Jurnal
Teknologi

Full Paper

CRACKING PROCESS OF REINFORCED CONCRETE INDUCED BY NON-UNIFORM REINFORCEMENT CORROSION

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Article history
Received
2 September 2015
Received in revised form
26 January 2017
Accepted
15 February 2017

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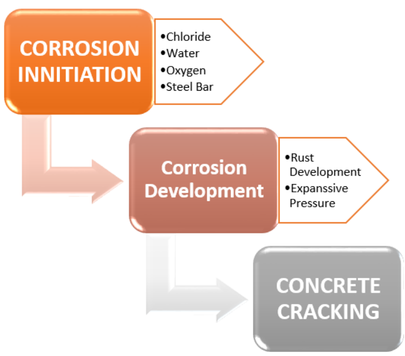
Graphical abstract



Abstract

Expansion of rust, as a result of reinforcement corrosion, can cause additional internal expansive pressure and initiate cracking to the concrete. This paper presents experimental test and numerical modeling of concrete cracking induced by reinforcement corrosion. The simulation was performed using finite element based program Abaqus CAE using concrete smeared cracking approach. The numerical modeling used non-uniform and uniform corrosion assumption to get more accurate result. Based on the result, the numerical modeling has 3.01% lower stress than the experimental test. The result of the simulation using non-uniform assumption showed more similar cracking pattern with the experimental test compared with uniform assumption.

Keywords: Non-uniform corrosion induced crack, accelerated corrosion test, smeared cracking

1.0 INTRODUCTION

In recent years, corrosion is one of the most predominant factors responsible for durability problems of reinforced concrete [1]–[3]. Corrosion in reinforced concrete greatly affects the strength of the concrete. Corrosion causes damage to the bonding between concrete and steel reinforcement. As a result, it decreases the ability of the reinforcement to provide tensile strength and ductility to the concrete [4]. Corrosion is initiated by depassivation of passive layer of the steel bar as the presence of chlorides ion involves the coupled transport processes of chloride and moisture through the porous concrete cover [5], [6]. The corrosion process induced by chloride ingress is presented in Figure 1. On steel surfaces, there is a thin passive layer which is useful to protect the steel from corrosion. However, when corrosion occurs continuously in reinforced concrete, the passive layers of the steel can disappear. Corrosion of the reinforcement is initiated by the reaction between the passive layers of the steel with oxygen and water. This process causes deterioration of the bonding between concrete and steel reinforcement which is well known as steel depassivation [[5]; Saitoh, 2000 in [12]]. After depassivation occurs on the reinforcement, corrosion product (rust) is formed at the interface between the steel and concrete and this is known as a corrosion-filled paste (CP) [5].As the corrosion process develops, the volume of the corrosion product also increases. The volume of the corrosion product, or rust, can exceed 2-6 times the volume of the original steel and it can cause cracks in the interface of steel and concrete. This situation can cause internal expansive pressure to the concrete and initiate cracking process [1, 6, 7], [8], [9].

Many types of research have been conducted by researchers regarding corrosion induced cracking. Research conducted by Liu and Weyers [9] focused on developing a model to predict time to corrosion cracking. This research was continued by Li *et al*. and produced an empirical equation to predict the crack width due to uniform corrosion [10]. The research conducted by the previous researchers assumed that corrosion was formed uniformly along the perimeter of the steel bar [2], [5], [12]. However, it was recently found that corrosion product formed non-uniformly along the perimeter of the steel bar [4].

As stated before, there are two major types of corrosion which are widely known: uniform corrosion and non-uniform corrosion. Many researchers used the assumption of uniform corrosion for their calculation because this assumption is simpler [2], [9]–[14]. Previous researchers assumed that concrete was subjected to uniform corrosion as thick walls are subjected to uniform internal expansive pressure. However, the corrosion product is in fact formed unevenly along the perimeter of the steel bar [1], [8], [15], [16].

