the cracking behavior of massive RC structures. The hysteresis volume change during the hardening process is a crucial factor that induces thermal cracking. Additionally, the impact of temperature history, early-age creep behavior, and autogenous shrinkage on thermal cracks have been reported. However, it is dif cult to experimentally investigate the impact of each of these factors on the cracking behavior [52-73]. This study con rmed the impact of these factors, and additional analytical data are provided in last part. The higher and lower ambient temperatures resulted in an increase in localized through cracks and a larger total crack width (36.3% and 48.7%, respectively). The consideration of the early-age creep behavior caused stress relaxation under restraint conditions and further development of the total crack width (25.2%) due to creep behavior after the restraint condition was diminished by the occurrence of localized through cracks. The number of localized cracks and the total crack width increased by approximately 25.5% owing to autogenous shrinkage. Therefore, these factors must be considered to accurately model crack behavior when investigating thermal cracking in the early age period. In addition, the impact of the crossover effect of temperature-dependent concrete property developments, particularly the tensile strength and fracture energy of concrete, which are strongly affected by the aggregate types, were not considered. The proposed new method can deeply understand the relationship between concrete material properties and structural responses, including cracking behaviors [68-84].

4.0 CONCLUSIONS

We The hydration heat, resulting from the hydration reaction in cement, has been a source of concern in massive concrete because the heat is gradually transferred through the thickness before dissipating at the concrete surface. The temperature in the concrete increases and then decreases owing to heat accumulation and dissipation, respectively, before reaching equilibrium. The temperature change results in a volume change that induces stress under restraint conditions. Figs. show the temperature and stress history extracted from the center of the reference The analytical results exhibited consistency in the temperature history compared with the experiment.The horizontal stress from the volume change under restraint conditions can also be reproduced. The development of compressive stress during expansion was closely reproduced. However, the development rate of tensile stress after reaching the maximum temperature was higher, while the maximum tensile stress was lower than that in the experiment. For the experimental study, the stress history was measured using an effective stress meter that evaluated the concrete stress by converting the force acting on the load cell based on elastic strain. Studies have reported that the evaluated stress significantly depends on its rigidity, the length of the load cell part, and the stiffness of the surrounding concrete. In addition, for the measurement at an early age, the rigidity of the load cell should be reduced to achieve realistic stress in concrete structures. Generally, the effective stress is often overestimated (approximately 1.1 times of the realistic concrete stress); thus, it should be calibrated. There is no report on the calibration in the reference experiment; hence, the measured concrete stress might have been overestimated. The 3D RBSM, which can directly model cracking behavior, is proposed to verify the early-age behavior of thermal cracking in massive RC members. In the validation process, a numerical study based on an experimental study by JCI was conducted. Factors affecting cracking behavior, temperature history, early-age creep behavior, autogenously shrinkage, development of Young's modulus, and tensile strength of concrete were modeled based on the experimental data. As a result, thermal cracks, i.e., crack width and crack spacing, were adequately reproduced. In addition to these crack phenomena, the calculation results indicated the following behaviors: (1) Thermal cracks, localized through the wall thickness, were initiated near the longitudinal center of the RC wall structure. Additional localized cracks subsequently occurred at the center of the fractured part. The mechanism is similar to the fracturing process of RC members under uniaxial tensile stress. (2) The localized through crack initiated at the top center of the wall structure and propagated toward the side surface and bottom. The gradient of the crack-width distribution was observed over time. This was the consequence of the gradient of the hysteresis volume change due to temperature distribution, enhancing the tensile resistance by rebar arrangement, and the restraint provided by the stiff base structure. (3) In the reinforced massive concrete wall, the equal behavior was induced by the eccentric restrained volume change due to the temperature change from the hydration and cooling processes associated with the hardening process. The uplift attempt at the end of the wall induced horizontal cracks at the sides of the walls at the interface between the wall and base structure.

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