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ANALYTICAL INVESTIGATION OF THE INFLUENCE OF REBAR ARRANGEMENT ON CORROSION CRACK PATTERN BY RBSM

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Abstract: When the corrosion occurs, the corroded portion of the rebar turns into a voluminous rust product which creates the internal pressure on the surrounding concrete. This internal pressure results in the cracking of concrete. However, the surface crack location may not correspond directly to the location of rebar corrosion. There are many parameters that affect the corrosion crack patterns, namely, concrete cover depth, amount and spacing of the rebar, the arrangement of rebar and so on. Due to the contribution of these parameters, identifying the corrosion location from the given surface crack information is difficult. In the real field, the structure condition is usually evaluated by the exterior surface inspection. Even though there are many technologies for observing the external condition of the structures, like a drone or digital image analysis technique, the method for investigating the internal corrosion condition are still limited and unclear. Hence, this paper aims to improve the understanding of the factors that affect the corrosion crack pattern through the use of numerical methods. The numerical system was developed based on the three-dimensional discrete analysis model, Rigid Body Spring Model (RBSM). Based on the characteristics of the discrete analysis model, by giving the expansive strain at the rebar-concrete interface, the numerical model can simulate the same expansion cracking as observed in actual cases of corrosion. Then, by using this model, the reinforced concrete models with different control conditions are simulated. The effect of stirrup confinement, concrete cover depth, diameter of rebar and number of rebars are studied through simulation results. Finally, the effect of influential parameters and the different crack patterns are discussed and presented.

1 INTRODUCTION

Concrete spalling is usually caused by the corrosion of the reinforcement bar (rebar) embedded in the concrete. The initiation of internal pressure caused by the formation of corrosion product results in the separation of the adjacent concrete, which is the cause of spalling or splitting in the old concrete structures [1]. Underestimating these internal damages can be dangerous. Spalling can lead to physical injuries and damage to the property.

Usually, in structure safety evaluation, optical observation is one of the most common methods. For example, the optical observation is the primary method that is always done for the routine monitoring of the railway tunnels in Japan, followed by a detailed inspection at the damaged locations. However, it is difficult to predict the spalling of concrete or the collapse of structure only from the external observations. Only surface crack width cannot be considered as an indicator that refers to the risk of spalling, but the internal crack pattern also affects the possibility of spalling of concrete. The crack pattern can be changed by many factors such as cover depth, number of rebars, rebar size, etc.

To understand the internal damage condition, numerical analysis is a beneficial tool. In this study, the three-dimensional Rigid Body Spring Model (RBSM) is used. A number of previous studies [2, 3, 4] reported that RBSM is an appropriate numerical model for simulating the local cracking damage. Bolander et al. [5, 6], Qiao et al. [7] and Tran et al. [8] also successfully used the RBSM to simulate the mesoscopic behavior and fracture of reinforced concrete. One key feature of the RBSM is the random polyhedral meshed elements at meso-scale. Therefore, the crack can be generated and propagated in the similar manner as in real specimen.

Thus, the objective of this study is to improve the understanding of corrosion crack patterns through numerical simulation. Reinforced concrete models with different control parameters are simulated to investigate their effect on corrosion crack pattern.

2 NUMERICAL MODEL

2.1 Rigid Body Spring Model (RBSM)

The numerical model used in this study is 3D RBSM, which is proposed by Kawai et al. [9, 10]. A 3D reinforced concrete model is meshed into polyhedral rigid elements whose phases are interconnected by one normal spring and two shear springs (Fig. 1). Each rigid body has six degrees of freedom (i.e., three translational degrees of freedom and three rotational degrees of freedom with respect to some point within its interior) (Eddy et al.) [11, 12]. The response of the springs provides the interaction between the rigid elements.

To enable crack propagation in arbitrary directions, a random geometry, based on a Voronoi Diagram, is used for element meshing. The size of each concrete element is made approximately 1^3-2^3 cm^3, in reference to aggregate size, while the size of steel elements is set according to the geometric complexity of the rebar arrangement.

To represent the reinforced concrete, two types of elements are used, the rebar elements and the concrete elements as shown in Fig. 2 (a). Fig. 2 (b) shows the geometry of steel elements which is modeled in an accurate manner to properly account for the interlocking between concrete and rebars. The simulation system is developed in previous studies by Eddy et al. [11, 12].

