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Three-Dimensional Finite Element Modelling for Prediction Corrosion-Induced Cracking Damaged in Reinforced Concrete Beam

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Abstract

The quality and condition of the reinforced concrete structure is critical, particularly in high-rise buildings where the danger of service life failure is extremely high. Usually, certain structures collapse as a result of cracks and spreading caused by corrosion. Due to this reason, there is a requirement for software program that can promptly measure and evaluate the strength, growth, and longevity of the structure. Researchers use Finite Element Modelling (FEM), a reliable approach to foresee the deterioration and fracturing of structures. The application of finite element modelling in determining the remaining strength of damaged components can provide crucial data, which is particularly relevant for engineers in real-world scenarios. Moreover, it has the ability to replicate the cracking caused by corrosion in reinforced concrete elements. A corrosion-induced cracking model is suggested to be included into a three-dimensional plane-stress finite element model. The cracking model provides an indication of the extent of corrosion-induced damage in the concrete, allowing for the study of strength and behavioural changes. The effect of corrosion-induced cracking in a thick wall cylinder model will be simulated by the finite element model in order to identify and analyse the cracks caused by corrosion in the concrete cover. A corrosion-induced cracking experiment will be conducted with two different cover thicknesses and reinforcement using the Midas FEA commercial software to create a three-dimensional model. There is a slight discrepancy between the numerical analysis modelling and the analytical approach in terms of the crack's initiation and propagation, mostly resulting from variations in modelling assumptions, methods, and parameters. This disagreement arises when comparing the numerical analysis model with the previously published work. Nevertheless, the numerical model may be used to simulate both crack propagation and the critical pressure needed to produce corrosion-induced concrete cover cracking.

Keywords: Finite Element Modelling, Finite Element Method, Finite Element Analysis, Beam, Softening, Crack, Corrosion Induce Cracking, Stress – Strain Cracking, XFEM

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1. Introduction

According to Bohni (2005), construction materials that are extensively employed in buildings, bridges, platforms, as well as underground structures such as tunnels and pipelines, ought to possess two key characteristics–affordability and long-lasting quality. A corrosion-induced cracking experiment will be conducted with two different cover thicknesses and reinforcement using the Midas FEA commercial software to create a three-dimensional model. There is a slight discrepancy between the numerical analysis modeling and the analytical approach in terms of the crack's initiation and propagation, mostly resulting from variations in modeling assumptions, methods, and parameters. This disagreement arises when comparing the numerical analysis model with the previously published work. The application of finite element modelling in determining the remaining strength of damaged components can provide crucial data, which is particularly relevant for engineers in real-world scenarios. Thus, corrosion of reinforcement in concrete structures is an expensive economic problem due to the high costs of rectification, rehabilitation, and maintenance.

Despite this, the reinforcement is naturally protected by the presence of calcium hydroxide in the cement paste due to its high alkalinity of pH ranging from 12 to 13. This is due to the formation of a passive ferrous oxide ($Fe2O3$) film around the reinforcement at high pH, which insulates and protects the steel from corrosion. However, the formation of this passive film is usually disrupted by carbonation of concrete and chloride attack. Carbonation of concrete happened when carbon dioxide in the atmosphere reacts with the concrete pore water producing carbonic acid. The neutralization of the alkaline constituent lowers the pH of the reinforcement to around 8, a pH at which the $Fe2O3$ passive film becomes unstable and thus unable to perform its protection function. As previously stated, the $Fe2O3$ passive proactive film can also attack chloride ions. Ions from various sources act as catalysts, allowing the protective layer to breakdown and thus starting the corrosion process (Broomfield, 2002, E K Arya and B S Dhanya 2021).

Corrosion occurred as a result of electrochemical reactions involving two coupled cathodic and anodic half-cell redox reactions. In this reaction, iron is oxidized from Fe to Fe2+ in the anodic reaction, while oxygen (from the atmosphere) is reduced in the presence of water by accepting the electrons liberated in the cathodic reaction. The anodic and cathodic reactions occur at the same rate. Carbonation takes place on a microcell level, with corrosion sites evenly distributed around the perimeter and length of a reinforcing bar, whereas chloride attack takes place on a macro-cell level, with reaction sites geographically separated.

