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CONCRETE CRACK MODELING DUE TO NON-UNIFORM CORROSION USING SMEARED APPROACH

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Numbers of researchers has been conducted the finite element analysis to predict cracks due to corrosion and assumed the corrosion as uniform expansive pressure. However, the analysis cannot reflect actual stress and crack occur in concrete. The corrosion volume could be bigger in several point at interface between concrete and steel bar. This condition causes the concentrate stress and gives different response with the uniform expansive pressure assumption. This study developed series of finite element model to study the crack propagation of the concrete due to non-uniform corrosion. The analysis is conducted with Abaqus finite element program used smeared cracking approach. Reinforced concrete was modeled in 2D using the Zhao experiment at edge section. This paper also discusses the effect of usage a deformed reinforcement to the spread of rust and crack pattern. Based on this study, the result of finite element modeling shows fairly good agreement with experimental data. It also shows that the usage of deformed reinforcement affect the non-uniformities level of the rust and cause the crack pattern at the concrete propagate differently compared with concrete which use plain reinforcement.

Keywords: Non-Uniform Corrosion, Concrete Smeared Cracking, Crack.

1 INTRODUCTION

Reinforcement corrosion in reinforced concrete structure is the main cause of the deterioration in reinforced concrete structure related to durability problems (D. Chen and Mahadevan 2008, Zhao, Hu, Yu and Jin 2011, Zhao, Yu, Hu and Jin 2012). As the exposure time increases, the chloride reaches the certain threshold and accelerates damage process of the passive film. At this stage, the corrosion process starts to initiate and corrosion products formed. The volume of corrosion product is increased as increased of time and it can exceed 2 to 6 times the volume of the original steel. The corrosion product will generate internal expansive pressure to the concrete and leads to concrete cracking. As time passed, the propagation on further corrosion will eventually lead to spalling of the concrete cover, cause more severe durability problems and also collapse of the structure.

A lot of research, involving the experimental, analytical and numerical modeling, has been carried out to investigate the damage process of concrete due to reinforcement corrosion. Numbers of experimental test has been conducted to the critical corrosion amount and rate to induced the concrete cover cracks due to steel reinforcement corrosion based on the electric corrosion test method (Liu and Weyers 1998, Vu, Stewart and Mullard 2006). These experimental studies are focused on generate empirical models to analyze the expansive pressure and cracking properties on concrete due to corrosion.

The analytical studies was developed and produced some equation to analyze the cracking properties and predict the time to crack initiation in the concrete cover (H.-P. Chen and Xiao 2012, Lu, Liu and Jin 2010, Vu *et al.* 2006, Xiao-gang, Xue-zhi, Zhao-hui and Feng 2011). However, most of the model is assumed that the corrosion of reinforcing bar was uniform and also generates uniform expansive pressure around the perimeter of reinforcing steel.

Aside from the experimental and analytical studies, the numerical modeling using finite element based program also has been developed. Most current studies indicated that many researchers no longer are using the assumption that the corrosion is formed evenly along the perimeter reinforcement. The model used on the study was assumed that the rust spread non uniformly along the perimeter of steel bar (E. Chen and Leung, 2015, Du, Jin and Zhang 2014). However, the model still assumed that the reinforcing bar is plain. Most of the researcher did not consider the deform shape of the rebar on their model.

The aim of this study is to model the damage process of reinforced concrete due to non-uniform corrosion. This study used smeared cracking model approach and the deformed shape of rebar also considered in the model.

2 THE NON UNIFORM CORROSION IN REINFORCED CONCRETE STRUCTURE

Corrosion is an electrochemical process which initiate with the presence of water and oxygen. Concrete actually a porous materials which is possible for aggressive agent to infiltrate into the concrete (Silva 2013). Steel reinforcement have thin passive layer which can protect them from aggressive agent. However with the actual concrete condition, which has a lot of pores, this layer can be damaged. Corrosion of the reinforcement is initiated by the reaction between the passive layers of the steel with oxygen and water, well known as steel depassivation [(Zhao, Xu and Jin 2013); Saitoh, 2000 in (Sudjono 2007)]. After the depassivation occurs on the reinforcement, corrosion product (rust) is formed at the interface between the steel and concrete and it known as corrosion-filled paste (CP) (Zhao *et al.* 2013). At the anode reaction, the discrete ions formed and it can react into an insoluble corrosion product. Corrosion reaction of a metal are generally written with a simple reaction (Liu 1996)