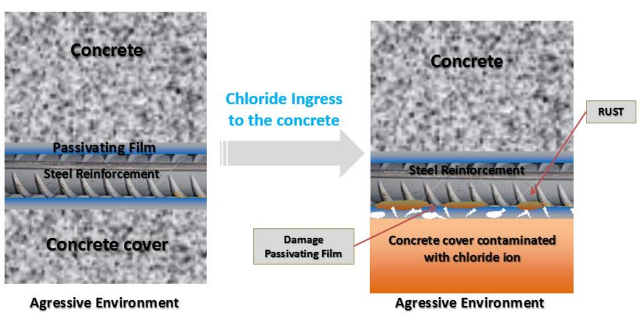


Figure 1 Corrosion Process Induced by Chloride Ingress

The non-uniform corrosion in reinforced concrete is easy to be confused with pitting corrosion. This situation happened because they both occur unevenly. In fact, these two have slight differences. The non-uniform corrosion is related with corrosion product which is widespread non-uniformly along the perimeter of steel bar. Nevertheless, the pitting corrosion is localized at the reinforcing bar [15].

Some researchers have performed studies on cracking induced by reinforcement corrosion. The research include experimental, analytical and numerical analysis. The experimental analysis was conducted after testing some samples to see how fast the crack occurred [22] and the critical amount of chloride on concrete. The numerical analysis [18] focused on analysis using a FEM-based computer model. The model applied to evaluate the time of cover cracking using plasticity theory. The analytical analysis was purposed by Liu and Weyers [9] to analyze the expansive pressure due to the presence of rust at the interface of concrete and steel reinforcement. The empirical model was produced based on the experimental result.

Analytical studies were also performed by some researchers to investigate the cracking process and properties of the concrete due to corrosion [19]–[22]. However, most of those researchers assumed that corrosion occurred uniformly around the perimeter of steel bar. This makes the cracking result also spread uniformly and it is different with the real condition.

This paper focuses on investigating the cracking process of concrete induced by reinforcement corrosion. This study is performed by numerical modeling and experimental test to get a deeper analysis. The numerical modeling used the concrete smeared cracking approach. The corrosion was assumed to occur uniformly and non-uniformly along the perimeter of the steel bar to investigate differences of cracking process due to the development of rust. The numerical modeling result was compared with experimental test result using accelerated corrosion method to investigate the cracking process of concrete due to non-uniform corrosion.

2.0 METHODOLOGY

2.1 Experimental Set Up

Experimental test for investigating the cracking process of reinforced concrete induced by reinforcement corrosion was performed by accelerated corrosion test using the galvanostatic technique. Reinforced concrete specimens used in this study were 150x150 –mm concrete cube with 150 mm thickness as shown in Figure 2. This size was chosen to present a beam element. To have more focused and profound investigation of the influence of reinforcement corrosion to the cracking, the small part of the beam with single reinforcement was selected. This configuration was also chosen to avoid the formation of additional rust from other reinforcement which can affect the formation of cracks. The steel reinforcement placed in the center of the concrete section with 40 mm covers.

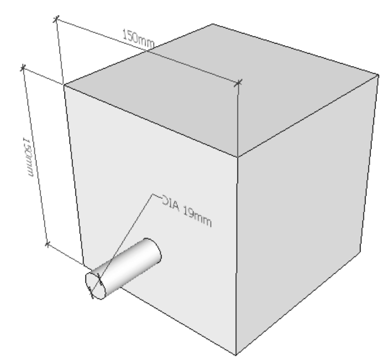


Figure 2 Concrete Specimen for Corrossion Test

Concrete mix for this specimen used local aggregate with 0.5 water per cement ratio. Table 1 shows the concrete mix used in this study. Before the mixing process, coarse and fine aggregates were washed to remove any fine dust which could increase the water demand and lower the bond strength. The materials were stored in sealed buckets at least one day in advance to allow moisture absorption. After casting, the specimens were moist cured for 28 days before testing. Standard test cylinders were tested at 28 days to determine concrete compressive and tensile (splitting) strengths.

Table 1 Concrete Mix

Materials	Value (kg/m^3)
Cement	348
Fine Aggregate	1105.69
Coarse Aggregate	701.12
Water	139.2

After the compression, it was found that the concrete has the actual compressive strength of 32.04 Mpa. The tensile strength of concrete was obtained from the splitting test and it was found that the concrete has a tensile stress of 2.72 Mpa. The yield strength of the steel reinforcement is 317.8 Mpa. These material properties will be used for the numerical modeling to simulate the cracking process due to corrosion.

To generate the corrosion process, 200 μA/cm^2 of electric current was used in this study. The accelerated corrosion process was achieved by applying a constant electrical current to the bars by a power supply via a current regulator. The current regulator kept the current constant over time. The steel bar acts as an anode, the stainless steel plate submerged in the NaCl solution acts as the cathode, and the pore fluid in the concrete is the electrolyte. The soffit of the specimen was immersed in a 5% NaCl solution. The accelerated corrosion equipment is shown in Figure 3.

