NUMERICAL SIMULATION OF NON – UNIFORM CORROSION INDUCED CRACKING

Sylviah R. N. Anwari[a], Harun Alrasyid[b*], Wahyuniarsih Sutrisno[b]

***Abstract**: This research is focused on modeling the damage of concrete due to corrosion. The load used in this paper is only focused on the internal load due to rust expansion. In this study, corrosion was modeled uniformly and non-uniformly to investigate the difference between these two configurations to the damage in concrete. The simulation in this study was carried out using the 3DNLFEA program. The results show that numerical simulation provides predictions that are in line with experimental and numerical modeling results performed by the previous study in terms of pressure and corrosion cracking patterns. From the crack analysis, the pattern found that a non-uniform corrosion model can be used to express a realistic rust corrosion development around the reinforcement. Meanwhile, uniform corrosion requires a larger loss of steel area to reach the damage stage. Therefore, for non-uniform corrosion, the corrosion rate cause cracks and reaches a limiting crack width at earlier times in the service life of the corroded part.*

Keywords: *Corrosion, uniform corrosion, non-uniform corrosion, corrosion induced crack, 3D-NLFEA*

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INTRODUCTION

Over the past several decades, reinforcement corrosion has been identified as the main cause of deterioration in concrete structures [1]. Chloride ions are the main cause of the initiation of reinforcement corrosion, and exposing concrete structures to environments rich in this ion significantly increases the risk of structural degradation. The initiation of chloride-induced reinforcement corrosion is a very complex process involving the interaction of several transport mechanisms and the exceedance of a chloride threshold level at the surface of the rebars [2-5].

Over time, the presence of corrosion in concrete can cause cracks in the concrete [6]. Cracking due to corrosion is the main cause of damage to reinforced concrete structures. As steel corrosion develops, corrosion products can have a larger volume than the original steel volume, which is about 2-6 times the volume of the original steel. This increase in volume produced expansive stresses on the surrounding concrete and eventually caused cracks in the concrete cover [7-8]. After the crack penetrates the concrete cover, the chloride ions enter the concrete faster and cause corrosion to occur even more aggressively. This accelerates the steel corrosion process, leading to the progressive deterioration and even spalling of the concrete cover. In addition to cracking around the concrete, chloride-induced corrosion of reinforcement results in the loss of the concrete-steel interface bond and a reduction in the cross-sectional area of the reinforcement, thereby reducing the capacity of these structural elements [9-11]. The various stages of corrosion damage must be well understood and reliable to implement an efficient and cost-effective repair and maintenance strategy [12].

Although many studies have been conducted regarding corrosion, most of these studies assume a uniform distribution of corrosion products around the reinforcement perimeter. The assumption of uniform corrosion is an assumption that significantly simplifies the rust distribution process to facilitate mathematical analysis and numerical modeling with finite elements so that modeling can be done more simply. However, in reality, the corrosion that occurs in the field and non-uniform corrosion where the part closest to the exposed surface is corroded first so that corrosion is formed and distributed non-uniform. The assumption of non-uniform corrosion has so far been applied because it is considered more realistic than the assumption of uniform corrosion [8]. Non-uniform corrosion produces a realistic crack pattern where the damage to the concrete closer to the exposed surface is more severe than that further from the exposed surface. This is because, in the part that is close to the exposed surface, more corrosion products occur, so that (expansive pressure) at the interface between concrete and reinforcement is also greater. In fact, looking at the conditions in the field, a structural element is rarely found that only uses one reinforcement. With more than one reinforcement, it is possible to find different damage patterns due to additional expansive pressure from two adjacent reinforcements.

In addition to the rust distribution pattern, there are other things that can affect the pattern of cracks and damage that occur in concrete due to the expansion of corrosion products, namely the configuration of longitudinal reinforcement and the presence of stirrup reinforcement. The configuration of longitudinal reinforcement, including the number and spacing of reinforcement, is one of the important things that affect the damage to the concrete. So far, corrosion modeling using non-uniform corrosion modeling is often carried out for single bars so that the effect of the reinforcement configuration cannot be seen in the modeling. In fact, if you look at the conditions in the field, it is almost never found a structural element that only uses one reinforcement. With more than one reinforcement, it is possible to find different patterns of damage due to additional expansive pressure from two adjacent reinforcements. Previous studies that simulated corrosion occurring in the main reinforcement without paying attention to the presence of corrosion on the stirrup reinforcement were also considered inaccurate because the original structure of the stirrup reinforcement is the outermost reinforcement and closest to the exposed surface, so it tends to corrode first and cause faster damage,

