En-echelon cracks can be divided into two types: left lateral shear and left step or right lateral shear and right step (LL), and left lateral shear and right step or right lateral shear and left step (LR). The conditions of interaction and stability of two en-echelon cracks are analyzed by using the linear elastic finite element method and theory of fracture mechanics. Then, the fracturing process and precursors of the main fracture in the staggered region of en-echelon cracks are studied by a series of rock experiments. It is found that the geometrical factors of en-echelon cracks influence the interaction and instability of faults and precursors of the main rupture.

1. Introduction

Faults often extend discontinuously or curvilinearly, where large earthquakes occur. The pattern of en-echelon faults is one of the very common types in such discontinuous sites. They consist of non-collinear parallel faults in stepping form and appear in the shear fault zone of different scales. En-echelon faults are characterized by left stepping or right stepping in the relative position of the fault segment as viewed along fault zone. The motion of faults is characterized by left lateral shear or a right lateral shear. Stepping patterns can be classified into two types LL and LR (Fig. 1(a)) depending on the state of stress, i.e., extensive and compressive, respectively, in a region between the two fault segments. A left lateral shear and left step or a right lateral shear and right step is denoted LL. A left lateral shear and right step or a right lateral shear and left step is denoted LR.

Seismicity, and formation and development of many basins are controlled by en-echelon faults. For example, the Brawley-Imperial fault system in the United States (Hill, 1977; Segall and Pollard, 1980) consists of two en-echelon fault segments. A right step on a right lateral shear fault (type LL) occurs near the town of Brawley, California. The Imperial fault extends from this point about 60 km to the southeast. From geophysical evidence, the Brawley fault is inferred to extend from this point about 30 km to the northeast. The right step between these two faults is about 6 km wide and the region between the faults shows topographic depression. The east boundary and west boundary of the depression are marked by normal fault scarps. The locations of the two largest earthquake swarms in June 1973 coincide with the geometrical structure. Another example is a system of Bohai-Zhangjiakou basins (Ma, 1982). It is a left lateral shear fault with a left
step (type LL). Between two fault segments, basins and depressions are formed. A series of strong earthquakes occurred in these sites. From a practical viewpoint, therefore, it may be worthwhile studying the problem of en-echelon cracks and faults in detail, such as the fracture developing pattern, the temporal and spatial distributions of earthquakes and precursors before the main shock. In addition, studying interaction between faults in a small scale is helpful to understand the mechanism of fault growth and failure processes.

For the sake of clear statement, two basic concepts are defined as follows:

1) Interaction: If stress field is induced by two cracks and these influence each other, we say that these two cracks are interacting. We imagine that when the distance between cracks is far enough, the interaction between cracks will be very weak and may be ignored. Therefore, we can discuss the effect of crack interaction by comparing the stress field induced by two or more cracks with that by an isolated crack. Strength of crack interaction is calculated by comparing stress components or other parameters between cases for two or more cracks and for an isolated crack.

2) Stability: In this paper we discuss two kinds of "stability": one is "loading stability," which is discussed by comparing stress concentration at the crack tip in the same loading level. The other is the "equilibrium stability." In this case let's consider a situation wherein a critical level of stresses required for crack propagation has been attained and that the system is in equilibrium. If the system can recover to the equilibrium state when a small perturbation is given, then we call that a stable state system. If the system cannot recover to the equilibrium state, then we call that an unstable state system.

There have been a number of studies on the problem of crack interaction, which may be summarized as follows: (1) The perturbation stress field due to crack interaction

Fig. 1. (a) The stepping patterns of a system of two en-echelon cracks, (b) the geometry of en-echelon cracks, and (c) the finite element meshes with 440 nodes and 535 elements.
The Instability of En-echelon Cracks

(ISIDA, 1970; YOKOBORI et al., 1971; RATWANI and GUPTA, 1974; CHANG, 1982; SEGALL and POLLARD, 1980), and the stress intensity factor; (2) the conditions of crack interaction (YOKOBORI et al., 1971; BOMBOLAKIS, 1964, 1968); (3) the stability of a system with interacting cracks (NEMAT-NASSER, 1978; NEMAT-NASSER et al., 1978, 1980); and (4) propagation of a crack interacting with other crack (NEMAT-NASSER et al., 1978, 1980; NEMAT-NASSER and HORII, 1982). However, a number of problems still remain unsolved, for instance, (1) effect of geometrical structure and the problem of compressive loading, (2) stability, particularly the equilibrium stability, (3) nonlinear problems, (4) microscopic mechanism for the stability of the system, (5) the relationship between crack interaction and brittle failure processes of geological material, and (6) the temporal sequence and spatial distribution of acoustic emissions in a rock sample with en-echelon cracks and other precursors of the main fracture, such as crack displacement patterns, stress state, etc. Problems (1), (2), and (6) will be discussed in this paper.

2. Interaction and Stability of Two En-echelon Cracks

The stress distribution near en-echelon cracks is estimated by using linear elastic finite element for different geometry. The results will be shown below to provide a basic understanding for the crack interaction. The results will be also examined on the basis of fracture mechanics.