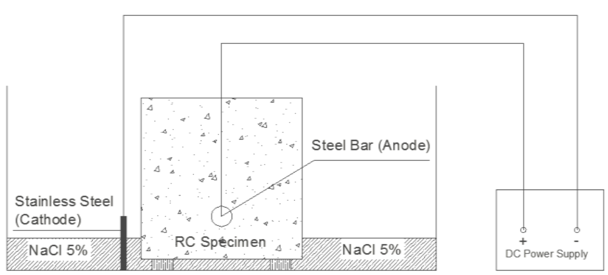


Figure 3 Accelerated Corrosion Test Set Up

The crack initiation on concrete was verified through conducting the frequent daily visual observation using a magnifying glass. The observation was conducted at the lateral and longitudinal direction. The first observation was conducted at the longitudinal direction. If the crack already appears in the longitudinal direction, the concrete was cut to observe its inner part. The concrete was cut through its cross sectional area into four identical pieces to observe the crack formation at the inner part of the concrete. The chloride analysis also performed to investigate the chloride profile trough concrete depth. The concentration of the chlorides at the given depth is determined by titration with Silver Nitrate ($AgN0_3$). The chloride profile of the sample obtained by grinding the samples and decomposed with a nitric acid to release the chlorides in the concrete.

3.2 Numerical Modeling

The numerical modeling performed using Abaqus CAE. The simulation used concrete smeared cracking approached to investigate the stress distribution in concrete due to corrosion which represents the cracking pattern. In this study, the concrete sample was modeled in two-dimensional (2D) to see the effect of corrosion to the concrete. Concrete was assumed to be a homogenous material. This model used CPS4R Quad dominated mesh. The young modulus of elasticity and the tensile stress of the concrete taken from uniaxial compression and tensile stress in accordance with the Indonesian Concrete Code (SNI). The constitutive material used for this model showed in Table 2.

Table 2 The Constitutive Material for Numerical Modeling

Elasticity				
Young's Modulus		25.74 GPa		
Poisson's ratio		0.2		
Plasticity				
Concrete Smeared Cracking				
Failure Ratio		Tens. Stiffening		
Ratio 1	1.16	σ/σc	1	0
Ratio 2	0.092	ε-εc	0	0.002
Ratio 3	1.28	Shear retention		
Ratio 4	0.3333	ρ =	1	
		ε =	0.2	

3.0 RESULT AND DISCUSSION

Series of experimental using accelerated corrosion test had been conducted to investigate the cracking process of reinforced concrete specimens. The corrosion and crack development were observed using daily visual observation. Besides the corrosion and crack, the chloride profile of the sample was also investigated at the end of the experimental test.

3.1 Rust Distribution and Cracking Pattern

Rust analysis was performed to get information regarding the distribution and properties of the rust. To investigate the distribution of rust along the circumference of steel bar, the reinforced concrete samples were cut into four pieces. The rust distribution observed using a magnifying loop.

The first crack can be seen with a magnifying glass in the longitudinal direction and had a width approximately 0.04 mm. The cracks appeared at concrete surface. As the increase of exposure time, the cracks was developed and propagate non-homogenously on their length and width. The propagated crack extend and join together to create continuous longitudinal cracking. Figure 4 (a) and (b) show the longitudinal and cross-sectional cracks at the concrete surface respectively.

(a) (b)

Figure 4 Cracking pattern at longitudinal direction (a) and the lateral direction (b)

Based on daily visual observation using a magnifying glass, it was found that the first visible crack occurred at the 4th day after the first exposure to the longitudinal direction. The crack width at the concrete surface increases along with the exposure time. Figure 5 shows the relationship between exposure time and cracks width. The width presented on the table is the maximum width chosen from all measured crack width at the longitudinal and cross-sectional area. The crack width varies at every location, thus the maximum width is chosen to show the worst effect of corrosion to concrete cracking.

As shown in Figure 5, the formation of rust caused the cracks to start to occur and propagate. The crack occurred due to the increase on the volume of the rust and formation of the ettringite. The excessive formation of the ettringite can enlarge the concrete pores which increases the permeability of the concrete. When the chloroaluminate started to form, the concrete pores was subjected to local stress and microcracks. Furthermore, the volume of the rust also increases over time which makes the concrete to receive more stress. As a result, the crack was propagated by getting wider and longer. The cracks have fast propagation at the beginning stage and they get slower with increase of exposure time. However, at 24th day, the excessive crack and concrete spalling occur due to the increased volume of rust and the number of microcracks wich are formed along the main crack. This condition reduces the concrete strength and causes the occurrence of excessive cracking.