Finite Element (FE) modelling is frequently used in research methods, capacity, and ductility estimation; stress distribution can be obtained from the modelling, and useful information can aid in drawing appropriate conclusions on the state of the structure. The corrosion behavior and element strength have already been tested with a large number of structure elements. The effects on concrete confinement, axial capacity, ductility, cracking, flexural strength, and bond strength (Z Hanjari et al. 2013) have all been studied in order to create appropriate models for analysis.

2. Objective

FE modelling is more useful in research applications, where it can help researchers make important discoveries about the stress distribution, capacity, and ductility of a structure. A large number of structure elements have already been tested for corrosion behaviour and element strength. As previously stated, extensive research has been conducted on the attributes and characteristics of the effects on concrete confinement, axial capacity, ductility, cracking, flexural strength, and bond strength (Torres-Acosta et al. 2004, Berto et al. 2008; Hanjari et al. 2013; Val and Chernin, 2012). As a result, a three-dimensional finite element model will be developed in this study to predict corrosion-induced cracking in reinforced concrete beams by applying different tensile strengths to predict the effect of corrosion pressure required to penetrate concrete cover and to observe the behaviour of concrete cover crack width against duration within a year.

3. Scope of Work

The simulation of steel corrosion in concrete beams using MIDAS FEA and concrete-induced damage. FEM is a powerful material technique for analysing building mechanical properties. The vast majority of numerical research on concrete cover cracking has focused on external bending issues or three-point bending tests, which simulate concrete fracture experiments. The load and crack mouth opening displacement of a concrete cover three-point bending beam were predicted using a finite element model based on the cohesive zone model (J Roesler et al. 2007).

In crack propagation investigations, an appealing technique has been employed that does not need re-meshing as the fracture propagates and therefore lowers computing time. This method is known as the Extended Finite

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Element Method (XFEM). XFEM has not only been used to model a discrete crack on a variety of specimens using a customised crack growth algorithm (FM Chitalu et al. 2020), but it has also been used to analyse the load and crack mount opening displacement of a concrete three-point bending specimen (J.M Sancho et al. 2007)

Unlike previous research, corrosion-induced fracture propagation has received a lot of attention in the last decade. A finite element-based smeared crack model was used to simulate corrosion damage in order to validate the model. The output of the model was compared to experimental data, and there was good agreement (Thybo et al 2017). Furthermore, they developed a numerical solution that incorporates concrete heterogeneities in order to more accurately 101 simulate corrosion-induced concrete cracking patterns. Given the advancement of FE methods, using XFEM to simulate corrosion-induced cracking is perfectly acceptable (Lu CH et al. 2014).

4. Methodology

Reinforcing steel in concrete can be thought of as a thick-walled cylinder due to the material's symmetry. The previous research and testing can be used to obtain the modelling units and feature parameters that are applicable to the case where the diameter of the steel bar can be changed as desired to carry out parametric analysis if required. In this model, we will assume that only one fracture will begin and progress from the cylinder's inner to outer borders. In two-dimensional thick wall cylinder shell, the model will be created in commercial software Midas FEA. Before meshing, material property data must be saved. The map mesh (Figure 1(c)) can be used to mesh 2D objects (Figure 1 (a)). It will be simple to create the element size using map mesh. In this thesis, the element size must be chosen carefully, and the property materials (Figure 1(b)) must be assigned.

