Damage Model for Reservoir with Multisets of Natural Fractures and Its Application in Hydraulic Fracturing Simulation*

Xinpu Shen[1]

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[1]Halliburton, Houston, Texas (Xinpu.Shen@Halliburtioon.com)

Abstract

Description and Introduction: The continuum damage method is an effective measure for simulation of fracture development caused by stimulation injection. Natural fractures existing in reservoir formations have an important impact on stimulation-induced damage evolution (Carnes 1966; Parvizi et al. 2015; Potluri et al. 2005; Rodgerson 2000; Shahid et al. 2015. This work establishes a numerical procedure for the calibration of a damage model with measured information of natural fractures multisets. Image logging data is used. The synthetic value of the damage variable was derived with the work-equivalence principle for the modeling of natural fracture multisets. An example of the procedure illustration is presented.

Application: The proposed procedure was used to determine the initial value of scalar continuum damage variable of a tight sand reservoir with three sets of natural fractures, and it was further applied during a simulation of hydraulic fracturing of a zipper frac of two horizontal wells in a tight sand oil formation.

Results and Conclusions: Three sets of natural fractures were identified from image logging data of the given tight sand reservoir formation. There is a value of damage variables for each set of natural fractures. The synthetic value of damage variables was derived; they represent effects of these three sets of natural fractures. Numerical results of the 3D-coupled hydro-mechanical finite element simulation on the zipper frac are presented, which include:
(1) contour of initial damage field,
(2) total damage distribution between two injection stages after stimulation,
(3) distribution of pore pressure and maximum principal strain components,
(4) comparison of damage distribution and stimulated formation volume for two different injection measures.

Significance: This work provides a workflow for modeling reservoir hydraulic fracturing with multisets of natural fractures using the continuum damage method. Also, it shows that the coupled hydro-mechanical finite element model is an effective tool for estimating stimulated volume in tight sand reservoirs.

Expression of Natural Fractures with Continuum Damage Variable

Geometrical information of a set of natural fractures is usually described by its volumetric density, azimuth angle, and inclination angle. Furthermore, its properties related to porous flow can be described by aperture, permeability, and porosity.

Value of continuum damage variable ω is determined by the value of volumetric density of the natural fractures ψ. Because there are various versions for definition of natural fractures' density (such as number/foot or area/volume), and therefore, the unit of ψ is not the same for each version; there is no direct relationship between ω and ψ. However, there is functional relationship between ω and ψ, and it is defined in general as a function f(ψ) in Equation (1):

$$\omega=f(\psi) \quad (1)$$

Direction of a set of natural fractures can be described by a unit vector. This vector has three directional components (*l*, *m*, *n*), and can be directly used as the direction of the continuum damage variable. Therefore, there is the following definition of damage vector in terms of vector of coordinate basis (i,,) in Equation (2):

$$\boldsymbol{\omega}=\omega \text{ , where } \mathbf{n}=l\mathbf{i}+m\mathbf{j}+n\mathbf{k} \quad (2)$$

In practice, these directional components (*l*,*m*,*n*) can be calculated in terms of the values of azimuth angle, inclination angle, and x-direction of the coordinate system adopted in a calculation. Figure 1 shows the spatial relationship between these angles and direction components of the vector, which represents the natural fractures set. In Figure 1, α is the azimuth angle, β is the inclination angle, and the x-direction of the coordinate system is taken in the north direction.

These relationships are expressed mathematically in Equation (3):

$$\begin{cases} l=\sin\beta\cos\alpha \\ m=-\sin\beta\sin\alpha \\ n=\cos\beta \end{cases} \quad (3)$$

For the case when there are multiple sets of natural fractures, the synthetic damage vector $\boldsymbol{\omega_T}$ equals the summation of the damage vectors for each one single natural fracture:

$$\boldsymbol{\omega_T}=\omega_1\mathbf{n_1}+\omega_2\mathbf{n_2}+\cdots\omega_N\mathbf{n_N} \quad (4)$$

Rewrite Equation (4) in the form of component, it is:

$$\omega_{Tj} = \sum_{i=1}^{N} \omega_i n_j \quad (5)$$

where N is the number of sets of natural fractures, subscript i varies from 1 to N, and subscript j varies from 1 to 3.

