Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Development of Spalling Crack Prediction Model with Infrared Thermography

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ABSTRACT

In Japan, many civil structures constructed during high economic growth period, and now these structures are suffering with various deteriorations. Therefore, effective and economic maintenance methods are required, and recently infrared thermography is focused on as an inspection tool for finding out spalling crack due to reinforcement corrosion. At this point though we can know whether any spalling crack exist or not with infrared thermography, however, it is difficult to evaluate spalling risk quantitatively. In this study, quantitative evaluation of spalling crack propagation with infrared thermography was investigated with experiment simulating corrosion expansion pressure, and with results it was tried to develop spalling crack propagation model with infrared thermography.

Keywords. Corrosion, Spalling, Inspection, Infrared Thermography, Prediction Model

INTRODUCTION

Reinforcement steel in concrete is usually protected by passive film. However, it is well known that the reinforcement will start to corrode when the film is destroyed by carbonation or chloride attack. When the steel bar corrodes, cracks are induced to cover concrete because the volume of corrosion product is much larger than that of steel. And deterioration factors such as water, oxygen or chloride ion penetrated through these cracks accelerate corrosion and consequently corrosion of steel may cause the load-carrying capacity of concrete structures.

Because Japan is surrounded by the sea, and also has many mountainous areas where deicing salt is used in winter, reinforcement corrosion is one of serious problem concerning concrete structures.

In order to maintain or management concrete structures more effectively, many non-destructive test methods are used. Infrared-thermography is one of such techniques. At this point, though we can know whether any detect exist or not with infrared-thermography, it is difficult to evaluate the results obtained by inspection with thermography quantitatively.

The purpose of this study is to develop quantitative spalling prediction method with infrared-thermography.

Experiment

Specimen. In this study, 400x400x150mm prism concrete specimen with cylindrical hollow inside was used. In order to simulate actual structures, transverse reinforcements were set in specimen. The detail of specimen is shown in Fig.2. The experimental factors were spalling type. In the past study[1)2)], authors reported that in the case cover thickness to bar diameter ratio C/D < 2.1 spalling crack appear on concrete surface, and in the case C/D > 2.1 spalling crack will propagate along behind reinforcement. In this paper, cracks propagate along behind reinforcement is defined as horizontal crack. In this study 2 types of specimen were prepared; one is the specimen with 20mm cover thickness and D19 reinforcement (Type I), and the other is the specimen with 40mm cover thickness and D19 reinforcement (Type II). In this experiment, 2 specimens were prepared for each case. Detail of each specimen is shown in **Fig.1**, and crack propagation model of each type is shown in **Fig.2**.

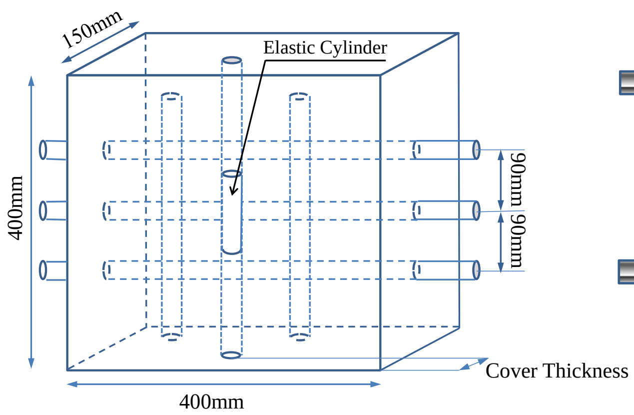


Fig.1 Detail of Specimen

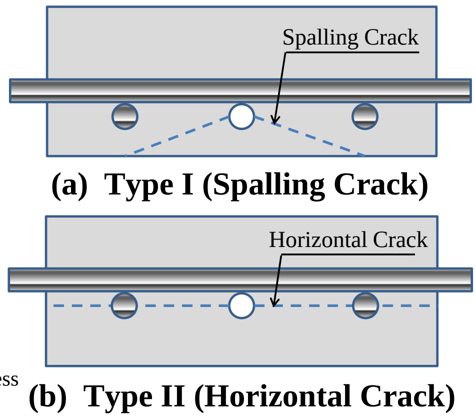


Fig.2 Crack Model

Principle of Experiment. Corrosion expansion pressure was simulated by compression of the elastic cylinder inserted into the hollow. Length of elastic cylinder used in this experiment was 100mm. Detail of loading is shown in **Fig.3**. When the elastic cylinder in concrete is deformed vertically, the elastic cylinder expands and the pressure due to the expansion is induced in surrounding concrete because of the Poisson's effect, as shown in **Fig.4**. Then the inner pressure, pi (N/mm^2) and the radius expansion, dr (mm) can be calculated by the following equations.