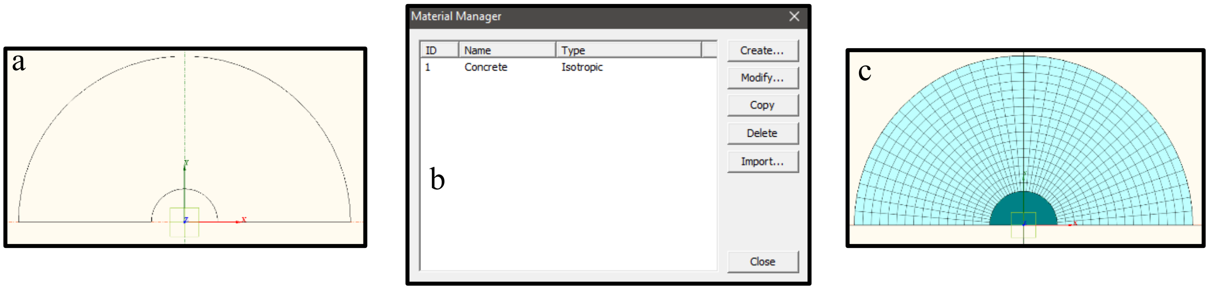

Figure 1. (a) 2D Modelling, (b) Assign Material Property, (c) Map Mesh

Midas FEA can be directly converted from 2D to 3D (Figure 2(a)) using the protrude mesh, which produces proper meshing and is more precise. As a result, if we create the mesh from a solid surface, the mesh will be created in a few different elements, resulting in a lot of analysis with a longer time. After obtaining the three-dimensional solid, the load and boundary conditions (Figure 2(b)) must be defined. Because only half of the cylinder was represented, a boundary condition was established to prevent vertical movement. A displacement load is applied to the inner surface. Once the model is ready, analysis mode then can be determined (Figure 2(c)).

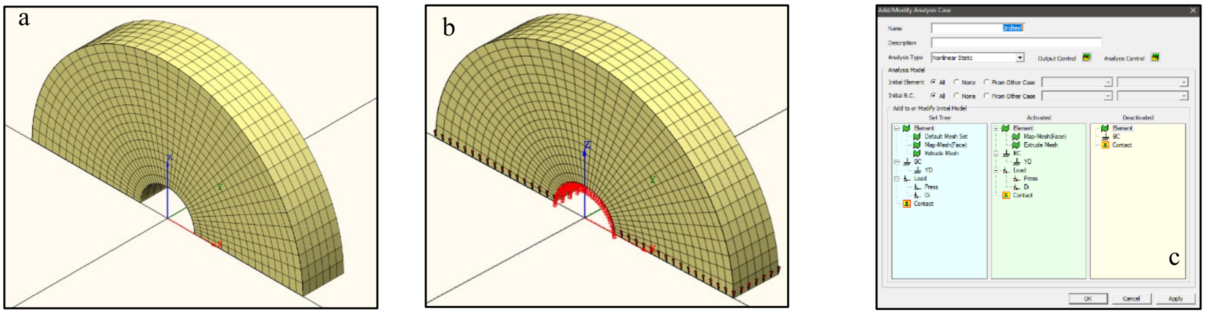

Figure 2. (a) 2D to 3D Modelling, (b) Assign Load & Boundary Condition, (c) Setup Analysis Mode

A few strict criteria must be followed in this study, including the data collection process and selecting an experiment that can be validated using software. Figure 3 depicts the study's process.