Validation Example

The proposed procedure was used to determine the initial value of continuum damage variable of a tight sand reservoir with three sets of natural fractures. Also, it was further applied during a simulation of hydraulic fracturing of a zipper frac of two horizontal wells in a tight sand oil formation.

Three sets of natural fractures were identified from image logging data of the tight sand reservoir formation as shown in Figure 2. There are a total of three sets of natural fractures.

Table 1 provides information on these sets of natural fractures.

The values of damage variable for these three sets of natural fractures are given as:

$$\omega_1=0.015,\ \omega_2=0.03,\ \omega_3=0.01 \quad (6)$$

The values of damage given in Equation (6) are taken by empirical method. These values will be calibrated later with phenomena match by using observed microseismic data related to hydraulic fracturing.

With reference to Equations (2) through (6), the synthetic damage vector for these three sets of natural fracture has the following value:

$$\omega_T=0.0372,\ \alpha_T=287.92^o,\ \beta_T=58.76^o,\ \gamma=0 \quad (7)$$

$$l_T=0.8136,\ m_T=0.2631,\ n_T=0.5186 \quad (8)$$

These values are used as initial damage and are shown in Figure 3.

Figure 4 shows the location of the zipper frac. Figure 5 shows the plain view of the zipper wells. Figure 6 shows the damage contour generated by hydraulic fracturing with the initial damage field shown in Figure 3.

This calculation simulates fracture generation under a bottomhole pressure (BHP) of 5730 psi, along with the following conditions:

- Initial reservoir pore pressure is 3000 psi, corresponding to true vertical depth (TVD) = 1700 m.
- Boundary conditions are taken from the numerical results of the global model described previously.

- Initial geostress values are taken from the numerical results of the global model described previously, which also corresponds to TVD = 1700 m.

Conclusions

There is a value of damage variables for each set of natural fractures. The synthetic value of damage variables was derived; they represent effects of these three sets of natural fractures. Numerical results of the 3D-coupled hydro-mechanical finite element simulation on the zipper frac are presented, which include the contour of initial damage field and total damage distribution between two injection stages after stimulation.

This work provides a workflow for modeling of hydraulic fracturing of reservoirs with multisets of natural fractures using the continuum damage method. Also, it shows the coupled hydro-mechanical finite element model as an effective tool for estimating stimulated volume in tight sand reservoirs.

In this work, the minimum horizontal stress direction is overlapped with the direction of the synthetic damage vector. In a general case, these directions can be different from each other. Impact of directions of principal stress and the one of synthetic damage vector on the effect of hydraulic fracturing will be investigated further in future works.

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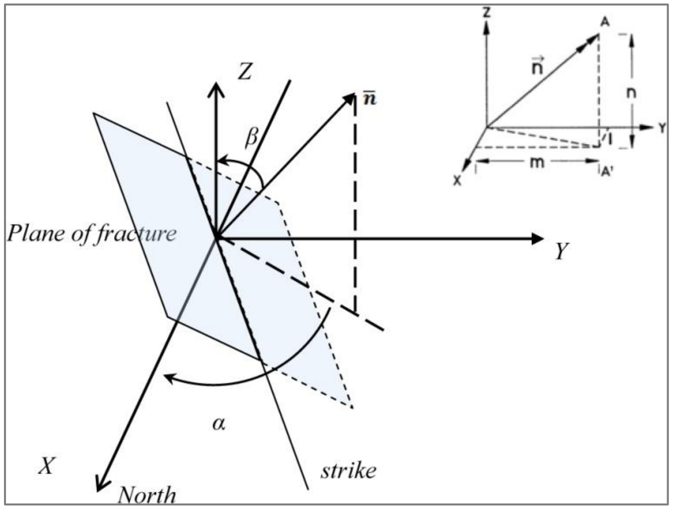

Figure 1. Illustration of the spatial relationship between these angles and direction components of the vector of natural fracture.