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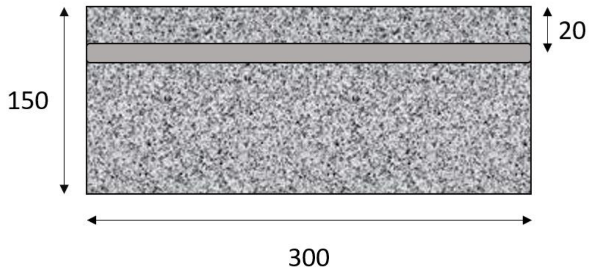
especially on the concrete cover section [6]. In addition, the presence of stirrup reinforcement also basically inhibits the growth of cracks caused by corrosion of the longitudinal reinforcement to the concrete surface.



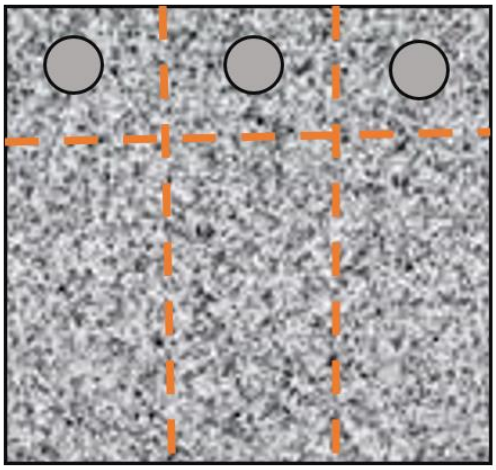


Figure 1 Illustration of reinforced concrete panels and cutting profile [8]

Therefore, by looking at the background described previously, this study discusses the effect of the configuration of flexural reinforcement and shear reinforcement on the damage that occurs in concrete due to corrosion. The distribution of corrosion products simulated in this study is uniform and non-uniform corrosion based on the study performed by [6] to investigate the difference between these two configurations to the damage in concrete. In addition, this study also compares the pattern of cracks and pressures that occur due to differences in the configuration of longitudinal reinforcement and the presence of stirrup reinforcement in concrete elements. Simulations were also carried out for the specimens by varying the configuration of the longitudinal bone and the stirrup reinforcement used. The simulation in this study was carried out using the 3DNLFEA program. This program is a relatively new program in modeling the volume expansion due to corrosion, so in the early stages of this research, validation of the model for corrosion that occurs in single bars was carried out. After the results of the resulting model are in accordance with the experimental results, the modeling proceeds to the next stage, namely conducting simulations for each model variation. In the final stage, a comparative analysis was carried out from the simulation results that have been carried out for each variation in order to conclude the effect of the configuration of flexural reinforcement and the presence of stirrup reinforcement on the crack pattern and pressure that occurs in concrete due to uniform or non-uniform corrosion.

RESEARCH SIGNIFICANCE

Corrosion is one of the durability problems in concrete structures, which can cause damage to the structure. Therefore, it is important to predict the damage pattern in concrete structures due to the corrosion process. This research aims to predict corrosion-induced cracking by using 3DNLFEA software. The results of the analysis of the 3DNLFEA model were checked for compliance with experimental results [8] through pressure parameters and crack propagation patterns.

METHODOLOGY

This section shows the methodology of this research, including the geometry, materials, and simulation method. The geometry data and reinforcement corrosion were taken from experiments conducted by [8]. The specimen is a reinforced concrete panel with three reinforcements, as shown in Figure 1. The panel was later cut into three parts with single reinforcement in the center position with a diameter of D16 reinforcement, as shown in Figure 2, while material properties can be seen in Table 1.