The titrimetric analysis of chloride was conducted using argentometric titration to investigate chloride profile of the sample. This analysis performed by taking the concrete sample located at the interface of steel reinforcement. Figure 6 shows the chloride profile for the sample.

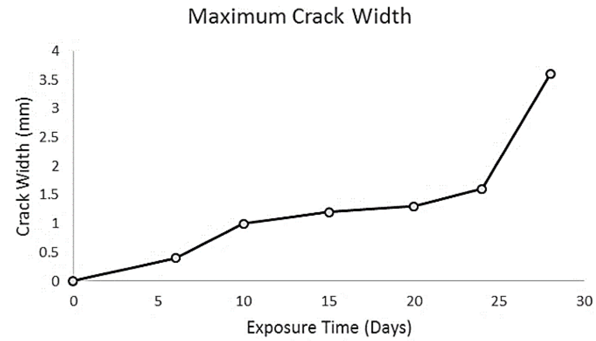


Figure 5 Relationship of Exposure time and crack width of the reinforced concrete specimens

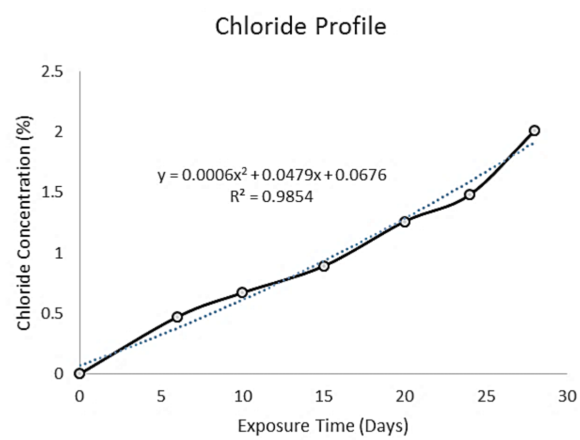


Figure 6 Chloride Profile of the Concrete Sample

Based on the analysis, it was found that the amount of chloride increased as the exposure time increased. At the beginning of the experimental test, chloride started to increase slowly. On day 4 until day 24, when the cracks were present in the sample, the chloride amount began to increase steadily until the concrete spalling started to occur resulting in the rapid increase of chloride amount. This condition occurred because of the excessive cracks which ended by spalling making more space for the chloride to ingress into the concrete.

3.2 Numerical Modeling Result

This section shows a numerical simulation of corrosion induced crack in reinforced concrete structures. The numerical simulation used Abaqus CAE with Concrete Smeared Cracking approached. Initiation of cracking process in concrete smeared cracking happens when concrete stresses reach one of the failure surfaces either in a combined tension-compression region or in the biaxial tension region.

Fracture energy is the amount of energy required to generate micro-cracks. It is also a decisive factor which is related to damage properties of the quasi-brittle material. Softening of concrete is partly a structural phenomenon, nevertheless, the fracture energy is treated as a material property.

This model used two approaches to simulate the internal pressure load due to corrosion, which are uniform and non-uniform, to investigate the effect of non-uniform corrosion to the concrete cracking. The load used in this model is based on laboratory investigation result. The non-uniform distribution of rust layer was analyzed using Gaussian Function developed by Zhao [1], [2]. Based on research conducted by Zhao [1], [2]. The thickness of rust layer around the circumference of steel bars is described in term of the polar coordinate. The non-uniform configuration of rust layer presented by Equation 1

$$T_r = \frac{a_1}{a_2\sqrt{2\pi}} e^{-\left(\frac{\theta-\pi}{\sqrt{2a_2}}\right)^2} + a_3 \quad (1)$$

Tr is the thickness of rust layer at coordinate which calculated with the parameters a1, a2 and a3 as the fitting parameters. The parameter a_1 is the non-uniform coefficient of the rust layer. The parameter a_2 is the spread coefficient of rust layer, and a_3 is the uniform coefficient of the rust layer. Figure 7 and 8 show the modeling result used uniform and non-uniform corrosion approach.