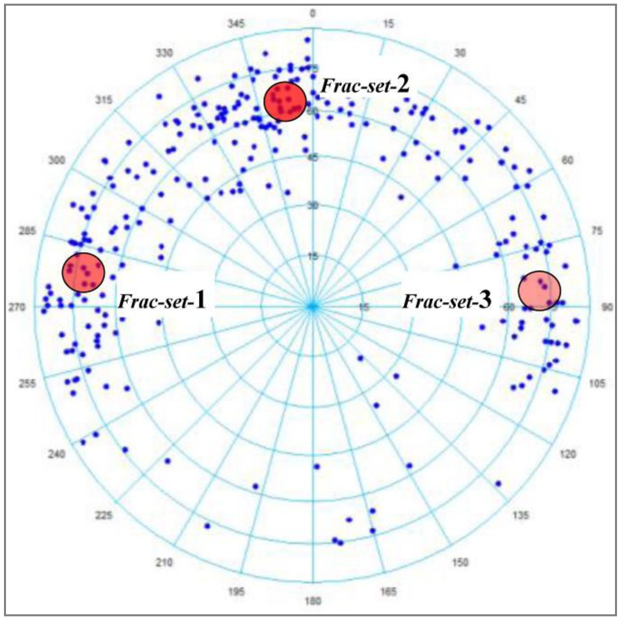

Figure 2. Illustration of the natural fractural information from logging data.

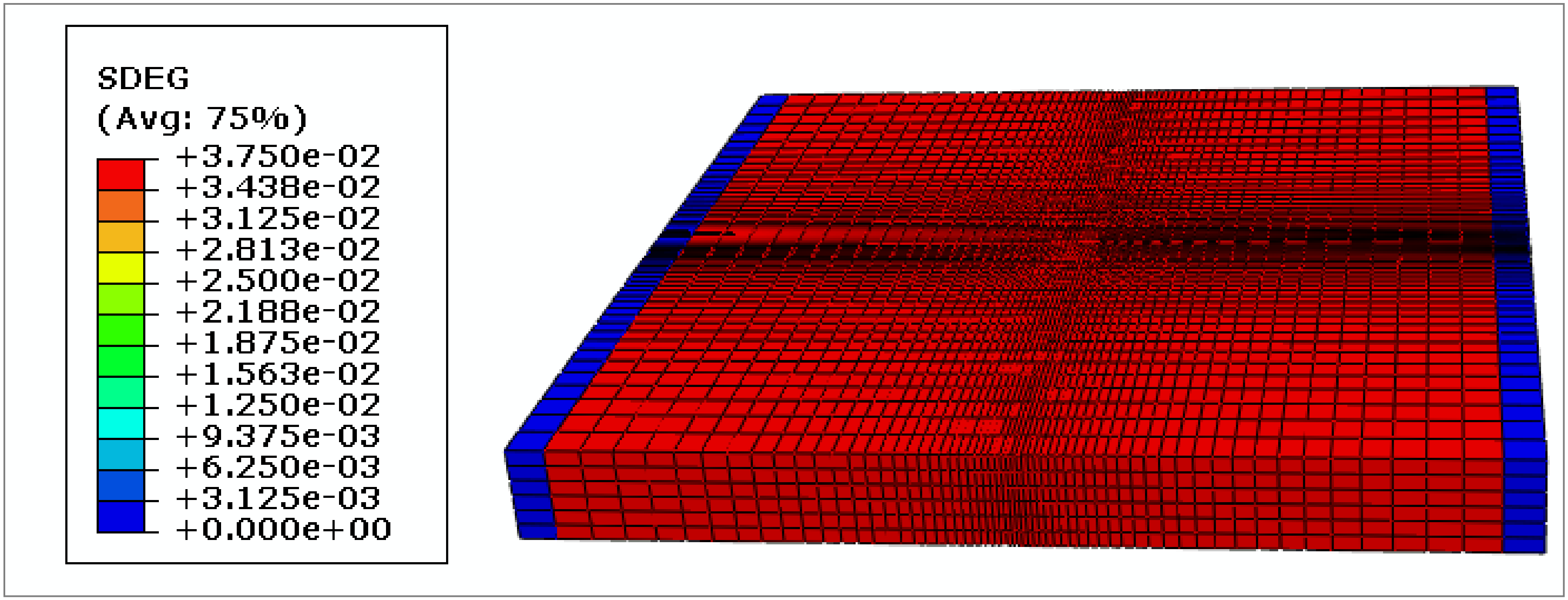

Figure 3. Contour of magnitude of initial damage SDEG0.