$$dr = \frac{\nu \cdot dL \cdot r_0}{L_0} \qquad (1)$$

$$pi = \frac{\nu E}{\nu - 1}\left(\frac{dL}{L_0} - \frac{P}{E r_0^2 \pi}\right) \quad (2)$$

where P is vertical load (kN), dL is vertical displacement (mm), r_0 is initial radius of the elastic cylinder (mm), L_0 is initial length of the elastic cylinder (mm), E is Young's modulus of the elastic cylinder (N/mm^2), and ν is Poisson's ratio of the elastic cylinder.

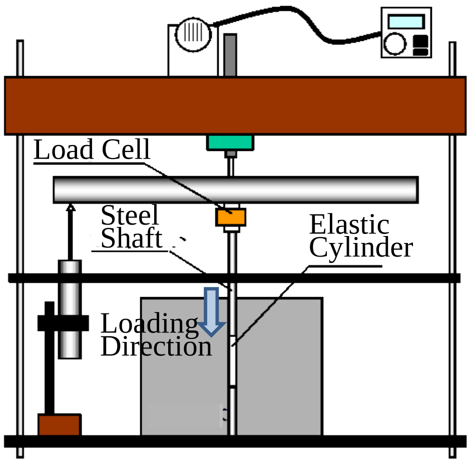


Fig.3 Details of Loading

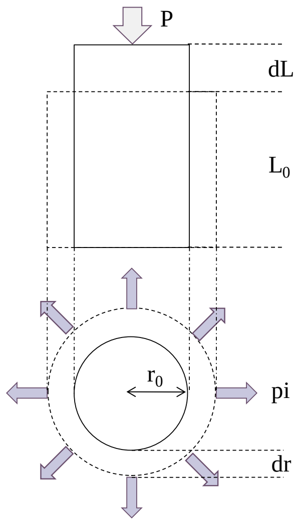


Fig.4 Deformation of elastic cylinder

Measurement of Infrared Thermography. In this experiment, when the deterioration level reached to a certain level, loading was once stopped and then measurement of infrared thermography was carried out under various thermal environments. Thermal environment (Te) means the difference of temperature between specimen surface (Tc) and surrounding air (Tex), and is defined as following equation.

$$Te = Tc - Tex \quad (3)$$

After measurement of infrared thermography, loading was restarted and stopped again when deterioration level reached to the next level. Deterioration level of each specimen is shown in **Tab.1-Tab.2**. Inner crack width was measured by laser displacement transducer as shown in **Fig.5**, and performance of infrared thermography camera used in this experiment is shown in **Tab.3**.

Results and Discussion

Evaluation of Infrared Thermography Picture. **Fig.6** is the infrared thermography pictures measured just before spalling crack appear on concrete surface. And **Fig.7** shows the temperature distribution on line A-B at the point. From the figure, it was observed that temperature gap between spalling area and sound area appeared due to spalling crack propagation. In this paper, this temperature gap is defined as spalling temperature gap (ΔT).

