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NUMERICAL MODELING OF RADIAL FRACTURING OF CEMENT SHEATH CAUSED BY PRESSURE TESTS

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ABSTRACT

To achieve an acceptable level of zonal isolation, well integrity should be guaranteed in hydrocarbon production and geological CO_2 *sequestration. Well pressure test can cause different types of failures in the well system leading to leakages through these failures. Laboratory evidences have revealed that occurrence of radial tensile fractures is likely during pressure tests.*

In this paper, we use a numerical code call MDEM which was formulated based on discrete element method. The code can model discontinuum feature of fractures. A model of a lab-sized pressure test was built and compared to an experiment previously published. The model was tested under different confinement levels and effect of the tensile strength of rock on the radial fracture was investigated at the same lab-scale. Fracture opening profiles are also presented showing the leakage potential of these fractures under different pressure level.

Keywords: Well integrity, cement sheath, well pressure test, fracture

INTRODUCTION

Efficient zonal isolation of the subsurface formations is one of the main objectives of well cementing. Cement sheath provides a barrier to fluid migration between different formations. Cement acts also as a support for wellbore and protects the casing in the corrosive medium of a well. However, the dynamic nature of hydrocarbon production or fluid injection (e.g. CO_2) imposes extreme loadings on the cement sheath in both short and long-term in terms of pressure and temperature variations. Failure of cement sheath can lead to problems in the integrity of production or injection wells as well as after well abandonment [1,2]. Therefore, it is important to maintain the cement sheath failure. The failure mechanisms of cement integrity of the cement and well system in the subsurface to shorten the economic and environmental issues raised by sheath in a well can be shear failure, tensile (or radial cracking/fracturing), debonding of cement-casing and cement-rock interface [3].

While performing the pressure test, the cement sheath can fail due to developed excessive tensile stress in the cement sheath. As a result, radial fractures can form which can act as leakage pathways compromising the cement sheath functionality. There are well-known researches published in the literature reporting pressure tests performed in the lab. Goodwin and Crook [4] carried out pressure tests measuring the permeability of the different cement sheath after failure [4]. They showed that the expansion of the casing due to internal pressure increase can create radial fractures in the cement sheath. Jackson and Murphey [5] also carried out similar tests, increasing and decreasing pressure inside the internal casing. They observed that air flows through the cement-casing system after reduction of the pressure followed by pressure test below a level [5]. Boukhalifa et al. [6] performed experiments simulating the expansion and contraction of the casing leading to the formation of radial fracture and microannuli. They showed how the radial cracks and microannuli contribute to the permeability of casing-cement sheath for different flexible, expanding and foamed cement systems under several conditions.

There are several papers in the literature modeling the well integrity using numerical simulations. Gray et al. [7] used a staged finite-element approach taking in-situ stress state, nonlinear behavior of cement and formation etc. into account to provide a more realistic calculation of well integrity. Ravi et al. [8] applied finite element method to model debonding, cracking, and plastic deformation of cement under different loadings such as pressure testing, well completion, hydraulic fracturing, and hydrocarbon production.

Skorpa et al. [9] performed a lab-sized experiment of pressure test in a cell under no confinement. They showed that radial fracture can form due to the pressure increase. They observed

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that the radial fracture initiates in the cement sheath and propagates into the rock formation. They visualized the crack path using CT-Scan.

In this paper, we investigate the propagation of radial fractures created in the well pressure test done by Skorpa et al. [9]. The paper first presents the pressure test experiment performed in the lab. Second, a numerical model is constructed to calibrate the model against the experiment and then we investigate the effect of rock tensile strength, stress confinement on the behavior of the radial fracture as well as its opening profile. At the end, the conclusions are given in the last section.

PRESSURE TEST EXPERIMENT

Skorpa et al. [9] developed a laboratory set-up to investigate cement degradation during pressure cycling. In this set-up, both debonding and cracking of the cement sheath are characterized by X-ray computed tomography. The set-up allows for tests with different types of rocks, casings and cement systems, as well as the inclusion of drilling fluids. They performed a cyclic pressure test of a carbon-steel (X-52) with outer diameter 60.3 mm and 2 mm thickness casing, Castlegate sandstone with 200 mm height, 152 mm diameter and a concentric borehole with 76 mm diameter. The cement had cured at 66°C for five days, the sample was exposed to 20 pressure cycles at 30 MPa, where one cycle consisted of 1 minute with and 1 minute without pressure [9]. A single radial fracture was created in the cement and penetrated the rock formation. Figure 1 shows the CT image of the casing-cement-rock system and the fracture is visible. For details about the set-up and the test the reader is referred to [9].