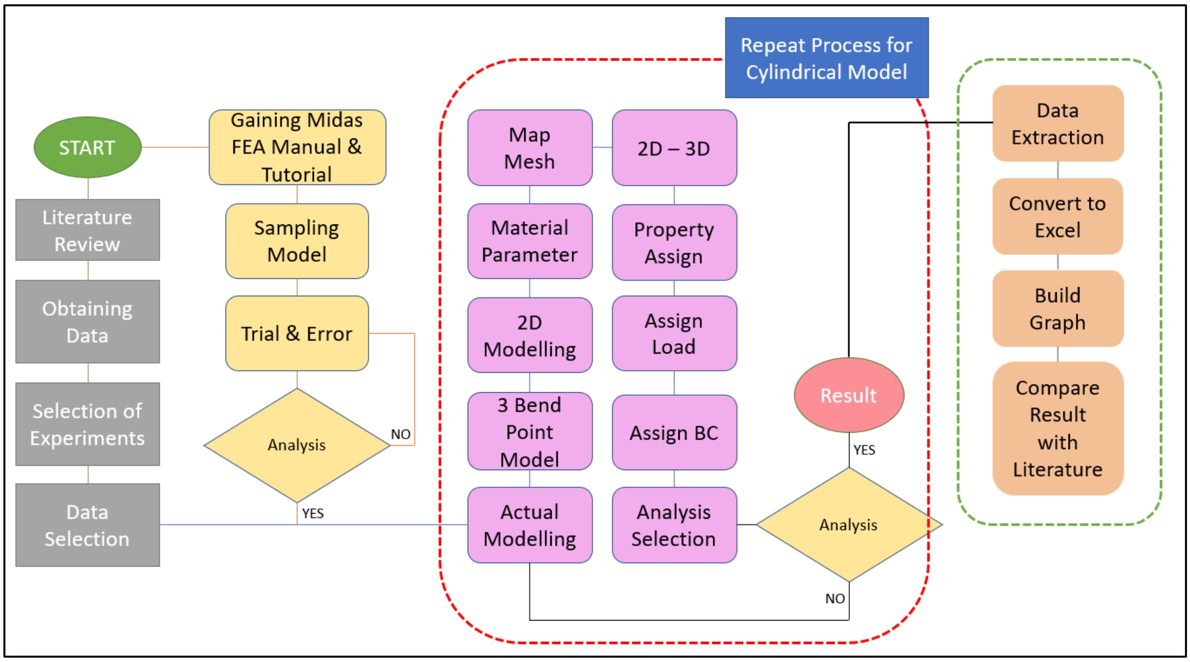

Figure 3. Process Flow

5. Result and Discussion

There is a previous benchmark model for corrosion cracking that validates the modelling technique before developing the proposed modelling procedure. For three-point bending specimens, this crack propagation model is commonly used (JM Sancho et al. 2007). A programme incorporating a cohesive crack method was developed to simulate crack propagation under displacement-controlled loads. The modelling differs slightly from that of other commercial software, which requires another wire instance as a crack guide, but in this project, it was created using Midas FEA. The crack instance was not added to the model. The model's mesh was a quadrilateral structured mesh. A triangular mesh was omitted because it does not support crack spread.

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5.1 Crack Propagation Model in Beam

Three points bending for beams and cylindrical crack propagation of cover cracking due to corrosion were calculated using the commercial software Midas FEA. Stress-strain analysis supports the use of isotropic damage for materials weakened by voids, whereas the use of micro-cracks to cause damage renders isotropic stiffness degradation only a first rough approximation. A 3D solid beam and a 2D solid beam were subjected to three bending tests. While the critical load for a 2D beam is approximately 8.1kN, the result of this Midas FEA analysis is 13.9kN higher. This could be because of the modelling, meshing technique, or material properties used. The difference is insignificant because the primary goal is to determine the model's suitability for crack propagation.