2.2 Expansive strain model

In the 3D RBSM adopted in this study, the expansion resulting from corrosion products forming around rebars is modeled by inducing a strain at the interface between rebar and concrete. The expansive strain concept is previously developed by Matsumoto et al. [13]. This expansive strain is added only to the normal springs at the interface as shown in Fig. 3.

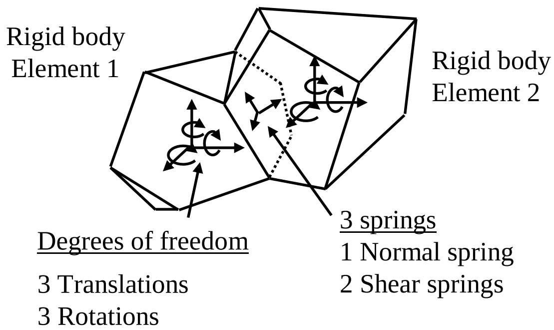
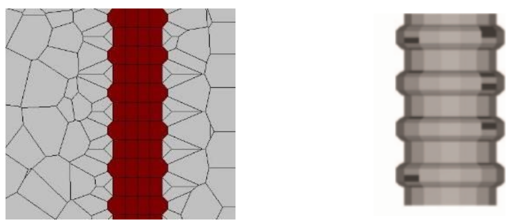


Figure 1: Concrete elements in RBSM



(a) Cross-section of steel and concrete elements

(b) 3D rebar shape (deformed bar)

Figure 2: Modelling of geometric shape of the rebar

3 MODEL VALIDATION AND GEOMETRY OF NUMERICAL MODELS

Previous experiment on RC beams by Dong et al. [14] is selected to validate the applicability of RBSM models. In Dong's study, 240×200×130 mm^3 concrete specimen with three 16 mm reinforcement at 60 mm spacing was tested in accelerated corrosion condition. In this study, the simulation model with the same cross-section and rebar arrangement was formed. The expansive strain is given at the interface of rebar and concrete until a clear crack pattern is exhibited. The simulation crack pattern is shown in Fig. 4 (b). It can be seen that the crack pattern obtained from the RBSM model is similar to the one obtained from the experimental test (Fig. 4 (b)). The numerical model could simulate the crack pattern appropriately. Thus, this validated RBSM model is selected for further parametric studies in the next sections.

Fig. 5 (a) and Fig. 5 (b) show the general geometry of the analyzed numerical models for the no stirrup specimen model and stirrup specimen model, respectively. The size of the model is 240×200×200 mm^3. The number of rebars, rebar diameter, clear cover depth and existence of stirrup are varied as the controlling parameters for this study. The specimens are reinforced with one or three rebars. The rebar diameter is varied as 16 mm or 25 mm. The cover depth is varied from 30 to 70 mm. By varying these parameters, 14 model cases are investigated.

In case of stirrup specimens, the clear cover depth of stirrup is 15mm. Fig. 6 (a) shows the cross-section of simulation model at stirrup plane in case of stirrup specimen reinforced with 3-DB16 at cover depth of 30 mm. The model contains 15,680 elements including 12,872 concrete elements and 2,808 steel rebar elements. Fig. 6 (b) shows its overview. Details of simulation cases are presented in Table 1. The first term 1B/3B, in the name of model, denotes the number of rebar, N/S represents the existence of stirrup, D16/25 is the diameter of rebar and C30/50/70 defines the cover of specimen. Table 2 shows the material properties of each material in the numerical model.

The interface expansion damage is introduced by applying the concept of initial strain (Matsumoto et al. [13]). The uniform expansive strain is introduced at the interface between rebar and concrete until the spring elongation at interface equals 0.075 mm. The crack pattern for each case is discussed in the next section.