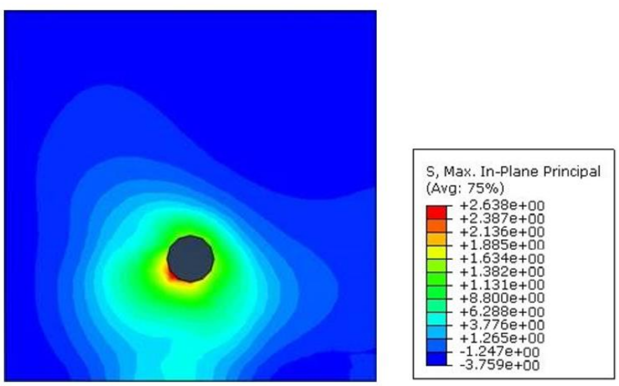


Figure 7 Stress Distribution for Uniform Corrosion

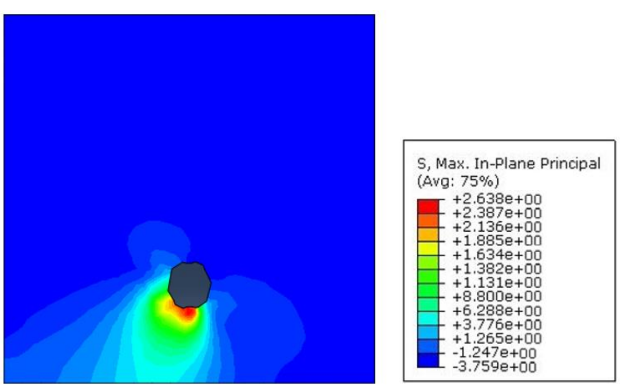


Figure 8 Stress Distribution for Non-Uniform Corrosion

The modeling was performed using smeared cracking approached which cannot show the cracking pattern directly like discrete approach. This condition makes the comparison of numerical model and experimental result was conducted by comparing the cracking pattern and maximum tensile stress. On the numerical modeling, the cracking pattern was assumed to have a similar pattern with the stress distribution pattern. The maximum tensile stress of the concrete due to internal expansive pressure based on numerical modeling is 2.638 Mpa. The numerical modeling has 3.01% lower stress than the experimental test.

Based on the modeling result, the stress distribution of the non-uniform approached has more similar cracking patterns compared with the uniform corrosion approach. The result of the non-uniform approach which was indicated by the stress distribution results has shown a similar pattern with the experimental results as shown in Figure 9.

Numerical modeling using non-uniform corrosion approach basically has very realistic results. If it is viewed from the exposure history, the sample basically has a greater chloride exposure at the bottom surface which facing the cover. This condition causes the biggest chloride infiltration to occur only in one direction. As a result, the bottom part of the sample was congested with chloride and fractured. However, the uniform corrosion approach has a tendency to overestimate the internal pressure due to corrosion. It can be seen from the load application which is evenly distributed along the perimeter of the steel reinforcement and produces uniform stress distribution as well. Therefore, non-uniform corrosion assumption is more suitable to be applied in modeling especially for applying the internal pressure loads.

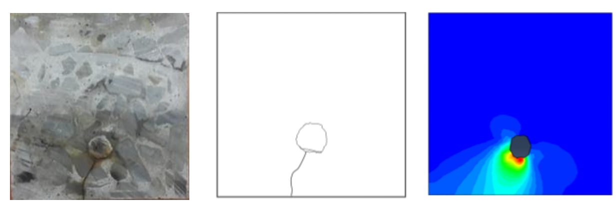


Figure 9 Comparison between modeling and experimental result

4.0 CONCLUSION

The experimental test and numerical modeling were performed to investigate the cracking process of concrete due to reinforcement corrosion. Based on the experimental test it was found that the chloride content and crack width increased as the exposure time increased. The numerical modeling has 3.01% lower stress than the experimental test. The numerical modeling result showed that the non-uniform corrosion assumption had the good agreement with the experimental test. The stress distribution has the same pattern with crack generated by internal expansive pressure due to corrosion.

Acknowledgement

We are Acknowledge the financial support from Directorate General of Higher Education (DGHE), Ministry of Education and Culture Indonesia.

References

[1] Y. Zhao, B. Hu, J. Yu, and W. Jin. 2011. Non-Uniform Distribution of Rust Layer Around Steel Bar in Concrete. *Corros. Sci.* 53(12): 4300-4308.

[2] Y. Zhao, J. Yu, B. Hu, and W. Jin. 2012. Crack Shape and Rust Distribution in Corrosion-Induced Cracking Concrete. *Corros. Sci.* 55: 385-393.