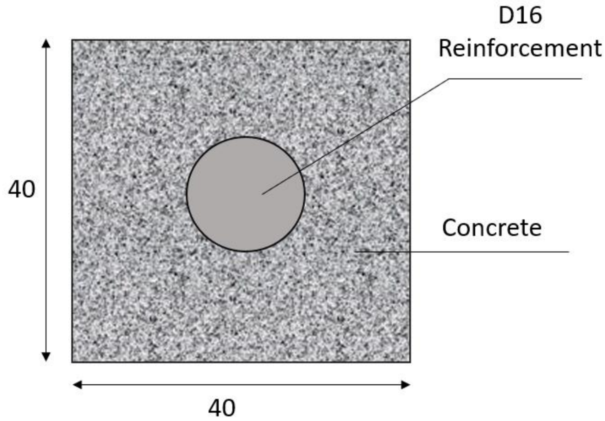


Figure 2 Illustration of cross section of concrete panel

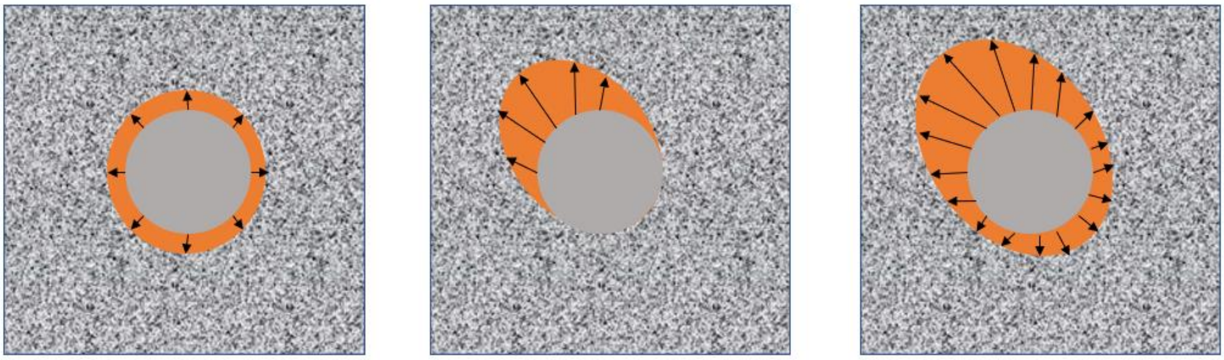
The experiments carried out by [8] also measured the rust thickness along the perimeter of the reinforcement. This data was later used as input for numerical modeling with the 3DNLFEA program.

Table 1. Material properties of HPC [8]

Panel	E_c	υ	F_t (MPa)	G_f (N/mm)
HPC	35.500	0.2	2.74	0.086

Material and load input is in accordance with research data performed by [8], where the corrosion simulation is divided into three scenarios, namely uniform corrosion, scenario (i), where corrosion occurs non-uniform and only occurs at the edges, and scenario (ii) where corrosion occurs non-uniform along the perimeter of the reinforcement as shown in Figure 3. The non-uniform corrosion states correspond to cases where only a segment of the rebar circumference was corroding and where corrosion was occurring unevenly around the whole circumference of the rebar.

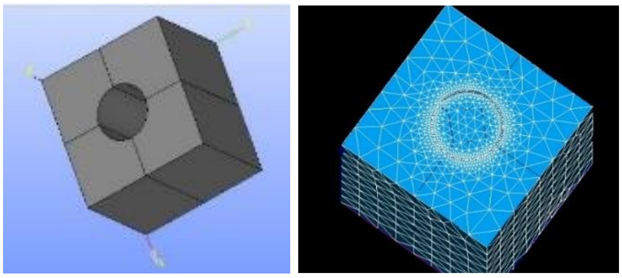
The 3D model was simulated using a cube specimen with a size of 40 x 40 x 40 mm, as shown in Figure 2 and Figure 4, using the Salome 9.3.0 program. Geometry data was obtained through the SALOME 9.3.0 [13] program, which later was inputted into excel and became the input



(a) (b) (c)

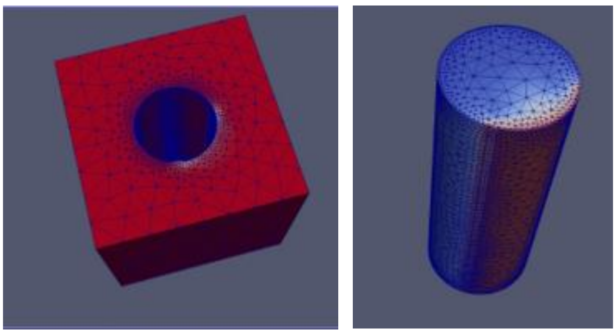
Figure 3 Modeled corrosion scenarios: (a) uniform corrosion; (b) non-uniform corrosion scenarios (i); and (c) non-uniform corrosion scenarios (ii)

file for the 3D-NLFEA program. The Piscesa et al plasticity- fracture constitutive model was used in this package [14]. The load input in the modeling stage is in the form of volumetric strain, which is calculated based on the loss of steel cross-sectional area for each damage stage obtained from [8]. For each scenario, the step calculation is carried out based on the loss of steel cross-sectional area with the results in Table 2. The results of the analysis were presented using the Paraview program, as shown in Figure 5.



a. Solid Configuration b. Meshing Model

Figure 4 Cube modeling using SALOME



a. Concrete Elements b. Reinforcing Elements

Figure 5 The result of modeling running of concrete and reinforcing elements using Paraview

The expansive pressure and cracking pattern based on the modeling results were compared with the study performed by [8], as shown in Figure 6.

