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Conclusions

This thesis presents a new finite element based on the eXtended Finite Element Method, which is able to represent complex phenomena of fracture intersection and crossing with frictional behaviour. In addition, the formulation takes into account fully coupled behaviour with exchange of fluid between the fracture and the surrounding medium. The use of a fracture face transversal conductivity allows the eventual loss of pressure given by a filter cake when leak-off occurs.

The main objective of this thesis was achieved, as the implemented code provides very good predictions of the coupled fluid-rock fracture behaviour and is capable of correctly simulating the interaction between hydraulic and natural fractures. Overall, it may be stated that the implemented element can bring a valuable contribution to a deeper understanding of the phenomena involving propagation of hydraulic fractures in naturally fractured rocks. This knowledge is fundamental to the correct modelling of hydraulic fracturing in unconventional reservoirs.

During the development of each different step of the thesis, i.e. literature review, formulation, implementation and application, many interesting considerations were registered and can be compiled in the following items.

Literature Review

- The XFEM is a recent technique (~20 years) that is being applied by many researchers that work with fracture mechanics. The growing interest in this technique to simulate hydraulic fracturing is even more recent and noticeable by the increasing number of research works published in the past few years.
- A few research works have focused on using XFEM to simulate intersection between hydraulic and natural fractures and none was found that could show all the capabilities proposed in this work.

- Only a reduced number of laboratory tests to simulate the interaction between hydraulic and natural fracture were found. The results are usually interpreted qualitatively, i.e. by describing the behaviour of fracture interaction in different patterns, mainly crossing, arresting and opening.
- Very simple analytical solutions to predict the behaviour of fracture interaction exist. Those have shown to be accurate when compared with laboratory tests of interaction between one hydraulic and one natural fracture.

Formulation and Implementation

- The presented element formulation may be generalized for any number of discontinuities and intersections within the problem domain.
- The XFEM discretization only requires the presence of enriched degrees of freedom in the nodes surrounding the discontinuities, leading to a very reduced influence in the global jacobian matrix size.
- Independently of the fracture position, the degrees of freedom that store the enrichment for the displacements and the pore pressure are coincident with the original mesh. On the other hand, to take into account the variable of the fluid pressure within the fracture, extra degrees of freedom must be considered
- The implementation of the proposed XFEM element is complemented with two algorithms. The first defines the geometric attributes of the discontinuities, such as the values of the enrichment functions in the mesh nodes, position of the pressure fracture degrees of freedom, fracture intersections and position of the integration points in the integration sub-domains. The second algorithm computes if propagation occurs based in user defined criterion and which direction and length the propagating segment takes.
- Abaqus is a powerful tool that allows the use of several user subroutines to be integrated with the solver. The proposed element is completely implemented by using two user subroutines: UEL and UEXTERNALDB.
- Despite the high level of usability provided by Abaqus user subroutines, some difficulties arise from the fact that only part of the process is accessible, i.e. the Abaqus software architecture is fixed and cannot be adapted. The main limitations are the limited number of degrees of freedom per node and the need to activate all the degrees of freedom beforehand.

Application

- Comparisons of permanent regime models with interface elements (Chapter 5.2) shows very good agreement in the problems of flow in fractured medium.
- The numerical procedure proves to be very efficient in predicting the results obtained in laboratory tests (Chapter 6.1).
- The example in Chapter 6.2 shows the capability of the proposed XFEM element to simulate different fracture paths in complex fractured rocks. Not only the hydraulic fracture but also the natural fractures tips were able to propagate in any direction.
- In this thesis the effect of some parameters on interaction between propagating and natural fractures was also investigated. In agreement with the literature, the computed examples indicate that differential in-situ stresses and angles of approach play an essential role.
- However, other parameters may completely change the fracture network affected by the treatment, such as the initial hydraulic aperture, which is directly related with fracture roughness.
- The fracture face transversal conductivity coefficient *c* represents a transversal conductivity of the fracture for cases of percolation through fractured media. It is visible that a very low fracture face transversal conductivity makes the fracture play as a barrier to the fluid flow, while high values facilitate the percolation into the fracture.
- As any other method based in the FEM, the accuracy of results depends on mesh quality. However, by using the XFEM technique the mesh geometry takes a less important role, as seen in all the examples of this thesis, where regular meshes are used.
- It is evident that fractures may take unpredictable paths in fractured rocks. Therefore, XFEM is a very effective tool on modelling fracture propagation in fractured mediums, as there is no need to previously conform the mesh to the fracture path.

Further research and implementation work

- As stated widely in the literature, the tip behaviour has extreme influence on the way a fracture propagates. Therefore, it is recommended that specific tip

enrichment is implemented. Tip behaviour prediction may also be improved if more realistic constitutive models are used, such as a cohesive one.

- The propagation criterion has a strong influence on the path that the fracture follows. Further studies should be addressed with the objective of clarifying which criteria suit better to each kind of problem.
- Considering that it was shown that fracture transversal and longitudinal transmissibility strongly influence the behaviour of the hydraulic and natural fractures, further numerical and laboratory research should focus on defining different longitudinal transmissibility laws that consider effects such as fracture roughness.
- Modelling the presence of proppant within the injection fluid may bring further knowledge about screen out in the intersections between hydraulic and natural fractures.
- Fractures are surfaces that develop in a three-dimensional space. Although some simplification assumptions may be taken to obtain good results in plane strain models, realistic predictions of field problems can only be achieved with 3D models. It must be taken into account that the level of complexity strongly increases when implementing geometric pre and post-processors in 3D.