$$M \rightarrow M^{2+} + 2e^- \quad (1)$$

The passive layer of the steel will be lost will act as an anode in reaction process of corrosion. Sudjono (Sudjono 2007) explained that the electrons released from the anode reaction causes the O_2 and water, which is contained in the surface of the steel, react. The part of this steel becomes the cathode of reinforcing steel corrosion reaction. Both anode and cathode ions react and generate the corrosion product.

As the result of the reaction, $Fe(OH)_2$ will be formed as the initial form of the corrosion product. The corrosion product is form around the perimeter of reinforcement. Many researchers assumed that the corrosion product form uniformly around the perimeter of the steel bar (Cao, Cheung and Chan 2013, Li, Lawanwisut, Zheng and Kijawatworawet 2005, Liu 1996, Zhao, Yu, Hu *et al.* 2012, Zhao, Yu and Jin 2011, Zhao, Yu, Wu and Jin, 2012). This assumption also causes the internal expansive pressure uniform around the perimeter of steel bar. However, the corrosion product actually forms non-uniformly around the perimeter of the steel bar (Cao and Cheung, 2014, Muthulingam and Rao 2014, Zhao, Hu *et al.* 2011, Zhao, Karimi *et al.* 2011). This condition cause non-uniform internal expansive pressure and crack at the concrete.

3 MODELING CONFIGURATION AND MATERIAL PROPERTIES

This study used two dimensional model to investigate the cracking process of reinforced concrete due to corrosion. All parameter, such as concrete and reinforcement geometry, corrosion rate and boundary condition, used Zhao experiment at edge section (R5) as shown in Figure 1.

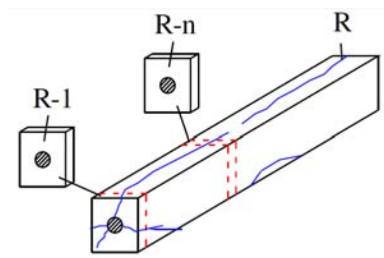

Figure 1. Geometry of Specimen (Zhao, Hu *et al.* 2011).

The model used sample with ratio of water per binder was 0.35. The diameter of reinforcing steel was 19 mm and the specimen used 40 mm concrete cover. This numerical model used finite element based program, Abaqus cae. The concrete smeared cracking approach was used in this model to simulate the cracking process of reinforced concrete. The load applied in this model was non-uniformed load used Gaussian function developed by Zhao (Zhao, Hu *et al.* 2011). The figure below shows the polar coordinate and measured thickness of corrosion layer for sample R5.

4 RESULTS AND DISCUSSION

The smeared cracking model was developed to analyze the cracking process of reinforced concrete structure due to reinforcement corrosion. This model used three main parameters such as failure ratio, tension stiffening, and shear retention factor. The parameters are based on biaxial and uniaxial curve. The biaxial curve was obtained from research conducted by (Poltronieri, 2014) because there was no data provided from the experimental test. This model used Quad dominate mesh with the young modulus 33000 Mpa and poisson's ratio 0.2 for elastic properties.

The simulation was tried to model the real geometric condition of the reinforcing bar to investigate the influence of the reinforcement deform shape to the stress concentration. The load applied was based on the experimental test conducted by Zhao *et al.* with assumption that the corrosion occurred non-uniformly along the perimeter of the steel bar. Also compared were the uniform and non-uniform corrosion model to see the stress concentration response which can use to predict the cracking pattern due to corrosion.