ANALYSIS AND DISCUSSIONS

A. GRAPH OF UNIFORM CORROSION PRESSURE AND NON-UNIFORM CORROSION (NON-UNIFORM) DAMAGE STAGE 1

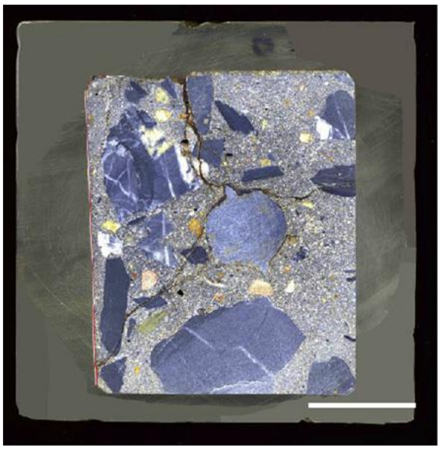


Figure 6 Experimental crack pattern [8]

Table 2 The result of step calculation based on loss of steel cross-sectional area

No	Scenario	Damage Stage	Loss of steel cross-sectional area (%)
1	Non-Uniform	1	0.025 %
2	Corrosion	2	0.045 %
3	(scenario i)	3	0.15 %
4	Non – Uniform	1	0.025 %
5	Corrosion	2	0.045 %
6	(Scenario) ii	3	0.065 %
7		4	0.325 %
8		1	0.025 %
9	Uniform	2	0.040 %
10	Corrosion	3	0.08 %
11		4	0.5 %

The pressure graph at Damage Stage 1 shows a graph of uniform and non-uniform corrosion scenario (i) and (ii). In scenario (i), the highest pressure occurs in the center or local in an area of two to four radians, where the largest rust thickness occurs, as shown in Figure 7. In scenario (ii), the pressure results are still localized in the two to four-radian region, as shown in Figure 8. However, slightly different from scenario (i), the differences between localized pressure and pressure in other regions are not as big as in scenario (i). In the uniform corrosion scenario shown in Figure 9, the pressure graph shows no significant increase or decrease in pressure because the rust is evenly distributed.