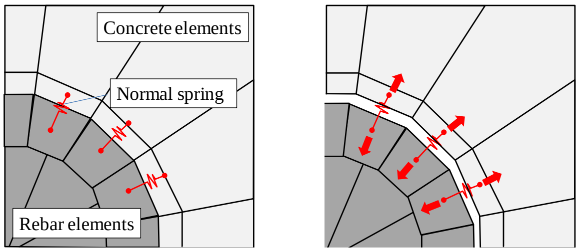
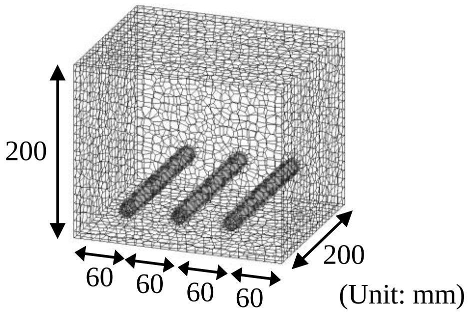
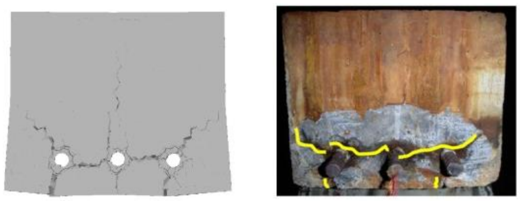


Figure 3: Interface between rebar and concrete and given initial strain



(a) RBSM model



(b) Crack pattern of RBSM model and test specimen [14]

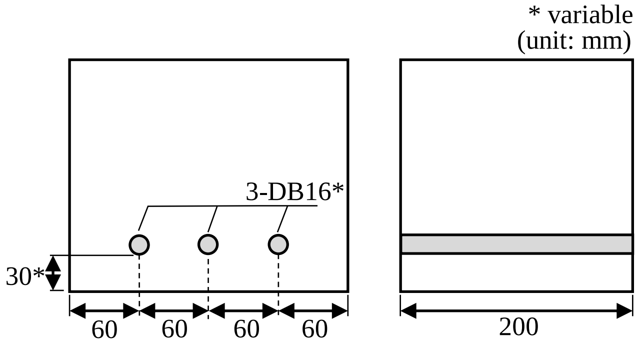
Figure 4: RBSM model and model validation

Table 1: List of simulation cases

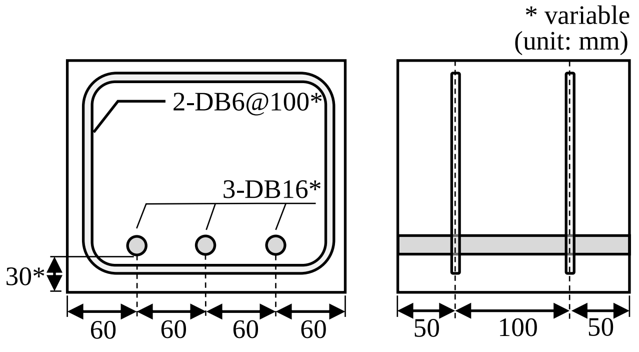
Case	Number of rebar	Stirrup	Diameter (mm)	Cover depth (mm)
1B-N-D16-C30	1	-	16	30
1B-N-D16-C50				50
1B-N-D16-C70				70
1B-N-D25-C30			25	30
1B-N-D25-C50				50
1B-N-D25-C70				70
1B-S-D16-C30		✓	16	30
1B-S-D16-C50				50
1B-S-D25-C30			25	30
1B-S-D25-C50				50
3B-N-D16-C30	3	-	16	30
3B-N-D16-C50				50
3B-S-D16-C30		✓		30
3B-S-D16-C50				50

Table 2: Input material properties

	Concrete	Rebar
Compressive strength (MPa)	30	-
Tensile strength (MPa)	2.7	-
Yield strength (MPa)	-	369
Elastic modulus (MPa)	28000	200000

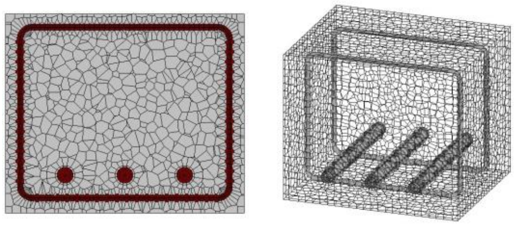


(a) No stirrup specimen model



(b) Stirrup specimen model

Figure 5: Simulation model dimensions



(a) Cross-section view (b) 3D overview

Figure 6: Example of the model used in simulations of corrosion product expansion