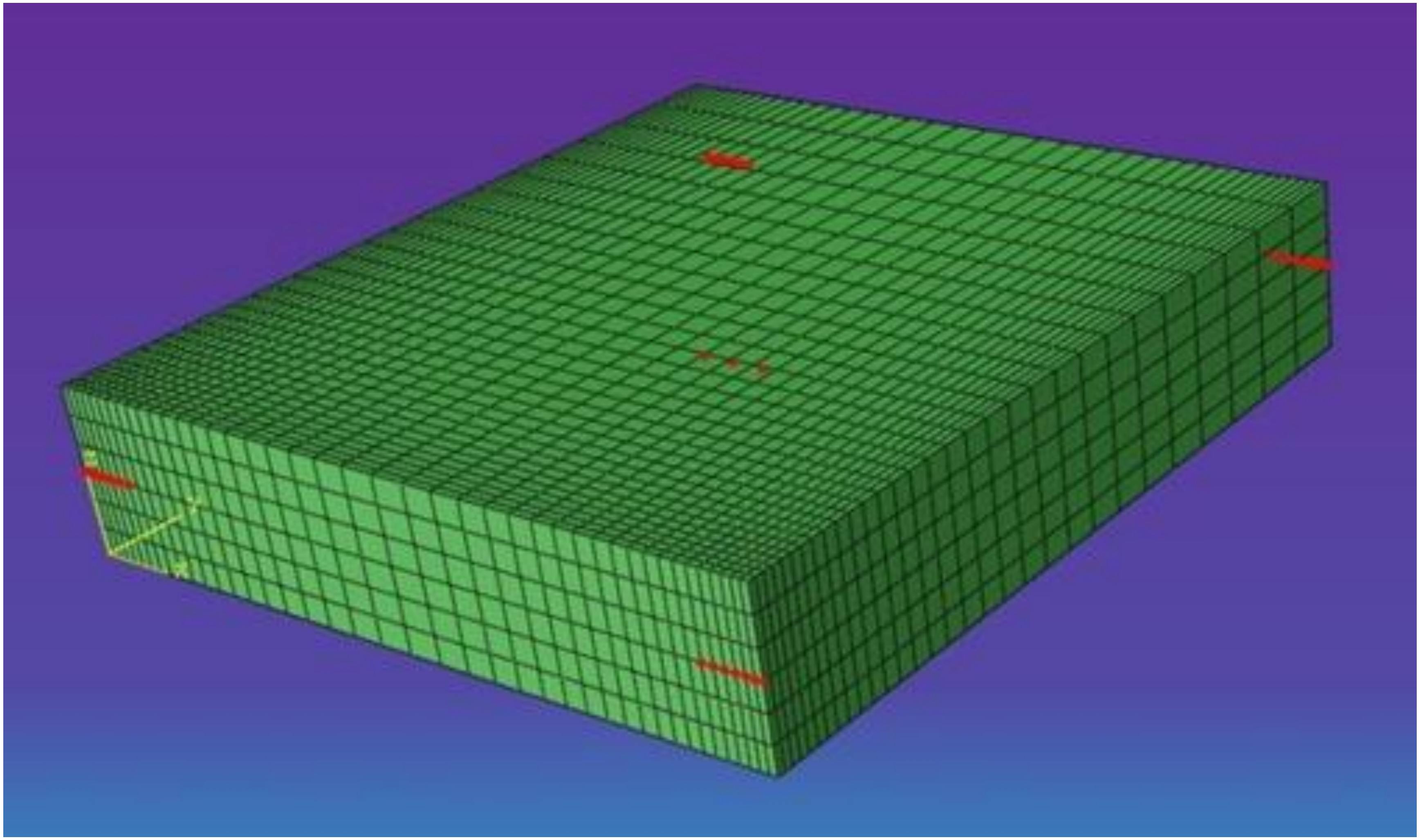

Figure 4. Mesh and geometry of the submodel.