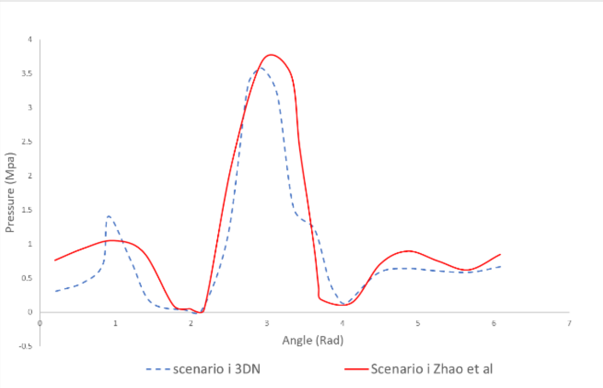


Figure 7 Graph of pressure damage stage 1 non-uniform corrosion scenario i

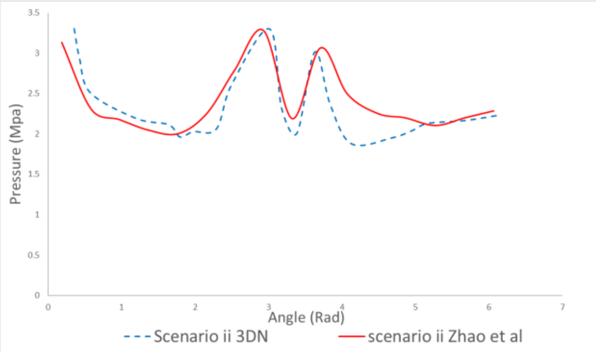


Figure 8 Graph of pressure damage stage 1 non-uniform corrosion scenario ii

Figure 9 Graph of pressure damage stage 1 uniform corrosion

B. GRAPH OF UNIFORM CORROSION PRESSURE AND NON-UNIFORM CORROSION (NON-UNIFORM) DAMAGE STAGE 2

The pressure graph at Damage Stage 2 shows a graph of uniform corrosion pressure and non-uniform corrosion scenarios (i) and (ii). In scenario (i), the highest pressure occurs in the center or locally in an area of two to four radians, where the largest rust thickness occurs, as shown in Figure 10. In other areas, the amount of pressure that occurs tends to be smaller due to the localization of corrosion. In scenario (ii), the pressure results are localized in several regions, as shown in Figure 11. However, it is slightly different from scenario (i). The evolution of pressure in other regions is not too extreme. In the uniform corrosion scenario, as shown in Figure 12. The pressure graph does not have a significant increase or decrease in pressure because the rust is evenly distributed.

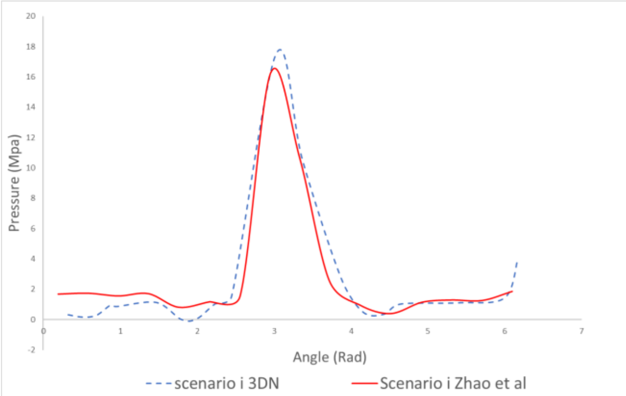


Figure 10 Graph of pressure damage stage 2 non-uniform corrosion scenario i

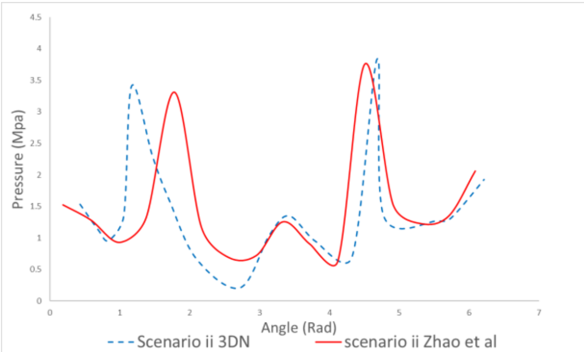


Figure 11 Graph of pressure damage stage 2 non-uniform corrosion scenario ii

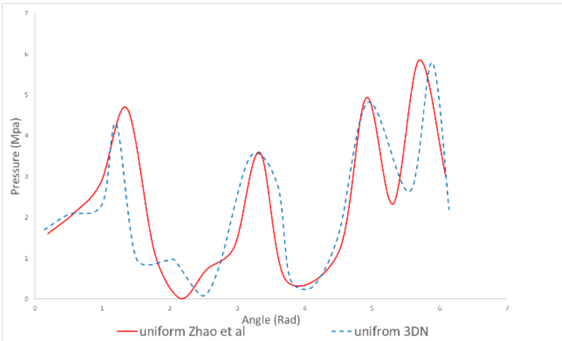


Figure 12 Graph of pressure damage stage 2 uniform corrosion

C. GRAPH OF UNIFORM CORROSION PRESSURE AND NON-UNIFORM CORROSION (NON-UNIFORM) DAMAGE STAGE 3

The pressure graph at Damage Stage 3 shows a graph of uniform corrosion pressure and non-uniform corrosion scenarios (i) and (ii). In scenario (i), the highest pressure occurs center of reinforcement or local in an area of three to five radians, where the largest rust thickness occurs, as shown in Figure 14. In other areas, the amount of pressure that occurs tends to be smaller due to the localization of corrosion that occurs. In scenario (ii), the pressure results that occur are also still localized in the four to six-radian regions, as shown in Figure 15. However, slightly different from scenario i, the pressure evolution that occurs in other regions is not too extreme when compared to scenario (i). In the uniform corrosion scenario shown in Figure 16. the pressure graph, there is no significant increase or decrease in pressure because the rust is evenly distributed.