NUMERICAL MODEL

To model the initiation and propagation of the radial crack under pressure test, a hybrid FEM/DEM in-house code called MDEM was used [10]. The code behaves like a regular continuum for elastic domain, but it becomes discrete as soon as a fracture forms. This enables the code to provide a more realistic analysis of fracture propagation. Pre-existing fracture and new fractures can form in the code having the possibility to close, open and shear depending of the loading condition. The code was described in Refs [10,11] in detail.

A model of the pressure test specimen was built including the casing, cement and rock domains with their actual sizes in the test performed by [9]. Figure 2 presents the geometry of the model and the colors refer to the different domains. The only difference between the specimen and the model is that the outer boundary is square instead of being circular and it is larger in the size (i.e. the region called “Surrounding” in Figure 2). The main reason to do this is to avoid numerical complication after the fracture reaches the boundary of the model. Table 1 summarizes the elastic parameters of each of the domains. We did not measure the values, but they were taken from the literature and the corresponding references were also provided in the table. The values for Castlegate sandstone were taken after consulting with SINTEF’s formation physics laboratory. The fixed boundary condition in all the models is constant pressure on the casing wall. And the minimum mesh size was 1 mm closer to the borehole and becomes larger as getting away from the borehole.

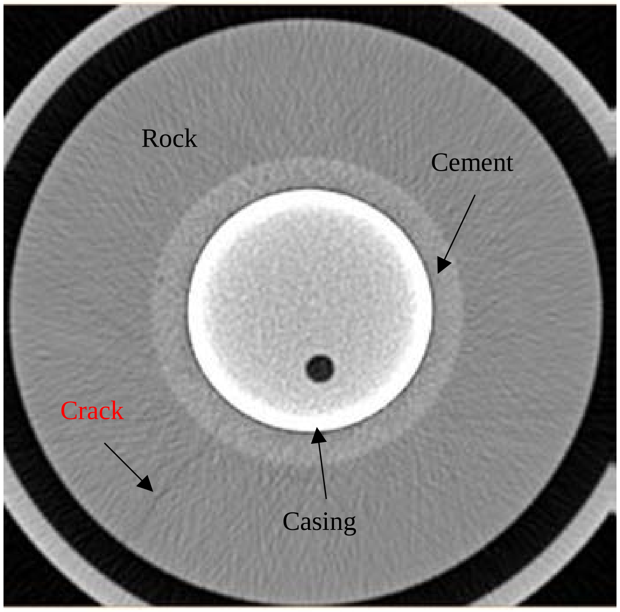

FIGURE 1: RADIAL FRACTURE INDUCED BY CYCLIC PRESSURE TEST [9]

Table 1: ELASTIC PROPERTIES OF THE MODEL

Domain	Young’s modulus (GPa)	Poisson’s ratio
Casing	210	0.3
Cement	9.2 [7]	0.15 [7]
Rock	5	0.25
Surrounding	5	0.25

3.1 Calibration of the Model

We performed a series of analyses to calibrate the model to the pressure test discussed in Section 2. The pressure was increased step by step to the final well pressure, 30 MPa. Actually, this is different than what performed in the test. Therefore, we neglect the dynamic effects and our simulation is a quasi-static loading. Also, the model does not include the cyclic pressure increase-decrease as in the lab and assumed that the failure occurs in the first loading. The reason was that the code is not yet able to consider the effect of cycling loading. Moreover, the cement and rock were assumed to be brittle even though rocks and cement show quasi-brittle behaviour. This assumption simplifies the model and enables a faster analysis of pressure test. Brittle behaviour means that the fracture will propagate if the absolute value of tensile stress exceeds the tensile strength. All of the assumptions in a way will affect the results. The simulations were performed under room temperature similar to the experiment in the lab.

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In the calibration process, we chose a set of tensile strength for the cement and the rock so that we create a single radial fracture at pressure 30 MPa obtained in the lab. The fracture must initiate in the cement, crossing the cement-rock interface and propagate the whole thickness of the rock (and stop before "Surrounding" region in Figure 2). In the first round, the homogenous value for the cement and rock was chosen. It was concluded that it was not possible to create a single fracture for a homogenous model, but multiple fractures were created. In the second round, we tried heterogeneous tensile strength for the cement and homogeneous model for the rock. Heterogeneity was imposed by a generation of random tensile strength value from a uniform distribution U (11.5, 16.5) MPa for the cement and a constant 7 MPa value for the rock. Figure 3 shows the numerical result and it is well in line with the fracture in the experiment shown in Figure 1.

