Numerical modeling of damage zones in rocks at reservoir scale using FEM

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Abstract. Damage zones are structural domains present in most geological faults that can act either as a preferential flow path due to fracture sets or as a barrier due to compaction bands. Therefore, the characterization of damage zones can be essential for adopting adequate production strategies in oil fields. Unfortunately, the geophysical methods used to characterize damage zones in geological faults hardly allow their identification due to low seismic resolution. Alternatively, the characterization of the damage zones can be done through superficial outcrops. However, there is a wide dispersion of data in this type of study. In this paper, we present a numerical model based on the finite element method (FEM) to analyze the structural evolution of damage zones at the reservoir scale. In the proposed model, the fault plane is included through two contact lines within a host rock that presents elastoplastic behavior. The obtained results allow the identification of different deformation mechanisms along the damage zone and confirm the capabilities of the proposed model to assess the damage zone width.

Keywords: Damage zones, Fault, Numerical modelling, Finite element method, Plasticity.

1 Introduction

Geological faults are structures defined as discontinuities that arise from the relative displacement between blocks of rock [1]. Faults are of great importance in the oil and gas industry. They usually act as barriers that compartmentalize reservoirs. However, if geological faults are reactivated they can trigger several problems such as seismicity, changes in flow paths and, in the worst scenarios, exudation [2], [3]. Therefore, the study of faults is essential for developing suitable production strategies for the oil and gas industry. Usually, geological faults are considered as planes due to the low resolution of seismic acquisition in deep formations. However, field observations on outcrops show that geological faults are not simple planes but complex geological structures with a variable width [4]. Therefore, the term "fault zone" is more appropriate to designate both core and damage zones which form a geological fault as illustrated in Fig. 1. The core accommodates most deformation and generally acts as a permeability barrier when the fault is dormant [5]. The damage zone consists of the region adjacent to the core where the deformation magnitude decreases towards the host rock [2][6].

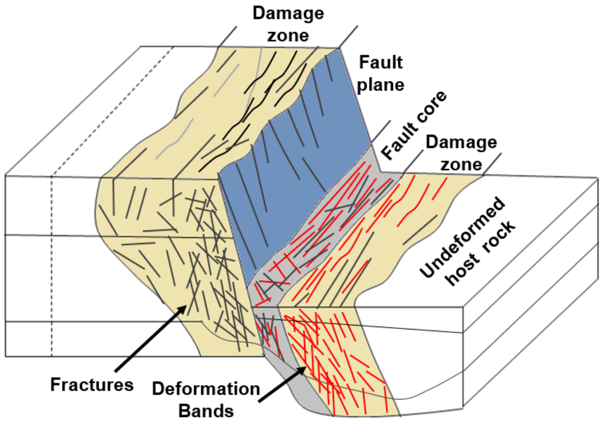


Figure 1. Schematic illustration of a fault zone, with representation of the fault core and the damage zone

The damage zone can contain several geological structures, such as fractures, small faults, stylolites and deformations bands. In geology, a parameter normally adopted to infer the presence of fracture or compaction bands in damage zones is the porosity. For example, low porosity rocks usually respond to strain or stress changes forming extension and shear fractures. On the other hand, high porosity rocks respond triggering compaction bands [1]. However, those assumptions can be affected by other parameters such as lithology, elastic and strength properties, and the deformation mechanisms acting on the host rock [2][6].

Despite their importance for hydrocarbon production, characterization of fault damage zones still remains an active research topic[6]. A method to infer the presence of damage zones and their geometric attributes is through field observations and study of superficial outcrops. In this form, some correlations have been proposed to define the width of the damage zones by analyzing the cumulative frequency of the structures (fractures or deformation bands) obtained through 1D scanlines [2][6]. However, outcrop studies are limited by the observation scale and spatial restriction [2].

Another option is through the numerical modelling of the processes that led to the formation and evolution of damage zones. Among the various numerical methods, the finite element method (FEM) stands out due to its ability to represent models with irregular and complex geometries, and to deal with complex boundary conditions and advanced constitutive models, including models with viscous, frictional and plastic response [7][8]. Similar to a previous study [9], in this paper we present a methodology based on FEM and elastoplastic constitutive models to study the structural evolution of the damage zones of normal faults in carbonate rocks in the reservoir scale. However, the current models are able to better represent the field conditions by using a different geometrical and load setting.