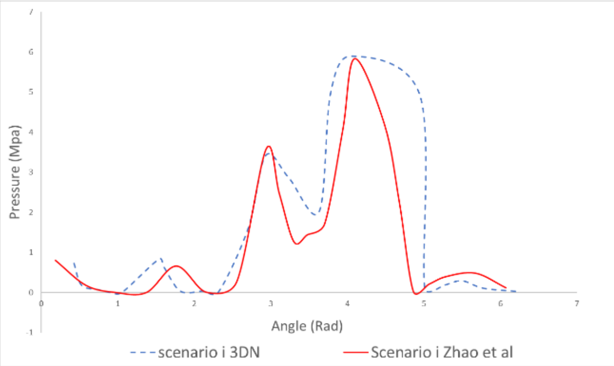


Figure 13 Graph of pressure damage stage 3 non-uniform corrosion scenario (i)

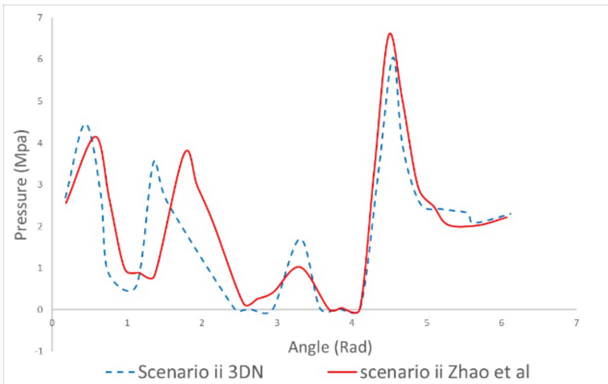


Figure 14 Graph of pressure damage stage 3 non-uniform corrosion scenario (ii)

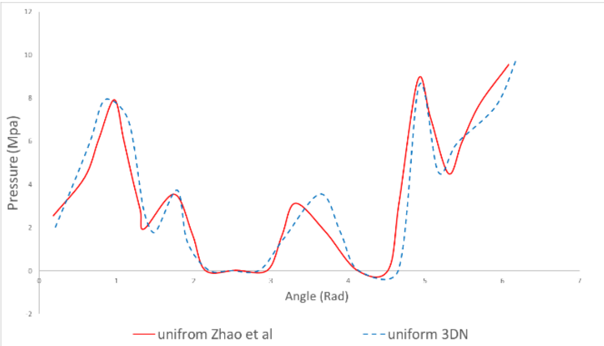


Figure 15 Graph of pressure damage stage 3 uniform corrosion

D. GRAPH OF UNIFORM CORROSION PRESSURE AND NON-UNIFORM CORROSION (NON-UNIFORM) DAMAGE STAGE 4

The pressure graph at Damage Stage 4 shows a graph of uniform corrosion pressure and non-uniform corrosion (non-uniform) scenario (ii). In scenario (ii), the pressure results that occur also occur throughout the region, as shown in Figure 16. However, slightly different from the uniform scenario, the pressure evolution that occurs in other regions is not too extreme when compared to the uniform scenario. In the uniform corrosion scenario shown in Figure 17. In the pressure graph, there is a significant increase and decrease in pressure because, at this step, cracks have occurred.

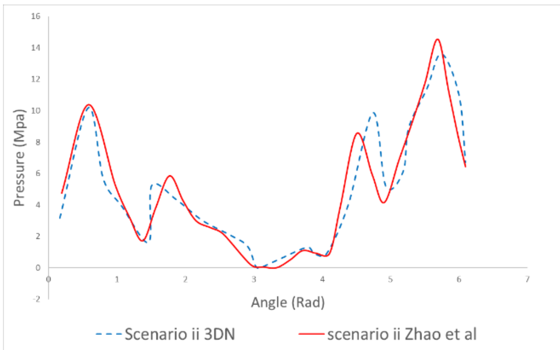


Figure 16 Graph of pressure damage stage 4 non-uniform corrosion scenario (ii)