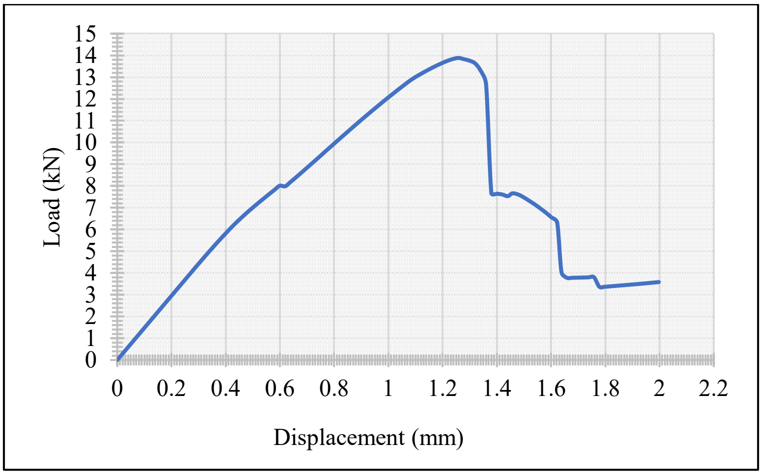

Figure 4. 2D Beam Graph Result

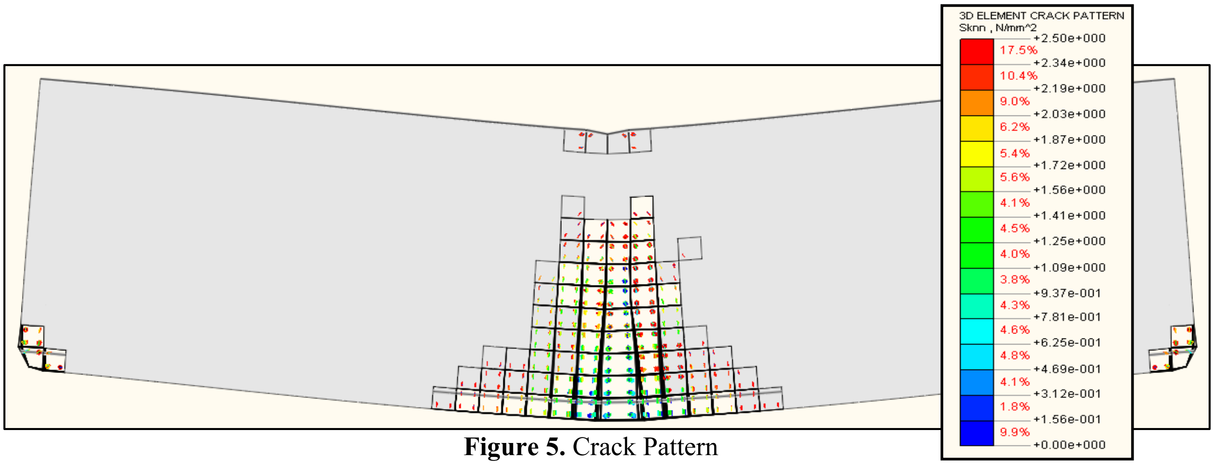

Figure 5. Crack Pattern

The crack progression during the analysis demonstrates that the crack began at the bottom, where the indication of the crack is fully open. This demonstrates that the crack propagation model developed using XFEM can accurately model the crack propagation, as illustrated in Figures 4 and 5.

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5.2 Crack Propagation from Inner Radius

The pressure change acting on the inner radius, which causes crack propagation, was simulated using the parameters learned from previous research (JM Sancho 2007). The stress distribution is symmetrical and concentrated at the pressure of the inner cylinder, as shown in Figures 6(a) and 6(b), implying that the crack propagates stably across the cylinder and that there is a small defect in the concrete that allows the stresses to concentrate at the point of maximum principal tensile, initiating and propagating the crack. Midas performs FEA loads and visualizes fracture propagation in accordance with the model.