2 Model description

The numerical model adopted in this study considers an isolated fault in an isotropic and homogeneous medium, as it is shown in Fig. 2. The model is equivalent to a 2D vertical cross-section with a geological fault in the central region. Therefore, we assume plane strain conditions. For simplicity, we also adopt an isotropic and uniform stress state (σ_c) of 10 MPa. The fault is represented by two superimposed lines embedded within the model. Then, during the simulation, the damage zone is created by applying displacements of opposite directions over each line. The displacements are applied incrementally following a parabolic distribution, with the maximum displacements in the central region of the fault and restricted displacements at its tips. The maximum displacements applied were 10% of the fault height.

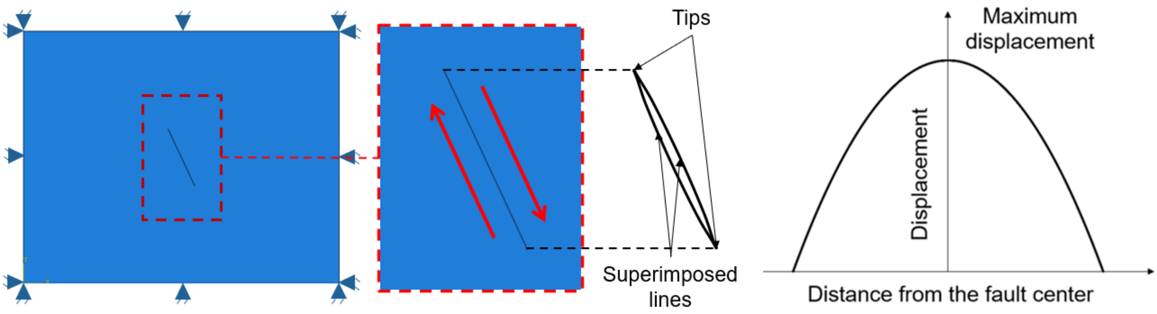


Figure 2. Geometry and boundary conditions of the model.

Figure 3 shows the dimensions and mesh used in the numerical model. The mesh is composed of 8-node quadrilateral elements with nine-point Gauss integration. In the central region, we use a structured mesh with constant element size while in the rest of the model we adopt an unstructured mesh with elements of variable size.

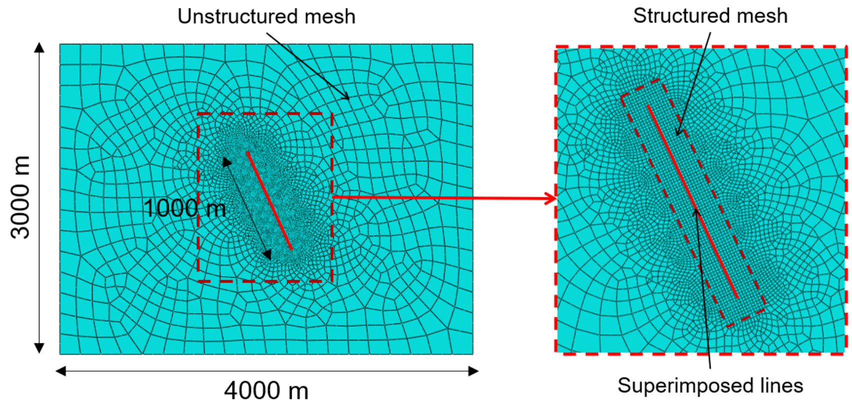


Figure 3. Dimensions and mesh of finite element model.

The mechanical behavior of the rock was represented through an elastoplastic model using the Mohr-Coulomb failure criterion with non-associative plastic flow law. This model was used due to its simple formulation, which requires a small number of properties that can be easily obtained in triaxial tests, predicting with some accuracy the shear strength of the material [7]. The properties adopted are presented in Tab. 1 and correspond to carbonate rocks tested in the laboratory [10].

Table 1. Properties of the carbonate rock [10].

Constitutive relation	Nomenclature	Value
Young's modulus (GPa)	E	17.0
Poisson's ratio (-)	ν	0.3
Friction angle (°)	Φ	34°
Cohesion (MPa)	C	6
Dilation angle (°)	ψ	24°

The simulations were carried out using the Abaqus/Standard® solver, considering a large displacement formulation. In each simulation, we assume that the damage zones correspond to the regions that presented plastic deformations, similar to other works in literature about damage zones in this type of rock [9][10]. Therefore, we use a scalar variable (PEMAG) that represents the magnitude of plastic deformation. Such parameter is defined through:

$$PEMAG = \sqrt{2/3({PE_{P1}}^2 + {PE_{P2}}^2 + {PE_{P3}}^2)} \tag{1}$$

where PE_{P1}, PE_{P2} and PE_{P3} are the principal plastic strains.