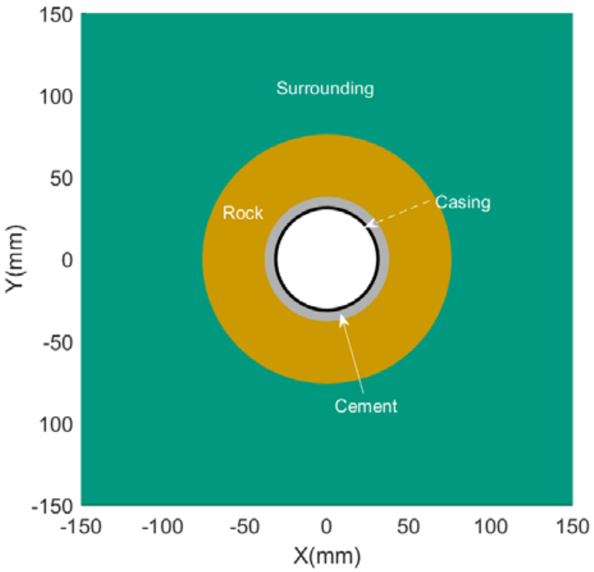

FIGURE 2: THE MODEL OF CASING-CEMENT-FORMATION

3.2. Effect of Rock Tensile Strength

Different ranges for the uniform distribution were also examined; however, U (11.5, 16.5) MPa for cement seems to lead to a better result. Different values (11-4.5 MPa) for the tensile strength of rock were also examined. Figure 4 shows the single radial fracture created for different tensile strength for the rock. It is clearly shown that if the tensile strength has a higher value the radial fracture is shorter and stops at some point in the rock. For models with rock tensile strength lower than 7 MPa branching occurred (Fig. 4d-e). Therefore, it was concluded that 7 MPa as the tensile strength of the rock in the model leads to a more similar result compared to the lab test in Section 2. It also seems that the radial fracture stops in the cement-rock interface if the tensile strength of the rock is 11 MPa. It is also interesting that in a model with tensile strength lower than 4.5, the radial fracture initiates first in the rock then propagates in two directions towards the cement and the outer boundary (shown by arrows in the figure). This implies that the absolute value of tensile stress evolved in the rock (in the rock-cement interface) is greater than 4.5 MPa. It is important to note that if the material model was assumed to be a quasi-brittle material (instead of being brittle) the set of strength values obtained during calibration would be different.

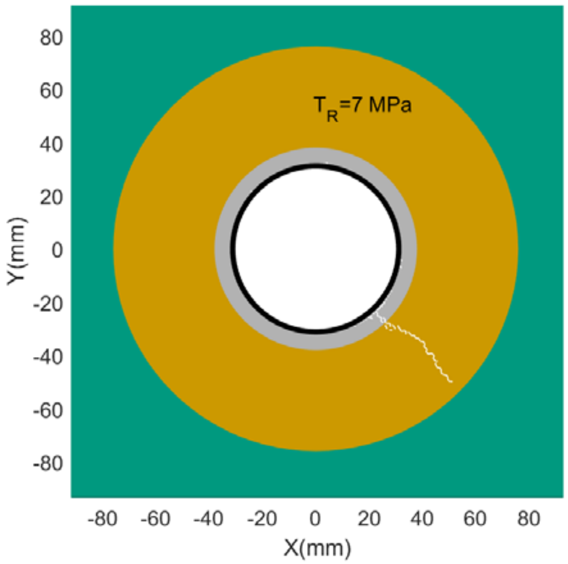

FIGURE 3: SINGLE RADIAL FRACTURE CREATED AFTER 30 MPA CASING INTERNAL PRESSURE

3.3. Effect of Confinement

As mentioned, no confinement case used in the test. However, in the field, the well-casing-cement-rock system is under confinement. Therefore, the confinement may affect the propagation of the radial crack due to pressure test. In this section will show to what extend the confinement level can influence the occurrence of radial fracture. The confinement level starts from being isotropic stress 1 to 20 MPa. In contrast to the cases in the previous sections, the pressure is increased well above to create more fractures to see the radial fracture pattern. Figure 5 shows the fracture pattern for different confinement level and the corresponding internal pressures. It shows that as the confinement increases the fractures become shorter. It is also important to note that the first radial fracture was created under 30, 33.5, 43 and 78 MPa pressure for increasing the confinement level, respectively. In higher confinement, the radial fractures do not penetrate the rock formation. It is surprising to see that increasing the well pressure is not in the favor of propagating the fractures into the rock, but rather the number of the fractures increases in the cement (Figure 5).