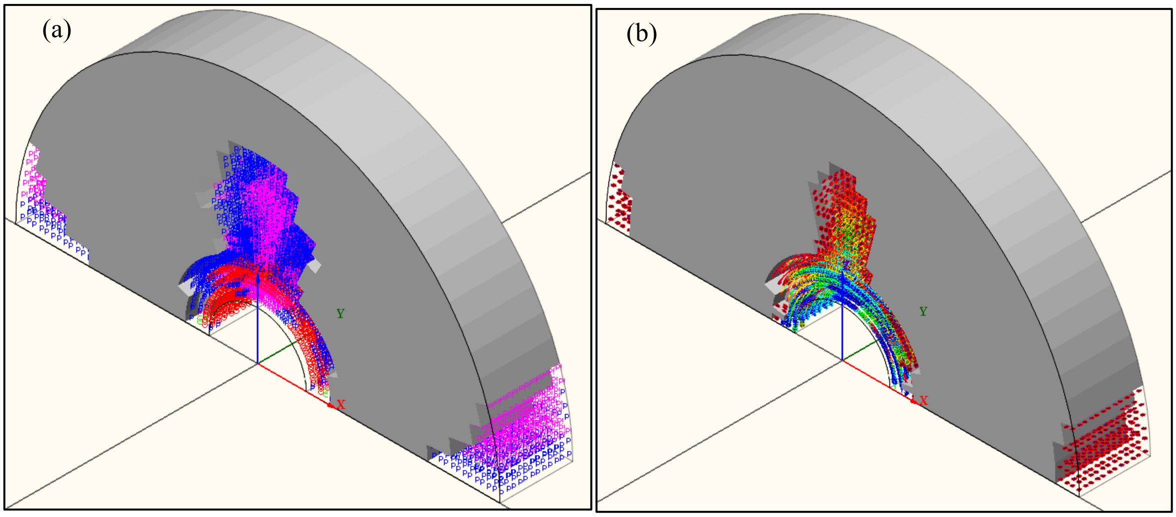

Figure 6. Crack Propagation Visualization

The change in pressure acting on the inner radius as a function of displacement can be displayed by extracting the data in the visualization module's post tab. The inner components have been chosen to maximize the pressure exerted over the applied displacement. More critical is the critical pressure at which the fracture propagates throughout the cylinder. The pressure rises linearly until it reaches a nonlinear point caused by the presence of the FPZ, as seen. Following a critical stress event, the model exhibits a linear softening behavior until the stress is zero.

It can be observed that when the pressure reaches 3.15 MPa with a tensile strength of 2.0 MPa, the cover begins to crack, resulting in cracking 0.7mm from the inside of the inner surface, indicating that there is an early crack to the cover area before the crack penetrates the cover (Figure 7). According to Lau et al. 2018, 8.58 MPa is the critical pressure at which a corrosion-induced crack can penetrate the cover. In order to investigate these three variables, a parametric study was conducted to determine the value of the critical pressure at which concrete begins to fracture. The critical pressure of the concrete has increased as the tensile strength of the concrete has increased. The critical pressure rises as the tensile strength of the concrete rises. By increasing the thickness of the concrete cover depth, the critical pressure is raised. Concrete cover cracking is caused by the critical crack depth and the fact that the critical crack depth is proportional to the critical pressure.

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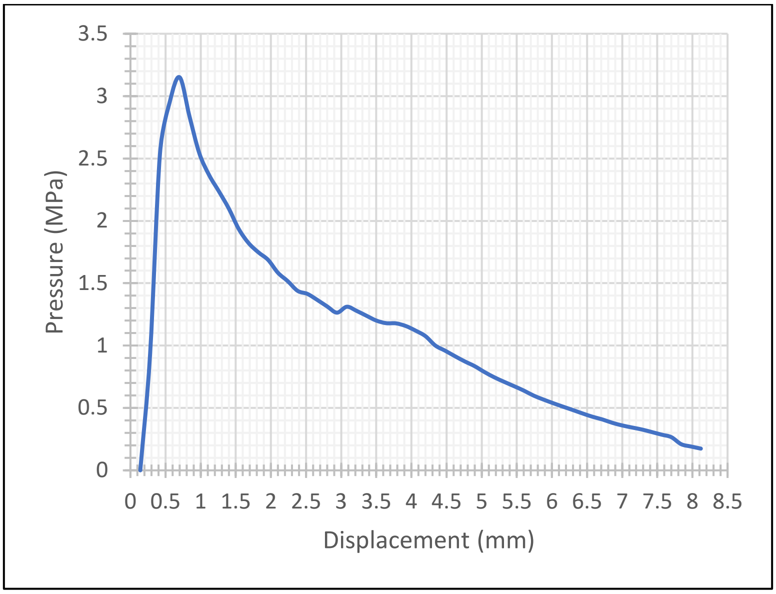

Figure 7. Crack Propagation Visualization

As shown in Table 5.1, the numerical model's findings are typically greater than those of the analytical model. The modelling techniques and assumptions used could explain this disparity. Despite the differences in modelling techniques, numerous studies have shown that both are adequate for simulating crack propagation and serve as the foundation for fracture mechanics investigations.