To measure the damage zone width, a path perpendicular to the fault plane is included in the model, as shown on the left side of the Fig. 4. Over this path, we obtain the PEMAG distribution at each step of the simulations. The limit of the damage zone is defined by the inflection point of the PEMAG distribution curve, as shown on the right side of Fig. 4.

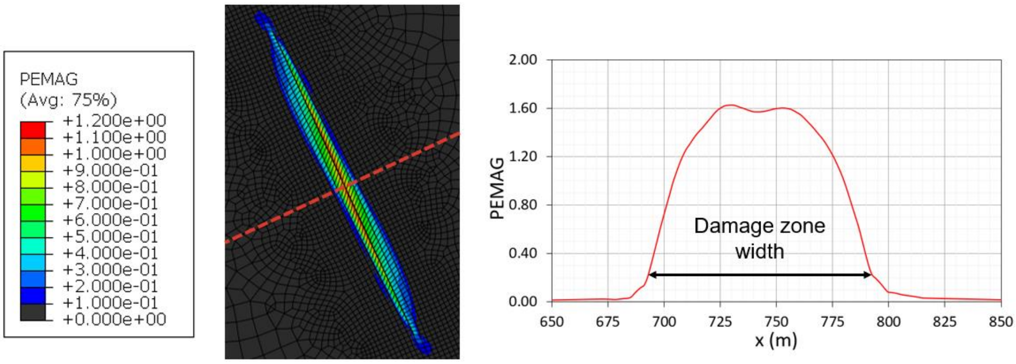
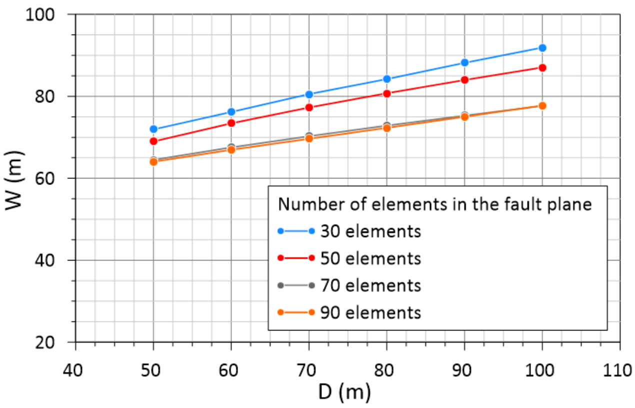


Figure 4. Damage zone width measurement process.

3 Results

As a first step, we perform a mesh sensitivity study considering different discretizations over the fault region. For each model, a curve relates the damage zone width (W) to the applied maximum displacement (D), similar to reported field observations [6][11][12]. Figure 5 shows the results of 4 models with different mesh discretizations. We observe that for a given displacement, the damage zone width increases with the element size. However, with mesh refinement there is a convergence of results when the number of elements over the fault region is greater or equal to seventy elements, along with a significant increase in analysis time. Hence, we adopt a mesh with seventy elements over the fault region (elements with an edge size of approximately 14 meters) in the fault plane for further sensitivity analyses. That mesh has 12678 nodes and 4088 quadrilateral elements.



Number of elements in the fault plane	Analysis time (min)
30 elements	1.8
50 elements	4.0
70 elements	7.1
90 elements	16.0

Figure 5. Results of damage zone width vs displacement and analysis time of the mesh sensitivity study.

The resultant damage zone for the model with 70 elements over the fault region can be observed on the left of Fig. 6. We can see that the damage zone has an antisymmetric shape. These results are expected since the applied displacement generates extensional and contractional zones in the zone adjacent to the fault, as seen on the right side of Fig. 6. We can also observe that the damage zone is widest in the contractional zones and narrowest in the extensional zones. In addition, we can see plastic deformations around the fault tip, which may indicate the formation of a tip damage zone as reported in field observations.