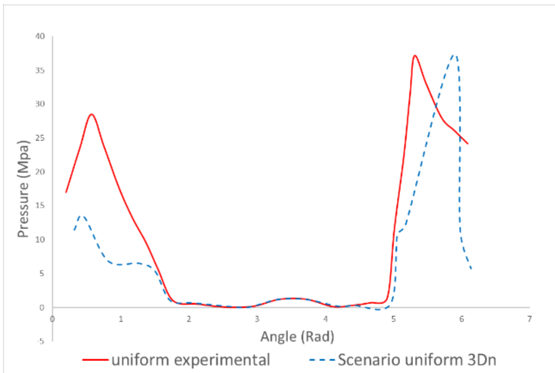


Figure 17 Graph of pressure damage stage 4 uniform corrosion

The result of the pressure at damage stages 1 to 4 shows that the location and value of the pressure that occurs in each damage stage is different depending on the percentage of corrosion and also the distribution assumption of corrosion. Compared to the analysis result performed by [8], the average difference in the pressure on the non-uniform corrosion-induced cracking in scenario (i) and (ii) at damage stage 1 are 22.3% and 8.43%, respectively. At damage stage 2, the differences between scenario (i) and (ii) reach 18.61 % and 5.38%. While at damage stage 3, the difference reaches 39.86 % and 18.04%. While for the uniform corrosion-induced cracking, the difference in pressure on damage stage 1 is 7.55%, damage stage 2 is 11.2%, damage stage 3 is 13.6%, and damage stage 4 is 18.54%.

E. CRACK PATTERN OF CORROSION-INDUCED CRACKING

The crack pattern due to uniform corrosion has a damaged stage reaching four stages of damage. In stage 1, a strain magnitude of 0.6 occurs at the interface between steel and concrete, and the pressure around the reinforcement is quite uniform. In damage stages 2 and 3, the strain magnitude ranges from 0.81 to 1.6. As the pressure increases, the crack pattern around the reinforcement also increases, and the cracks begin to reach the concrete cover. At damage stage 4, the strain magnitude of 9.4 occurs, and the crack evolves, which causes a complete loss of bonding between steel and concrete, as shown in Figure 18.

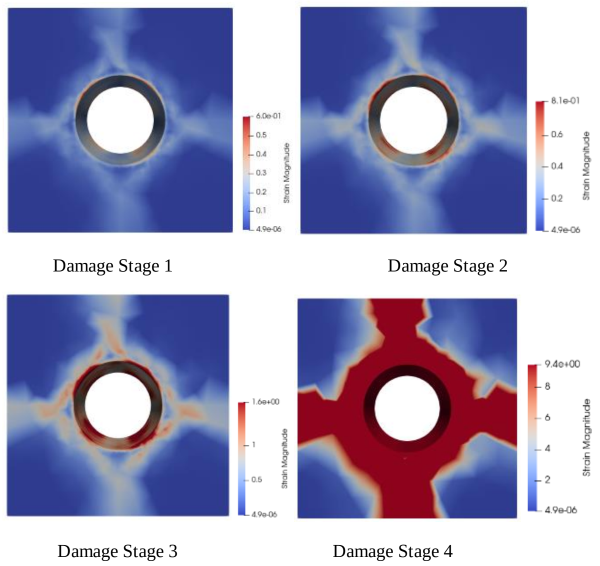


Figure 18 Crack pattern uniform corrosion

The crack pattern for the non-uniform corrosion of scenario (i) has three stages of damage. In damage stages 1 and 2, the strain values range from 0.84 to 1.2 at the interface between steel and concrete. The pressure mostly occurs in the area directly affected by rust. While in the damage stage 3, the strain magnitude reaches 6.1, the cracks spread evenly on the reinforcement, and the crack pattern occurs in the upper left quarter of the concrete, as shown in Figure 19.

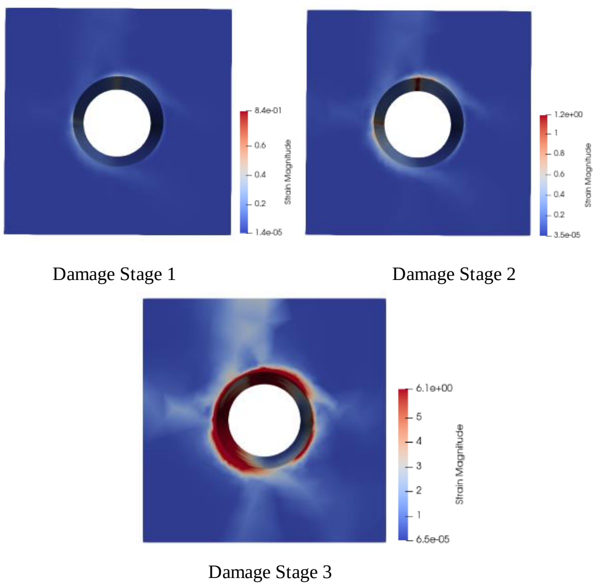
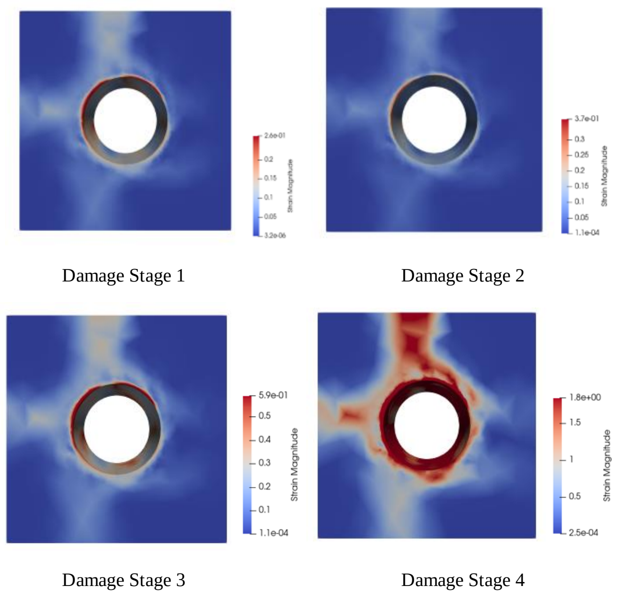