Influence of Thermal Environment. **Fig.8** shows the relationship between thermal environment (Te), and spalling temperature gap (ΔT). From the figure, it can be considered that spalling temperature gap increase almost linearly as thermal environment get large. This

Tab.1 Deterioration level (C20D19)

Specimen	Deterioration Level	Innner Crack Width (mm)	Details
C20D19-1	STEP 1	0.1	Longitudinal crack appear
	STEP 2	0.2	
	STEP 3	1.0	Spalling Crack appear
	STEP 4	2.0	
	STEP 5	5.0	Spalling
C20D19-2	STEP 1	0.1	Longitudinal crack appear
	STEP 2	0.2	Spalling crack appear
	STEP 3	1.5	
	STEP 4	8.0	
	STEP 5	15.0	Spalling

Tab.2 Deterioration level (C40D19)

Specimen	Deterioration Level	Innner Crack Width (mm)	Details
C40D19-1	STEP 1	0.5	Longitudinal crack appear
	STEP 2	0.6	Spalling Crack appear
	STEP 3	0.8	
	STEP 4	1.4	
	STEP 5	8.2	Partial Spalling
C40D19-2	STEP 1	0.2	Longitudinal crack appear
	STEP 2	0.4	
	STEP 3	0.8	Spalling crack appear
	STEP 4	2.6	
	STEP 5	8.1	Partial Spalling

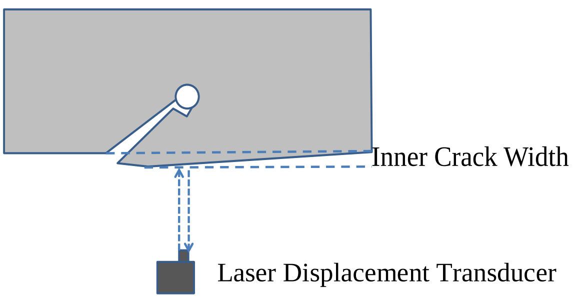


Fig.5 Measurement of Inner Crack Width

Tab.3 Performance of Infrared Thermography Camera

Device	InSb
Wave Length	3-5μm
NETD	0.025
Accuracy	±1%
Pixel	640x512

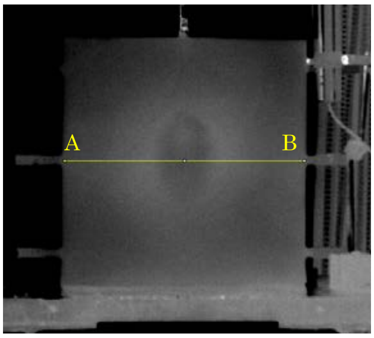


Fig.6 Infrared Thermography Picture before Spalling Crack Open

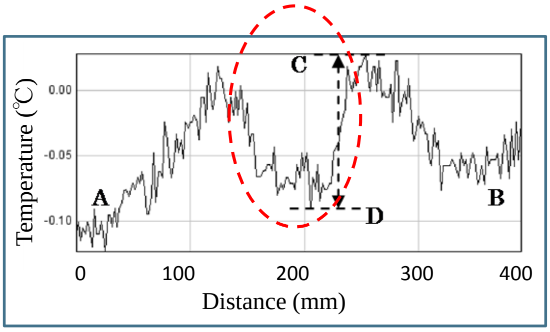
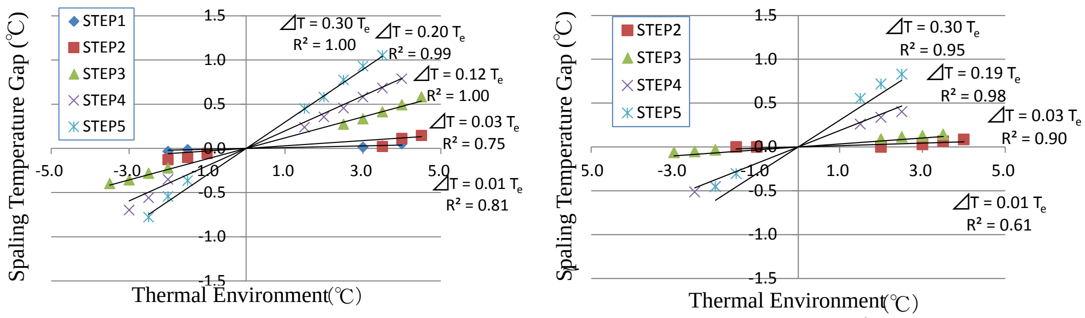


Fig.7 Temperature Distribution



(a) C20D19-1 **(b) C40D19-1**

Fig.8 Relationship between thermal Environment and Spalling Temperature Gap

tendency was also observed in the case C20D19-2 and C40D19-2. And it was also confirmed that gradient of approximation lines in **Fig.8** get large as degradation propagate. Therefore, it is thought that degradation level can be expressed by this gradient of approximation line, and the gradient is defined as thermal environmental coefficient (k).