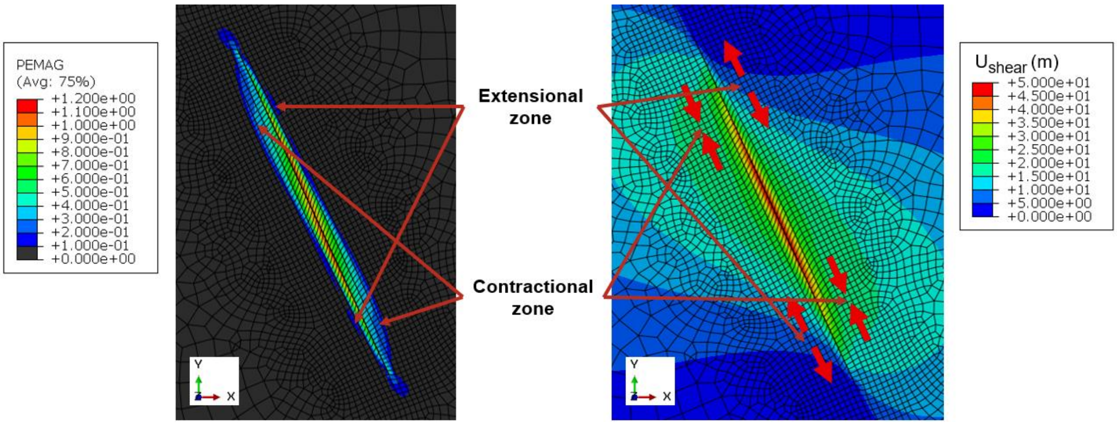


Figure 6. Results of PEMAG (left) and shear displacements (right) that occur in the damage zone, for a maximum displacement equal to 100 m.

To study the damage zone variation along the fault, we used several paths perpendicular to the fault plane. The results obtained at the end of the simulation are shown in Fig. 7. We can notice that the shape of the damage zone varies along the fault plane, with the maximum width occurring outside the central region. Thus, we can conclude that the width of the damage zone varies along the fault, and this variation may be related to the different deformation mechanisms triggered along the damage zone. Therefore, one of the causes for the dispersion of data obtained from observations on outcrops may be the location of the measurement since, in outcrops, observations are merely superficial, usually without knowledge of the fault's three-dimensional structure.

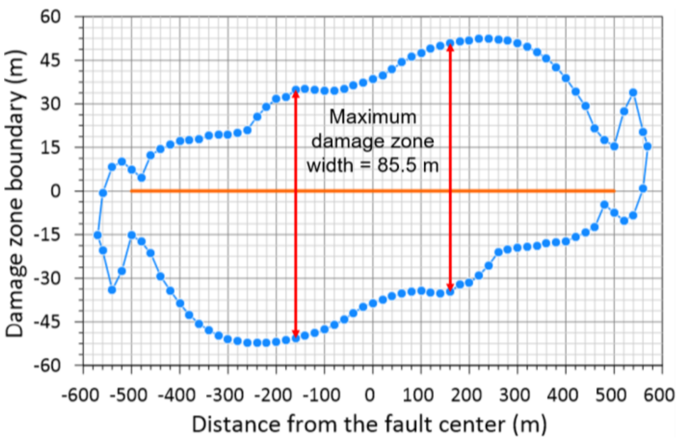


Figure 7. Damage zone boundary as a function of the distance to the fault center. The orange line represents the fault plan.

To better understand the deformation mechanisms that occur along the fault plane, we present the shear and volumetric deformation distribution in Fig. 8. Owing to the prescribed displacements, we can observe a predominance of shear deformations along the entire damage zone. The highest shear deformation values occur in the contractional zone, precisely where the damage zone is widest. These shear deformations may indicate the formation of fractures throughout the entire damage zone, predominantly in the contractional region. Concerning the volumetric deformations, we can notice that dilation deformations emerge in the central and extensional regions, where the shear deformations are the smaller. These results may also indicate an increase in porosity in these regions. Furthermore, it is possible to identify the appearance of compaction deformations in the contractional zone of the fault tips. This compaction may be the cause of the formation of the tip damage zone.