In one example, only the rock strength was decreased to 1 MPa under 20 MPa confinement stress. The results showed that for very weak rocks there is a low chance that the radial fracture propagates into the rock formation even in high confinement level (Figure 6).

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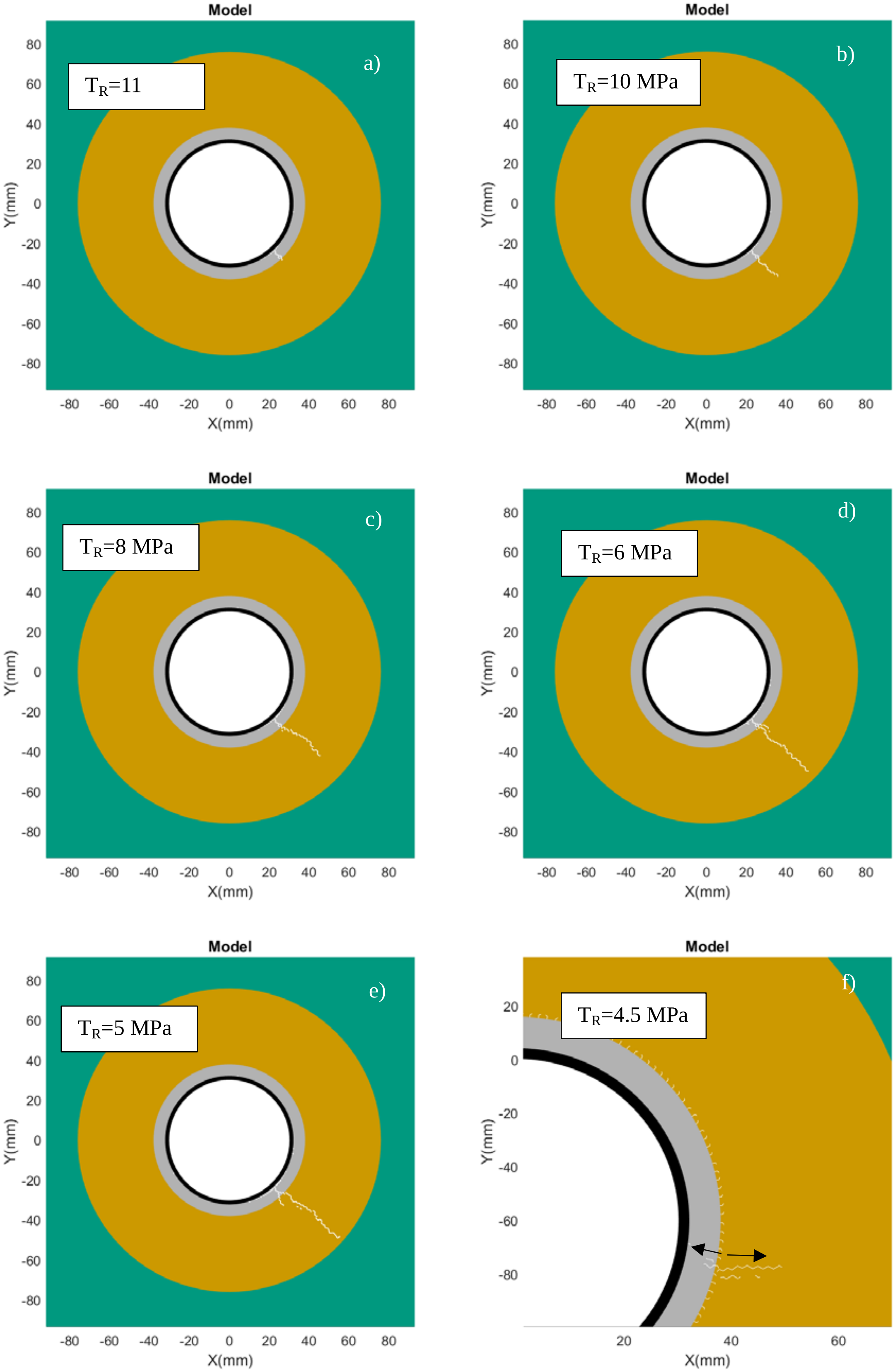