4 SIMULATION RESULTS AND DISCUSSION

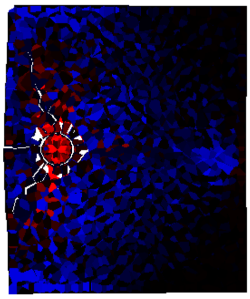
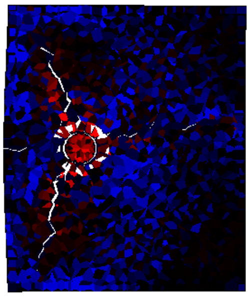
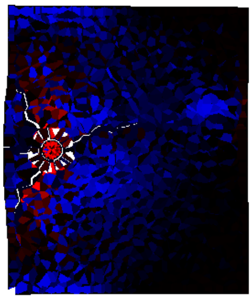
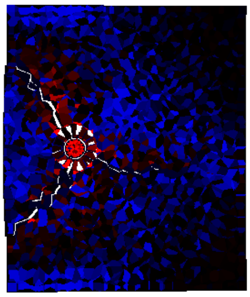
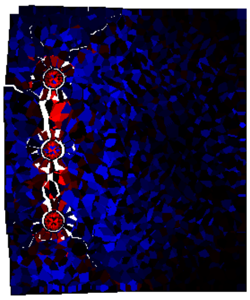
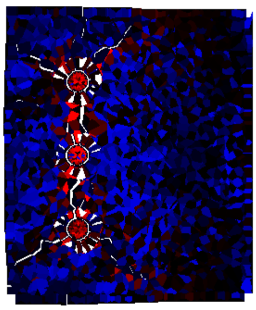
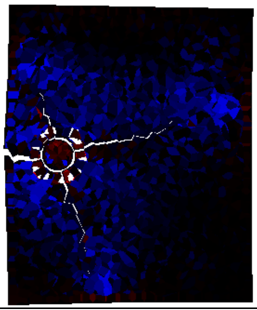
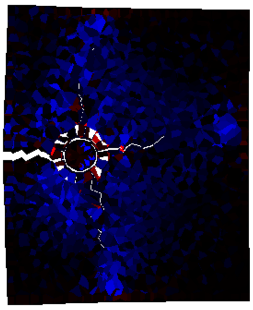
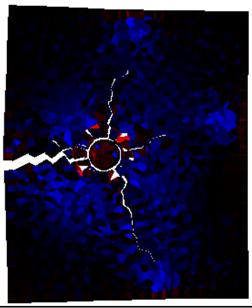
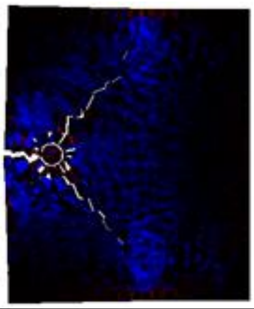
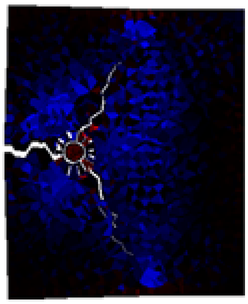
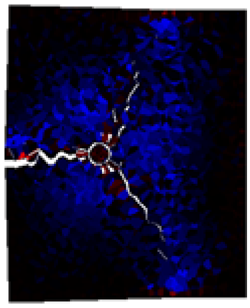
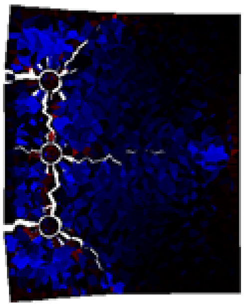
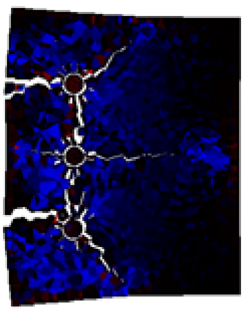
4.1 Crack pattern and internal stress due to rebar expansion

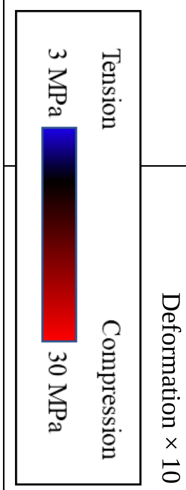
Table 3 shows the internal crack and internal stresses for each simulation case in mid-span (in longitudinal rebar direction) cross-section after 0.05 mm expansion is given to the interface. Based on these simulation results, the following discussions are drawn.