Table 1. Critical Pressure Penetrates Concrete Cover

Variables	ft	**Numerical model results (Using Midas FEA) (MPa)**	**Numerical model results (Using Abaqus) (MPa)**	**Analytical model results (From Experiments) (MPa)**
C = 30 mm D = 12 mm	2.0 MPa	6.3	6.6	6.4
	2.5 MPa	7.1	8.6	6.8
	3.0 MPa	14.8	10.2	7.1
C = 40 mm D = 12 mm	2.0 MPa	8.5	9.3	8.3
	2.5 MPa	9.08	10.8	8.8
	3.0 MPa	10.8	12.3	9.4
C = 40 mm D = 16 mm	2.0 MPa	9.3	7.2	7.2
	2.5 MPa	8.36	8.7	7.7
	3.0 MPa	8.78	10.0	8.1

5.3 Crack Width Result

As shown in Figure 8, an analysis of 30 mm concrete cover with varying tensile strengths demonstrates that varying tensile strengths result in varying crack widths from an early stage (day 3) after loading. Fracture energy is one of the factors considered in the numerical modelling of the softening distribution, and the implementation of the softening distribution concrete material is most likely the most critical. In the FE model, assuming a linear distribution results in an overestimation, whereas an exponential curve results in an underestimation in the analytical model.

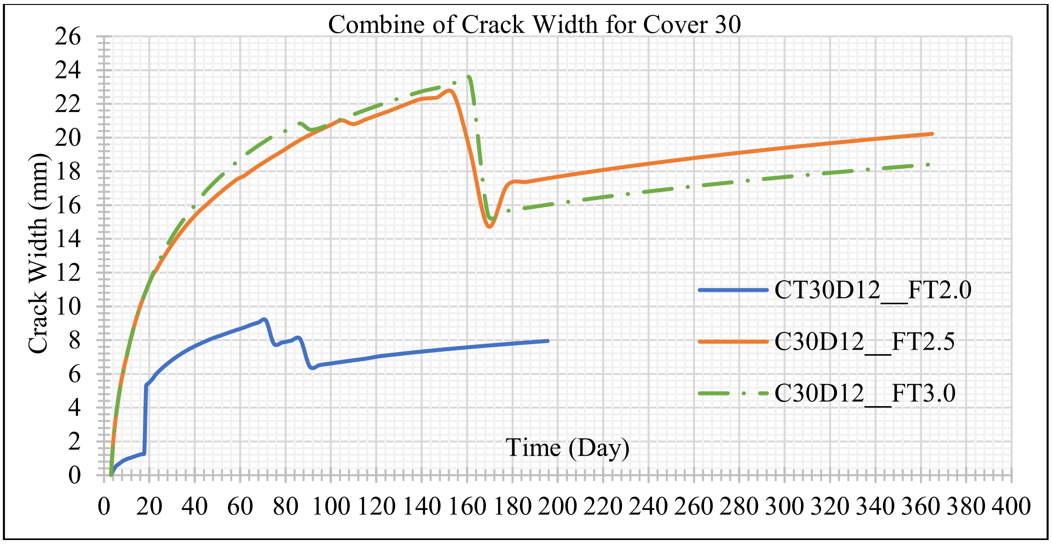

Figure 8. Combine of Crack Width (Cover 30)

While the material type (concrete) and fracture energy remain constant, the tensile strength applied to the material parameters varies, resulting in a different graph. After 71 days of loading, the concrete cover developed a 9 mm wide crack. This could be due to the inner pressure of the cylinder and the displacement load acting upward from the inner side of the cylinder, causing the crack to form quickly after loading. The higher crack and its location on 154 days, approximately 22 mm before the cover completely lost its stress, are depicted in Figure 8. Because no heaving occurred, it is safe to assume that the fracture began at the point of contact between the reinforcement and the concrete cover and spread outwards. In this case, the circumferential stress (tensile in nature) created by the pressure exceeded the tensile strength of the concrete.

It's interesting to note that corrosion-induced cracking does not always start on the inside of the structure and spreads outward to the reinforcing bar; rather, the top crack starts on the outside and spreads inward to the reinforcing bar. This is because, as shown in Figure 9, the top surface of the structure is in tension during non-uniform expansion, whereas the area surrounding the top of the reinforcing bar is in bi-axial compression. As a result, the fracture should logically start at the area of surface tension. A variety of tests have shown this effect (Mike BO, 2014). Spalling occurs when a side fracture propagates to the structure's corner. The fracture energy of concrete is frequently regarded as a critical factor influencing the cracking of concrete structures. Another critical factor influencing the failure of corrosion-affected RC structures is the distance between the steel reinforcing bars (Xun Xi et al., 2018).