[3] D. Chen and S. Mahadevan. 2008. Chloride-induced Reinforcement Corrosion and Concrete Cracking Simulation. *Cem. Concr. Compos.* 30(3): 227-238.

[4] C. Fang, K. Lundgren, L. Chen, and C. Zhu. 2004. Corrosion Influence on Bond In Reinforced Concrete. *Cem. Concr. Res.* 34(11): 2159-2167.

[5] Y. Zhao, H. Xu, and W. Jin. 2013. Concrete Cracking Process Induced By Steel Corrosion- A Review. 2: 1-10.

[6] C. Cao, M. M. S. Cheung, and B. Y. B. Chan. 2013. Modelling of Interaction between Corrosion-Induced Concrete Cover Crack and Steel Corrosion Rate. *Corros. Sci.* 69(24): 97-109.

[7] Y. Zhao, A. Karimi, H. S. Wong, B. Hu, N. R. Buenfeld, and W. Jin. 2011. Comparison of Uniform and Non-Uniform Corrosion Induced Damage in Reinforced Concrete Based on a Gaussian Description of the Corrosion Layer. *Corros. Sci.* 53(9): 2803-2814.

[8] Y. Zhao, J. Yu, Y. Wu, and W. Jin. 2012. Critical Thickness of Rust Layer at Inner and Out Surface Cracking of Concrete Cover in Reinforced Concrete Structures. *Corros. Sci.* 59: 316-323.

[9] Y. Liu and R. Weyers. 1998. Modeling Time to Corrosion Cracking in Chloride Contaminated Reinforced Concrete Structures. *ACI Mater. Journals*. 95: 675-681.

[10] C. Li, W. Lawanwisut, J. J. Zheng, and W. Kijawatworawet. 2005. Crack Width Due to Corroded Bar in Reinforced Concrete Structures. *Int. J. Mater. Struct. Reliab.* 3(2): 87-94.

[11] Y. Zhao, J. Yu, and W. Jin. 2011. Damage Analysis and Cracking Model of Reinforced Concrete Structures with Rebar Corrosion. *Corros. Sci.* 53(10): 3388-3397.

[12] A. S. Sudjono. 2007. Prediksi Waktu Layan Bangunan Beton Terhadap. *Civ. Eng. Dimens.* 7(1): 6-15.

[13] C. Cao, M. M. S. Cheung, and B. Y. B. Chan. 2013. Modelling of Interaction between Corrosion-induced Concrete Cover Crack and Steel Corrosion Rate. *Corros. Sci.* 69(24): 97-109.

[14] Y. Liu. 1996. Modeling the Time-to-Corrosion Cracking of the Cover Concrete in Chloride Contaminated Reinforced Concrete Structures. Virginia Polytechnic Institute and State University.

[15] C. Cao and M. M. S. Cheung. 2014. Non-Uniform Rust Expansion for Chloride-Induced Pitting Corrosion in RC Structures. *Constr. Build. Mater.* 51: 75-81.

[16] S. Muthulingam and B. N. Rao. 2014. Non-Uniform Time-to-Corrosion Initiation In Steel Reinforced Concrete Under Chloride Environment. *Corros. Sci.* 82: 304-315.

[17] E. Chen and C. K. Y. Leung. 2015. Finite Element Modeling of Concrete Cover Cracking due to Non-Uniform Steel Corrosion. *Eng. Fract. Mech.* 134: 61-78.

[18] T. Krykowski and A. Zybura. 2013. Modelling of Reinforced Concrete Element Damage as a Result of Reinforcement Corrosion. *Procedia Eng.* 57: 614-623.

[19] C. H. Lu, R. G. Liu, and W. L. Jin. 2010. A Model For Predicting Time to Corrosion-Induced Cover Cracking in Reinforced Concrete Structures the Various.

[20] Z. Xiao-gang, W. Xue-zhi, L. U. Zhao-hui, and X. Feng. 2011. Analytic Model of Non-Uniform Corrosion Induced Cracking of Reinforced Concrete Structure. 940-945.

[21] H.-P. Chen and N. Xiao. 2012. Analytical Solutions for Corrosion-Induced Cohesive Concrete Cracking. *J. Appl. Math.* 2012: 1-25.

[22] K. Vu, M. G. Stewart, and J. Mullard. 2006. Corrosion-Induced Cracking : Experimental Data and Predictive Models. 102: 719-726.