4.1.1 Effect of cover depth

When considering the models that have same control parameters except for the cover depth, it can be observed that the crack patterns are similar even when the cover depth is changed. For example, 1B-N-D25-C30 and

Table 3: Internal crack and stress in simulation models at 0.05 mm expansion

		1 Bar			3 Bars	
		C30	C50	C70	C30	C50
Stirrup	D25	 1B-S-D25-C30	 1B-S-D25-C50			
Stirrup	D16	 1B-S-D16-C30	 1B-S-D16-C50		 3B-S-D16-C30	 3B-S-D16-C50
No Stirrup	D25	 1B-N-D25-C30	 1B-N-D25-C50	 1B-N-D25-C70		
No Stirrup	D16	 1B-N-D16-C30	 1B-N-D16-C50	 1B-N-D16-C70	 3B-N-D16-C30	 3B-N-D16-C50



1B-N-D25-C70 exhibit the similar vertical crack to the surface and the horizontal cracks to the lateral sides of the specimen.

4.1.2 Effect of multiple rebars

When considering the crack pattern of case 3B-N-D16-C30 and 3B-N-D16-C50, a horizontal crack can be observed between the rebar due to the internal radial stress. For the vertical cracks, only the concrete near the outer rebars exhibits clear vertical cracks to the surface, while vertical crack of the central rebar is difficult to observe. The reason for this behavior is that when the expansion occurs, the corrosion product induces radial stress in the surrounding concrete. For outer rebars, the sides of specimen are free, which means there is less confinement to counterbalance the expansion force, as a result, the vertical cracks can easily open. On the other hand, the radial stresses from outer rebars provide compressive stresses to concrete surrounding the middle rebar, impeding the tensile stresses responsible for opening of vertical crack. As a result, it is difficult for the vertical crack to form and propagate to the specimen surface.

4.1.3 Effect of stirrups

Stirrups provide the confinement or the counterforce to the radial force induced by the corroded rebar. As a result, it is difficult for the vertical crack to propagate through the stirrup region. On the other hand, it is easier for the crack to propagate in the horizontal direction. As it can be seen from the case 1B-N-D16-C50 and 1B-S-D16-C50, that the crack pattern is changed from the vertical crack (in case of no stirrup) to two diagonal cracks inclined to the surface of the specimen (in case of stirrup). Also, in the case of 3B-S-D16-C50, the vertical crack disappears compared with the case 3B-N-D16-C50.

Furthermore, the vertical crack appeared on the concrete bottom surface is relatively small compared to the horizontal crack inside concrete (as shown in 3B-S-D16-C30 and 3B-S-D16-C50). This behavior is undesirable because the spalling of concrete may suddenly occur without any warning from surface optical inspection.

4.1.4 Effect of rebar size

For the rebar size, the crack pattern is quite similar even when the rebar diameter is increased from 16 mm to 25 mm (while the other parameters are same).

4.2 Expansion-crack width relationship

To measure the crack width at surface, the relative displacement between elements 75 mm away from the vertical plane of symmetry of the specimen, as shown in Fig. 7, was assumed to be the total crack width due to expansion. This total crack width was then divided by the number of rebar, i.e. 3, to get the crack width as a result of each rebar corrosion.

Fig. 8 shows the relationship between the bottom surface crack width and the given expansion. The lines with the same color represent the models that have the same control parameters (cover depth, number of rebars, rebar diameter), except the existence of the stirrups. The solid line represents the results of the no stirrup models, while the broken line represents the results of stirrup models.

When considering the effect of cover depth on the surface crack width, the specimens that have the deeper cover depth exhibit wider surface crack width. The vertical crack propagation in the specimens with stirrup is significantly decreased compared to no stirrup cases.

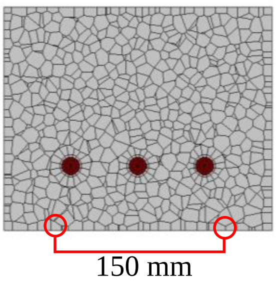


Figure 7: Crack width measurement

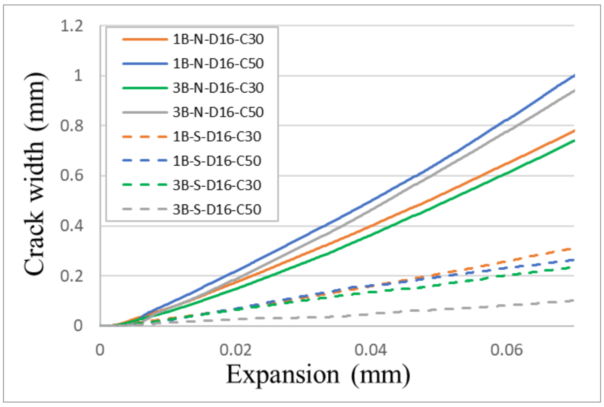


Figure 8: Crack width-expansion relationship

5 CONCLUSIONS

Based on parametric simulations of concrete cracking due to rebar corrosion, using 3D RBSM, the following conclusions can be drawn:

1. Without the confinement effect from the stirrup, the cross-sectional crack pattern is basically composed of vertical crack to the nearest surface and horizontal cracks due to the radial stress from rebar expansion. In the case of multiple rebars, the horizontal crack clearly propagates between the rebars. However, the vertical crack opening only occurs for the rebar at the sides, while the vertical crack for the middle rebar is less prominent due to the impeding expansion stress from the outer rebars.
2. In the cases where stirrups are present, the vertical crack propagation is restrained by the confinement from the stirrup. However, the horizontal crack inside the specimens keeps enlarging as the expansion due to corrosion continues.
3. Considering the cases of multiple rebars with stirrups, the corrosion under this situation can lead to the sudden failure of cover concrete without any observable warning because the horizontal crack propagation can occur while the surface cracking is barely visible. This situation can be dangerous because the external inspection cannot detect the damage level in concrete.

REFERENCES

[1] Zhang W., Chen J. and Luo X., 2019. Effects of impressed current density on corrosion induced cracking of concrete cover. *Construction and Building Materials*. 204 (20): 213-223.

[2] Jiradilok P., Nagai K. and Matsumoto K., Development of non-uniform corroded RC member simulation based on Rigid Body Spring Model, *12th fib International PhD-Symposium in Civil Engineering*, August 2018, Czech Technical University, Prague, Czech Republic; pp. 467-475.

[3] Nagai K., Jiradilok P. and Matsumoto K., Development of bond deterioration model in corroded RC member for discrete analysis model, *17th International Symposium on New Technologies for Urban Safety of Mega Cities in Asia (USMCA 2018)*, December 2018, Hyderabad, India.

[4] Nagai K., Sato Y. and Ueda T., 2005. Mesoscopic simulation of failure of mortar and concrete by 3D RBSM. *Journal of Advanced Concrete Technology*, 3: 385-402.

[5] Bolander Jr. J. E. and Saito S., 1998. Fracture analyses using spring networks with random geometry. *Engineering Fracture Mechanics*. 61 (5, 6): 569-591.

[6] Bolander Jr. J. E. and Saito S., 1997. Discrete modeling of short-fiber reinforcement in cementitious composites. *Advanced Cement Based Materials*. 6 (3, 4): 76-86.

[7] Qiao D., Nakamura H., Yamamoto Y., Miura T., 2016. Crack patterns of concrete with a single rebar subjected to non-uniform and localized corrosion. *Construction and Building Materials*. 116: 366-377.

[8] Tran K. K., Nakamura H., Kunieda M., Ueda N., 2011. Three dimensional behaviour of concrete cracking due to rebar corrosion. *Procedia Engineering*. 14: 419-426.

[9] Kawai T., 1977. New element models in discrete structural analysis. *Journal of the*

Society of Naval Architects of Japan: 187-193.

[10] Kawai T. and Takeuchi N., 1990. Discrete limit analysis program, series of limit analysis by computer, 2. [in Japanese]

[11] Eddy L., Matsumoto K. and Nagai K., 2016. Effect of perpendicular beams on failure of beam-column knee joints with mechanical anchorages by 3D RBSM. *Journal of Asian Concrete Federation*. 2 (1): 56-66.

[12] Eddy L. and Nagai K., 2016. Numerical simulation of beam-column knee joints with mechanical anchorages by 3D rigid body spring model. *Engineering Structures*. 126: 547-558.

[13] Matsumoto K., Osakabe K. and Niwa J., Effect of shrinkage and strength development histories on high strength concrete beams in shear, *13th fib Symposium Proceedings*, 2015, Copenhagen, Denmark.

[14] Dong W., Murakami Y., Oshita H., Suzuki S. and Tsutsumi T., 2011. Influence of bond stirrup spacing and anchorage performance on residual strength of corroded RC beams. *Journal of Advanced Concrete Technology*. 9 (3): 261-275.