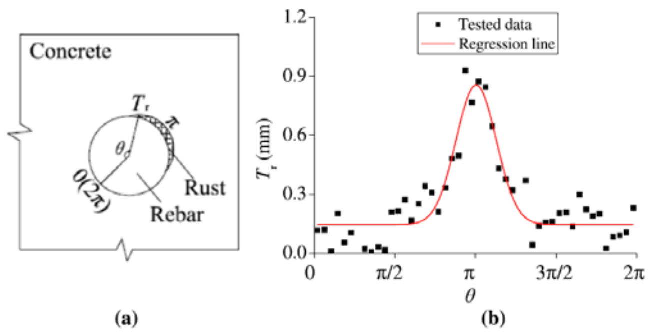

Figure 2. (a) Polar coordinate system for measurement; (b) the measured thickness of corrosion layer around the rebar perimeter (Slice R-5) and its fitting line (Zhao, Hu *et al.* 2011).

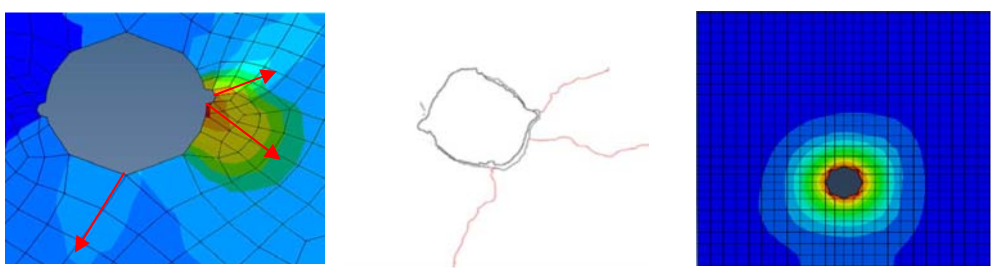

Figure 3. The Modeling Result for Non Uniform Corrosion (Left) compared with the cracking pattern based on Experimental investigation (Center) and Modeling Result Used Uniform Corrosion (Right) (Zhao, Hu *et al.* 2011).

Based on the modeling result, the smeared cracking approach shows that it provides a good fit to the experimental results conducted by Zhao (Zhao, Hu *et al.* 2011). The stress concentration have same pattern with the cracking pattern. The picture above also showed the comparison between the uniform and non-uniform stress concentration response.

The usage of deform steel bar also affect the stress concentration response. Most of the researchers used plain reinforcement at their model. If the model used uniform corrosion assumption and plain rebar at their model, the stress concentration and cracking response was obviously spread uniformly along the interface of steel bar and concrete. However, this study tried to simulate the uniform corrosion using deformed rebar. The result showed that the stress concentration mostly occurred at the bulge of steel bar. Further simulation was performed with the non-uniform corrosion assumption and it showed very good result. The cracking pattern and the stress concentration, which indicate the probability of cracking propagation, showed a good fit with the experimental result.

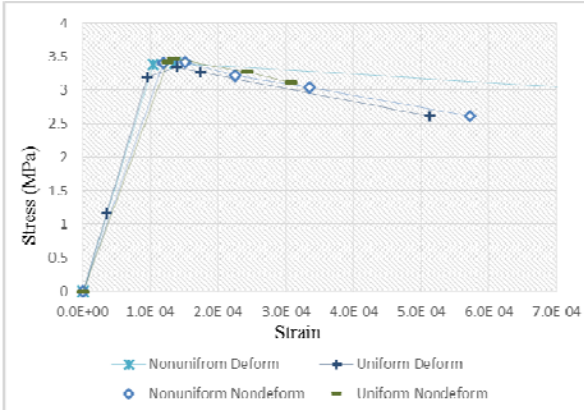

Figure 4. The Stress Strain Response (Analysis).

5 CONCLUSION

Corrosion is major cause of durability problems which can lead to concrete cracking. This paper presents simulation using concrete smeared cracking approach to analyze the differences between uniform and non-uniform corrosion assumption to the stress concentration and cracking pattern of the concrete. Based on this modeling, it can be concluded that the smeared cracking approach can be used to model the process of cracking due to corrosion. The simulation used non-uniform assumption and deformed steel bar geometry can show more realistic cracking pattern and a good fit to the experimentally obtained result. It also had better result compared to the simulation using the uniform assumption and plain steel bar.

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