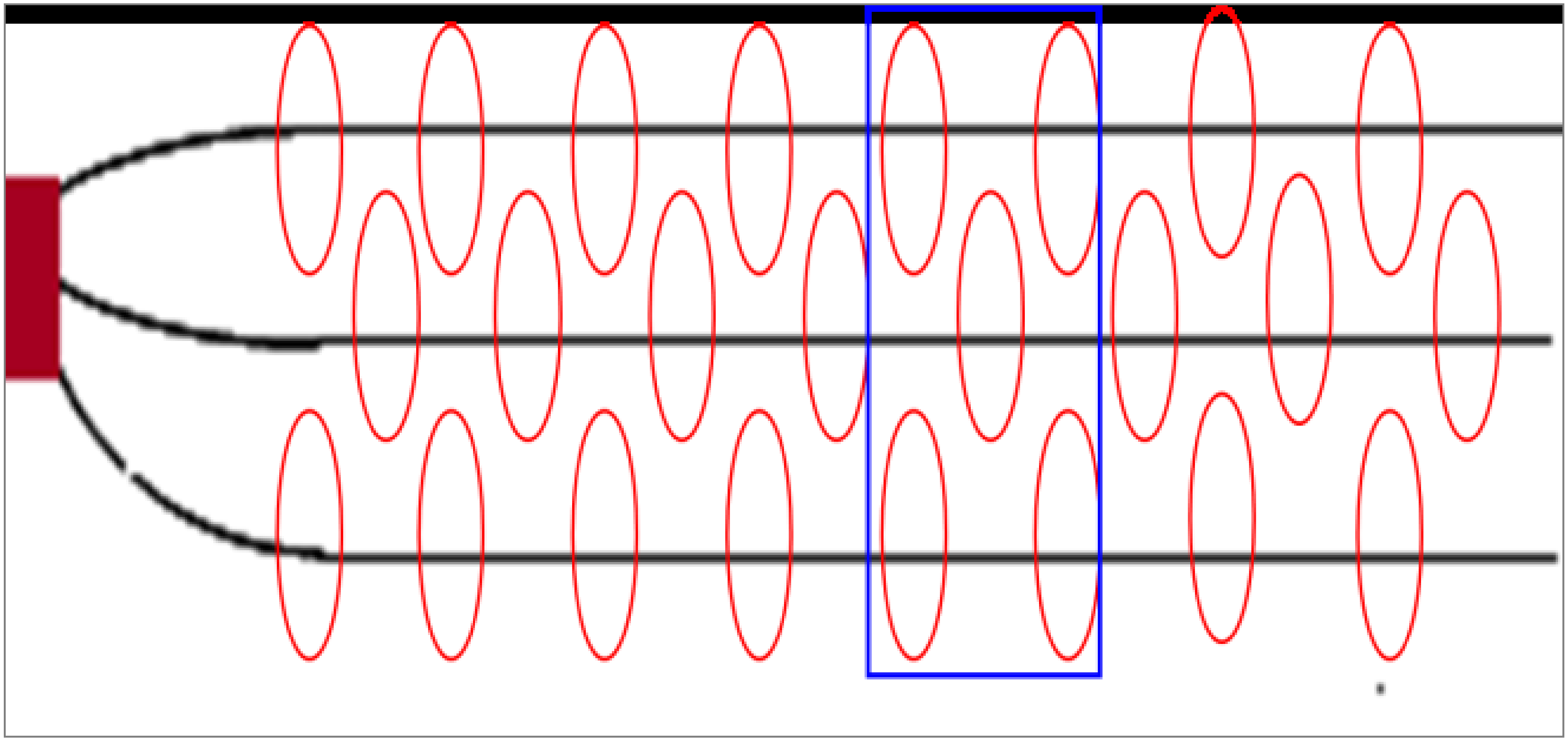

Figure 5. Illustration of the parallel well horizontal well sections designed for zipper frac.