Figure 19 Crack pattern non-uniform corrosion scenario i

The crack pattern for non-uniform corrosion with scenario (ii) reaches four stages of damage. In damage stages 1 and 2, the strain magnitude range from 0.26 to 0.37 when cracking starts at the interface of reinforcement and concrete. The stresses around the reinforcement are fairly uniform. Furthermore, as the crack network develops and becomes wider during damage stages 3 and 4, in which the strain magnitude ranges from 0.59 to 1.8, this stress loss is amplified by stresses that eventually reach zero in some locations shown in Figure 20.



. Figure 20 Crack pattern non-uniform corrosion scenario ii

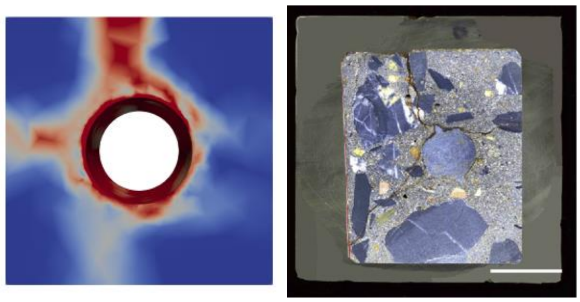


Figure 21 Comparison of simulation result and experimental

The crack pattern for uniform and non-uniform indicates the severity of corrosion-induced cracking, which is presented in the form of damage stage one to four. This phenomenon is illustrated in Figures 18 to 20. At damage stage 1, the crack is initiated at the interface of the concrete and steel reinforcement. As the pressure increase, the crack is developed, and at some point, the steel reinforcement starts to lose the confinement due to excessive cracks. Furthermore, it also can be seen from the result that uniform corrosion exhibits more excessive cracks compared to non-uniform corrosion at the same damage stage. This condition can happen due to uniform build-up pressure at the circumference of the steel bar, which causes excessive pressure at the interface of concrete and steel bars. However, in non-uniform corrosion, the build-up pressure only occurs at a particular area where the corrosion occurs. This assumption resulting a more realistic crack pattern compared with uniform corrosion.

At damage stage 4, the extent of the crack is very large, so the fracture area was further developed, which can cause spalling in the area of the concrete cover. The crack pattern for damage stage 4 consists of a lot of cracking, which is concentrated in the damaged area. The predicted crack pattern was obtained due to the idealization of concrete as a homogeneous material in the finite element model. In fact, these fine cracks usually coalesce into smaller but wider cracks that follow highly tortuous paths around the aggregate particles in the cement matrix. From some of these conditions that have been generated from corrosion modeling using the 3DNLFEA program, it can follow the pattern of experimental results by [8], so it can be concluded that this simulation approach model is in line with the experimental test.

CONCLUSIONS

A finite element model simulation of corrosion-induced cracking is presented in this thesis. The distribution of uniform and non-uniform corrosion was varied in the analysis, resulting in pressure graphs and crack patterns. Based on the results of the research discussed in the previous chapter, it can be concluded that the FEM simulation of corrosion-induced cracking using the 3DNLFEA program can provide predictions that are in accordance with the experimental results. The uniform and non-uniform corrosion shows a different pattern of pressure and crack development. At the same damage stage, the uniform corrosion tends to have more severe overall damage due distribution of the pressure. In contrast, non-uniform corrosion tends to have more severe damage only in the particular area where the corrosion occurs.

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