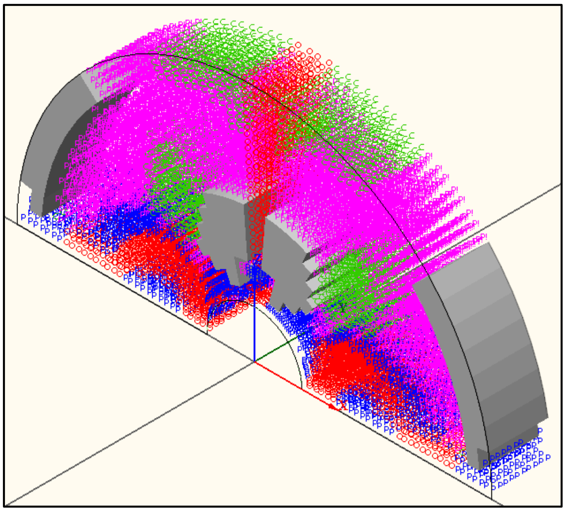

Figure 9. 3D Crack Modelling

Furthermore, this study may establish that fracture energy, along with the assigned materials' tensile strength, ft value, is one of the parameters that affect cracking. When a side fracture reaches the side surface, it moves rapidly until it reaches the opposite side surface, releasing energy. The structure abruptly and dramatically releases its displacement during this time. As a result, failure mode influences the critical corrosion amount to fracture significantly. Fracture formation allows concrete to expand, slowing it down and propagating cracks. Thickness, or layer, has a greater influence on the onset of top surface cracking in concrete. More corrosion products are required to complete the task.

6. Conclusion

To determine the critical pressure required to cause concrete cover cracking, a numerical analysis modelling has been developed. The fracture mechanics theory and crack propagation modelling are used in the model. A linear softening curve is used to simulate the fracture process zone, with fracture energy and tensile strength specified as fracture parameters. In a local coordinate system, the pressure applied to the inner cylinder radius is displacement controlled. According to the analysis, increasing the tensile strength and concrete cover increases the critical pressure required for the crack to penetrate through the cylinder model, as more force is required to propagate the crack.

The numerical analysis of crack initiation and propagation was subjected to accelerated corrosion testing. It was discovered that as the concrete cover increased, the time to crack initiation and crack propagation increased, and this also reflected in the crack width of the concrete cover. Corrosion-induced cracking is also influenced by rebar size, cover size, and material tensile strength. As a result of the findings, it is possible to conclude that these three major criteria have the greatest influence on corrosion-induced cracking that occurs on the rebar surface or the concrete cover surface. Corrosion-induced cracking is also influenced by rebar size, cover size, and material tensile strength. As a result of the findings, it is possible to conclude that these three major criteria have the greatest influence on corrosion-induced cracking that occurs on the rebar surface or the concrete cover surface.

The slight difference in results between the numerical and analytical models is due to modelling assumptions that differ. Despite this, the numerical model can be used to simulate crack propagation as well as the critical pressure required to cause corrosion-induced concrete cover cracking.

Although no research has been conducted using MIDAS FEA, the software has been used in industry, primarily in bridge design. As a result, the following recommendations are highlighted for further consideration and research.

i. Extend the experiment using the MIDAS FEA software with other elements such as columns and slabs.
ii. To demonstrate the potential use of the proposed combined modelling approach. In the example the influence of various parameters of the corrosion model on the crack propagation were investigated.
iii. The presented results highlight the need for a realistic prediction of the corrosion rate as well as the selection of corrosion products formed to simulate the formation of corrosion induced concrete cover cracking.
iv. Future research should look into the effect of concrete material parameters, model geometry, and the mechanical properties of the corrosion products formed.

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

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