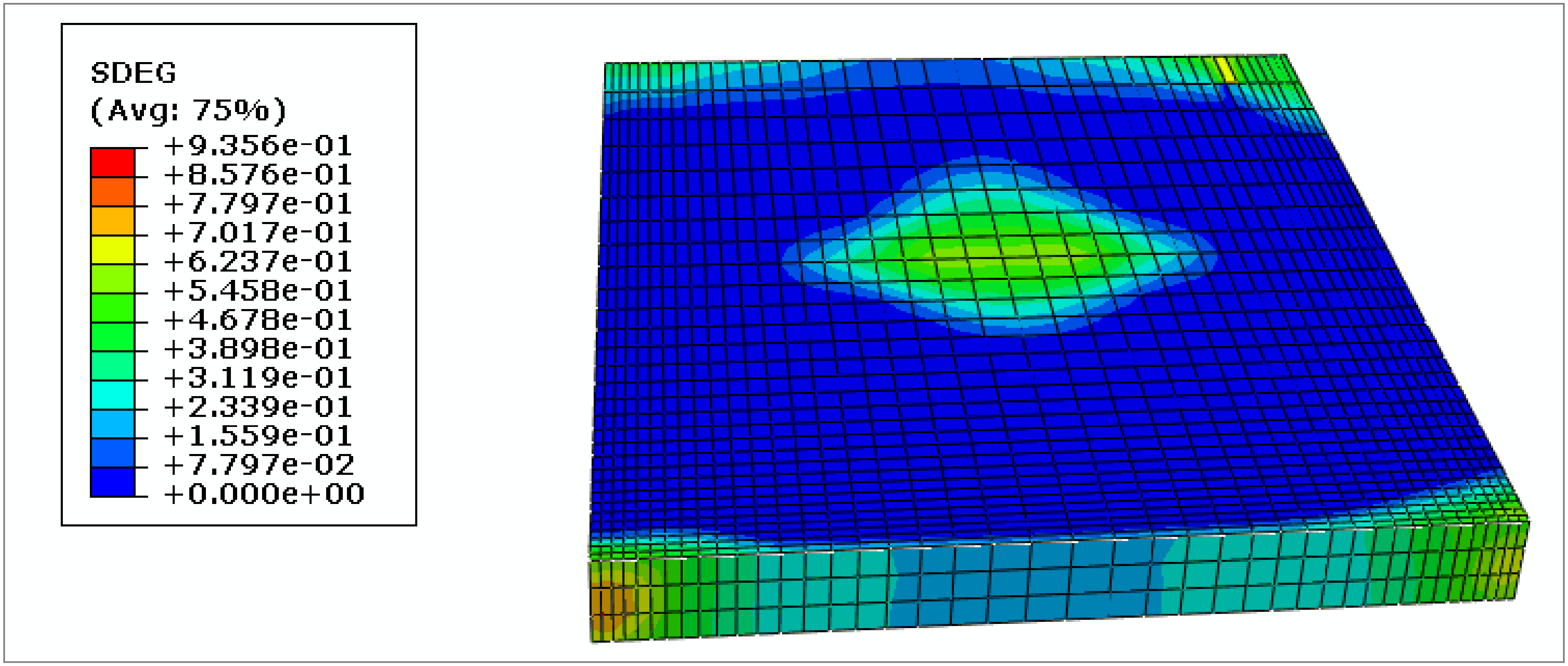

Figure 6. Contour of synthetic damage after fracturing.

	Azimuth Angle	Inclination Angle	Density (1/m)	Aperture (mm)
Frac Set 1	275	72	1	0.5
Frac Set 2	350	68	0.6	0.5
Frac Set 3	80	70	0.4	0.5

Table 1. Natural fractures' geometrical information.