FIGURE 4: EFFECT OF THE ROCK TENSILE STRENGTH ON RADIAL FRACTURE

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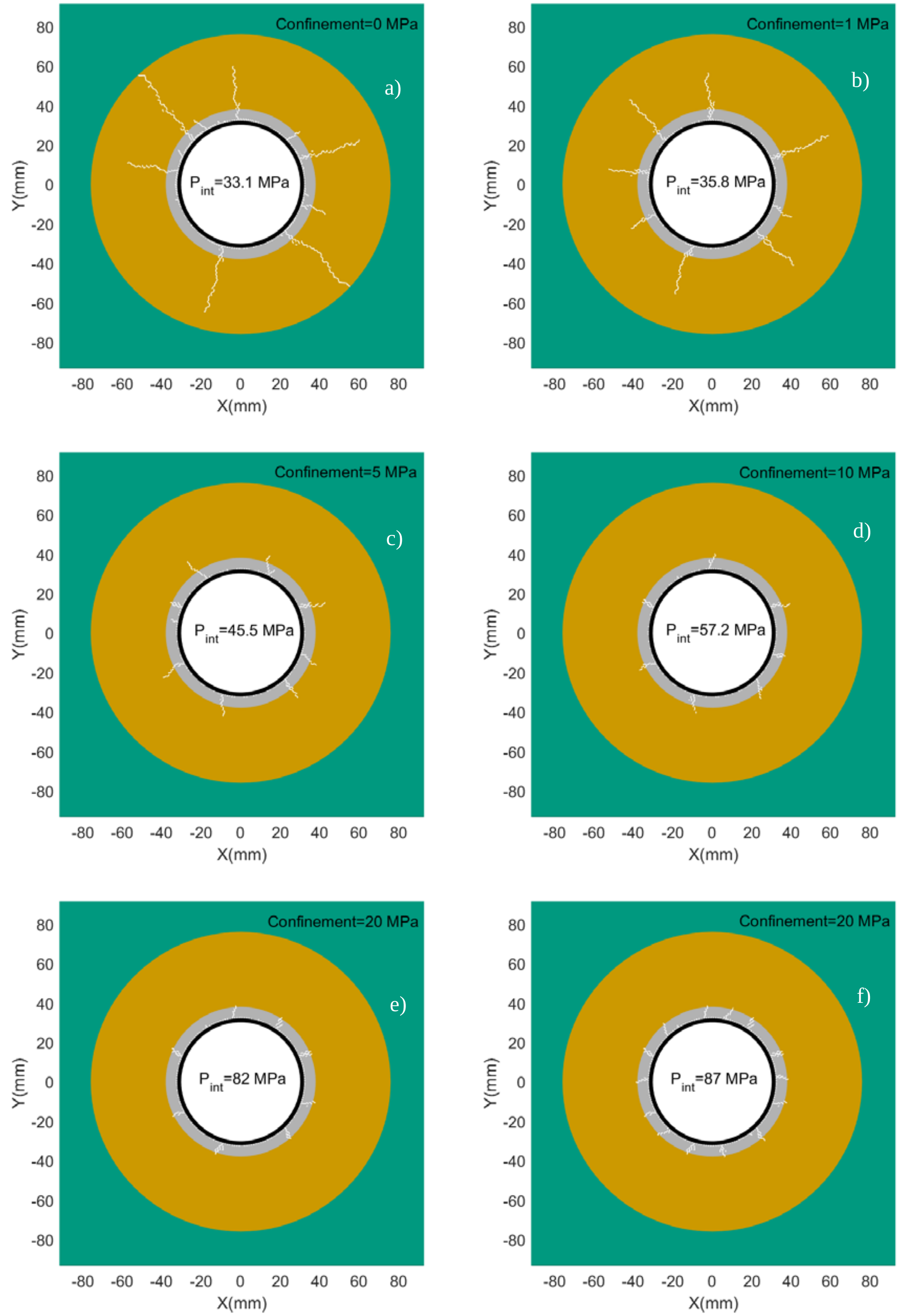