Spalling Prediction Method. In this paper, spalling risk (Rs) is used as an index which signify degradation level, and spalling risk is calculated by the following equation.

$$Rs = dr/dr_s \quad (4)$$

where, dr; radius expansion (mm), dr_s; radius expansion when cover concrete fall down by spalling.

Fig.9 shows the relationship between thermal environmental coefficient (k) and spalling risk (Rs). From the figure, it is observed that spalling risk increase as thermal environmental coefficient (k) get large, and its increase rate become smaller as thermal environmental coefficient get large. Then, it was tried to investigate the relationship between √k and spalling risk (**Fig.10**). From the figure, it was made clear spalling risk increase linearly as √k get large, and spalling risk can be expressed by following equation with √k. There was no influence of spalling pattern or cover thickness on the relationship.

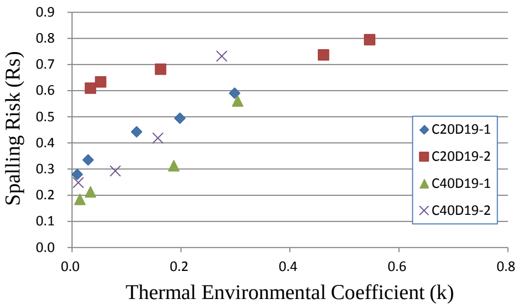


Fig.9 Relatiomship between Thermal Environmental Coefficient (k) and Spalling Risk (Rs)

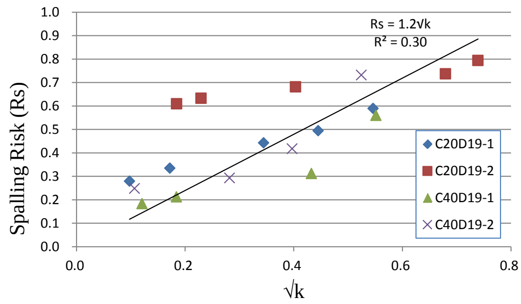


Fig.10 Relatiomship between √k and Spalling Risk (Rs)

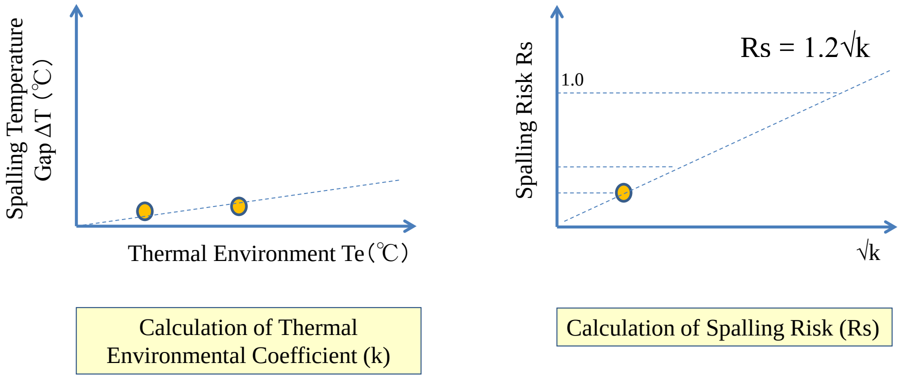


Fig.11 Spalling Prediction Model

$$Rs = 1.2\sqrt{k} \tag{5}$$

And with this equation, spalling risk can be evaluated by following method as shown in **Fig.11**. 1) Measurement of thermal environment (Te) and spalling temperature gap (ΔT). 2)Calculation of √k. 3) Calculation of spalling risk (Rs).

Conclusion

In this paper, development of spalling prediction model with infrared thermography was tried. And as a result, it was made clear that thermal environmental coefficient (k) can be obtained by infrared thermography measurement under different thermal environment, and that spalling risk (Rs) can be evaluated with obtained thermal environmental coefficient (k). And it was also confirmed that cover thickness or spalling pattern does not have any influence on this method.

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