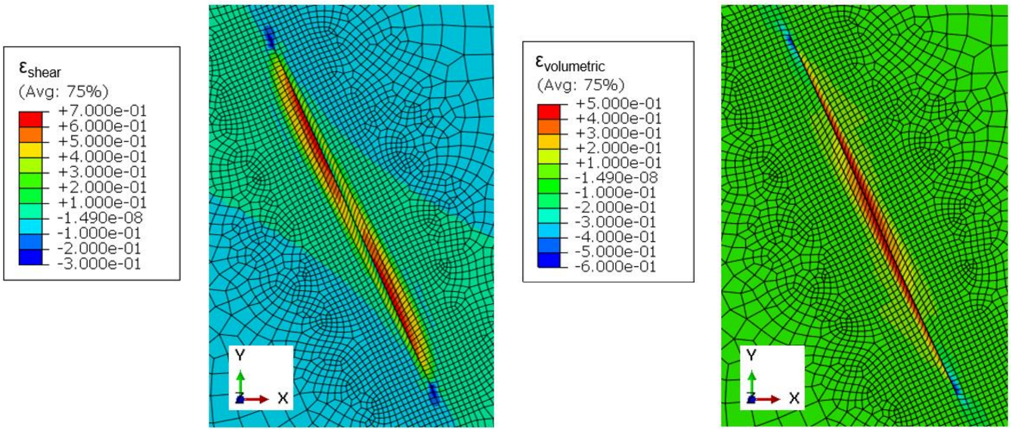


Figure 8. Shear strain (left) and volumetric strain (right) values for a maximum displacement equal to 100 m.

Finally, we obtain the hydrostatic stress distribution, as shown in Fig. 9. We can observe the predominance of hydrostatic compression stresses acting in the damage zone, with the highest values occurring in the contraction zone (Fig. 6B). These high values must be related to the high level of shear strain in this region, which may cause a wider damage zone. We can also identify the predominance of hydrostatic tensile stresses in the extensional zone of the fault tip, which may be related to the formation of mode I fractures in this region. Thus, the tip damage zone must have an asymmetrical shape, with a region of mainly compaction damage and another region with damage by traction.

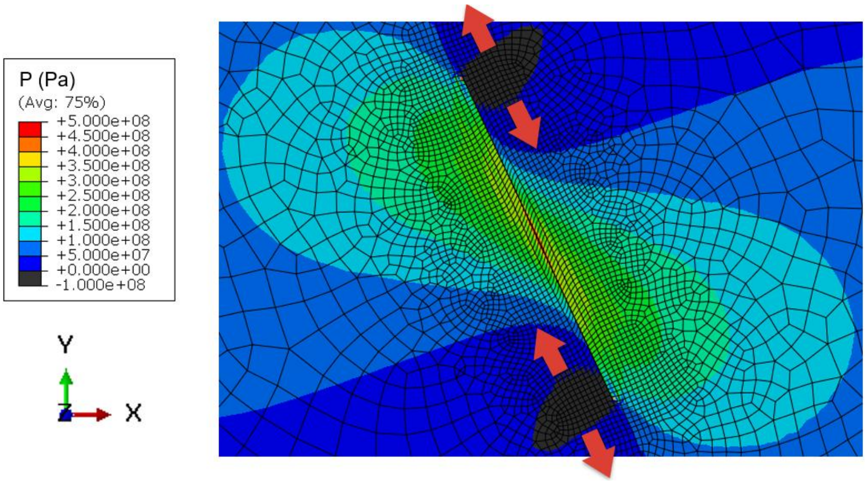


Figure 9. Hydrostatic stress values for a maximum displacement equal to 100 m.

4 Conclusions

In this study, we present a model to study the evolution of the damage zones of normal faults in carbonate rocks in the reservoir scale. The novelty in the proposed model is that the fault plane is included through two superimposed lines within a host rock that presents elastoplastic behavior. We assume that the damage zones correspond to the regions that presented plastic deformations.

The results showed that the damage zone of a normal fault has an antisymmetric shape along its height These results are expected since the applied displacement generates extensional and contractional zones in the zone adjacent to the fault. Thus, the shape of the damage zone reflects the existing extensional and contractional zones. From the defined model, we obtain the damage zone boundaries at different points along the fault plane. The results showed that the damage zone width could vary widely along the fault plane, with its maximum value occurring outside the central region. Thus, we conclude that the measurement location is a relevant factor in the process of obtaining the damage zone width.

The deformation mechanisms that occur along the fault plane were studied. We observed that most of the deformation that occurs in the damage zone is of a shear nature, which may indicate the formation of fractures, especially in the contractional zone. Furthermore, there are still volumetric deformations in the central and extensional zones, which may also indicate an increase in porosity in these regions. Finally, we conclude that the tip damage zone has an asymmetrical shape, with a region under compression (contractional zone) and another region with tensile damage (extensional zone).

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