FIGURE 5: EFFECT OF LEVEL OF CONFINEMENT ON THE EXTENSION OF RADIAL FRACTURE PROPAGATION

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3.4. Fracture Opening Profile

The permeability of the induced fractures depends on their opening and length. In this section, we show the profile of the fracture opening in the no confinement case under different internal pressure after the single fracture was created. First, the fracture profile is plotted as soon as the internal pressure reaches 30 MPa so the single fracture shown in Figure 3 is created. Afterwards, the pressure was reduced, and the closure of the fracture surface was monitored, and the opening profile is plotted until the pressure reaches zero. Figure 7 shows the fracture profiles corresponding to the pressure level after the fracture appears. As expected, the maximum opening is observed in the maximum pressure and the fracture closes as the pressure decreases.

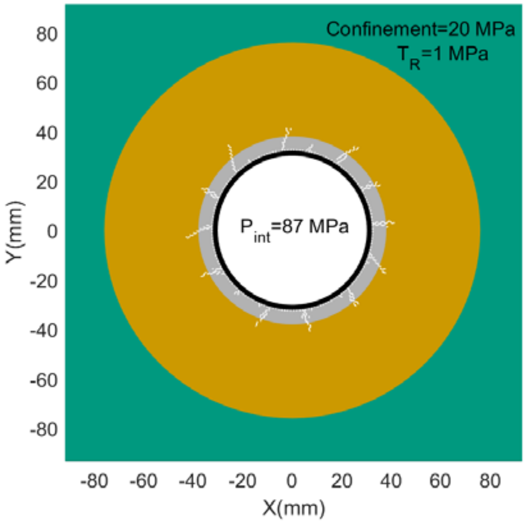

FIGURE 6: RADIAL FRACTURE PATTERN IN HIGH CONFINEMENET FOR VERY WEAK FORMATION

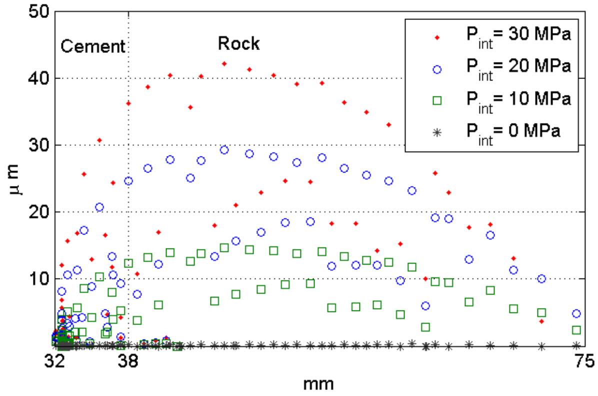

FIGURE 7: FRACTURE OPENING PROFILE IN DIFFERENT PRESSURE LEVEL FOR THE SINGLE FRACTURE

It was also observed that the fracture opening is not uniform through the cement sheath and rock formation and the peak opening was in the rock formation at a distance from the cement-rock interface in this case. In this example, we observe a residual opening after the pressure is reduced to zero. The internal parameters of the model could be adjusted such a way that the fracture closes completely or up to a certain range of values. This provides a possibility in calibrating for the permeability of fractures in pressure tests. It is important to note that the resolution of the CT imaging is 100-200 μm and width of the fracture in the experiment is much greater than the value calculated in Figure 7. The main reason is the fact that the opening of the fracture was suppressed by the surrounding domain. However, the capability of calculating the fracture opening enables a relative comparison of the effect of different parameters.

CONCLUSION

A modified discrete element approach was adopted to model the formation of radial fractures under pressure testing of casing-cement-rock system. The model was calibrated against a pressure test experiment. Effect of tensile strength of rock, confinement on the radial fracture were investigated. The length of the radial fractures is influenced by the value of tensile strength of the rock; stronger the rock, shorter the fracture. Below a specific value for the tensile strength, the fracture can initiate first in the rock formation not in the cement sheath. The level of confinement can also affect the fracturing pressure level and also the extend of fractures, lower the confinement lower the pressure required to fracture and longer the its length. In higher confinement, the radial fracture is confined in the cement sheath not penetrating the rock formation. It was also observed that the number of fractures increases rather than propagating to the formation by elevating the internal pressure in higher confinement. We also concluded that the confinement is a more influencing parameter than the tensile strength of rock.

The fracture opening profiles was plotted for different pressure levels. Higher the pressure level greater the fracture surface opening, therefore, a greater leakage.

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