2.1 The stress field near two en-echelon cracks under biaxial compressive loading obtained from an analysis of linear elastic finite element

A plane strain problem is considered, and its geometry is shown in Fig. 1(b). The medium is assumed to be infinite, homogeneous, isotropic, and linear elastic. We denote by \( \sigma_1 \) the minimum compressive stress, by \( \sigma_2 \) the maximum compressive stress, and by \( d \) step width between crack segments. By \( s \) we denote separation (\( s > 0 \)) or overlap (\( s < 0 \)) distance between the two neighboring (inner) crack tips (Fig. 1(b)). Half crack length is denoted by \( L \). The angle between the direction of \( \sigma_2 \) and the direction of the crack is fixed to be 35°. The SAP5 program* was used. Figure 1(c) shows the finite element meshes. Because of the limited number of finite elements, the solution may not be highly accurate near stress concentration points. However, it is sufficient for the following rather qualitative arguments.

2.1.1 The stress field near two en-echelon cracks

For plane strain problem, the strain energy density \( W \), stress intensity \( f_s \), maximum shear stress \( T_m \), and mean stress \( \sigma_m \) can be expressed as follows:

\[
W = \frac{1}{8G} (1 - 2v)(\sigma_1 + \sigma_2)^2 + (\sigma_1 - \sigma_2)^2
\]

\[
f_s = \sqrt{(1 - v + v^2)(\sigma_1^2 + \sigma_2^2) - (1 + 2v - 2v^2)\sigma_1 \sigma_2}
\]

\[
T_m = \frac{1}{2} (\sigma_1 - \sigma_2)
\]

* SAP5 is a finite element program for static and dynamic analysis.
\[ \sigma_m = \frac{1}{2} (1 + \nu) (\sigma_1 + \sigma_2) \]

where \( G \) is rigidity and \( \nu \) is Poisson's ratio. These quantities will be used as parameters of crack interaction.

Two types of stress distribution are produced by en-echelon cracks. For LL type, stress in the staggered region between the two cracks is in a tensile state, while for LR type, stress in the staggered area is in a compressive state. Figure 2 shows the distribution of strain energy density \( W \) near LL and LR type cracks for \( d = 0.1L \) and \( s = 0.1t \). It is shown from the figure that the strain energy density in the staggered region is comparatively low for LL en-echelon cracks and high for LR en-echelon cracks. We calculate the mean stress \( \sigma_m \), the maximum compressive stress \( \sigma_2 \), stress intensity \( f_\sigma \), the maximum shear stress \( T_m \), and the strain energy density \( W \) from the computed stress components in the three finite elements A, B, and C shown in Fig. 1(b), neighboring to the inner crack tip, and those in A', B', and C', neighboring to the outer crack tip. These values are compared with those for an isolated crack and their ratios are shown in Fig. 3 for different geometry of en-echelon cracks. They are shown as a function of \( s/L \) and \( d/L \). From Fig. 3, we conclude the

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**Fig. 2.** Distribution of strain energy for (a) left lateral shear and left stepping fault (type LL), (b) left lateral shear and right stepping fault (type LR). Contoured values are normalized by the far-field strain energy.
Fig. 3. (a) The ratio of stresses and strain energy density at the crack tip A for type LL en-echelon cracks \( (f_{ij}) \) to those near an isolated crack tip \( (f_{ij})_I \) as a function of \( s/L \) and \( d/L \) and (b) the strain energy densities at points A, A', B, B', C, and C' normalized by the strain energy density near an isolated crack as a function of \( s/L (d=0.1L) \). In (a) the ratios of mean stress \( \sigma_m \), maximum principal stress \( \sigma_2 \), stress intensity \( f_s \), maximum shear stress \( T_m \), and strain energy density \( W \) are shown by the lines 1, 2, 3, 4, and 5, respectively, shown at the bottom of the figure.

following:

1) The crack interaction is strongest when \( s \) is equal to zero, and the interaction becomes weaker either as \( s \) increases (\( s>0 \)) or decreases (\( s<0 \)). The crack interaction becomes stronger as \( d \) decreases (Fig. 3(a)).

2) For LL type, strain energy density \( W \) is higher near the outer crack tip (points A',
B', and C') than near the inner crack tip (points A, B, and C). When \( s \) equals zero, the strain energy density becomes smallest near the inner crack tip, and largest near the outer crack tip (Fig. 3(b)). However, for LR type, strain energy density is lower near the outer crack tip than near the inner crack tip, and it becomes highest near the inner crack tip and lowest near the outer crack tip when \( s \) equals zero (Fig. 3(b)).

2.1.2 The potential fracture of en-echelon cracks

The stress concentrations near en-echelon cracks may cause secondary fracturing. We attempt to estimate the distribution of potential fracture near en-echelon cracks on the basis of the conventional fracture criteria. The mechanism of the tensile fracture is different from that of the shear fracture, and accordingly the fracture criteria are different between the tensile and shear cracks. In fracture mechanics, several criteria have been suggested to predict the development of the tensile cracks, such as minimum strain-energy-density criterion (Sih, 1973), maximum tangential stress criterion (Erdo\-gan and Sih, 1963), and maximum energy-release-rate criterion (Palaniswamy, 1972). The minimum strain-energy-density criterion is most easily used among these criteria. Therefore, we apply minimum strain-energy-density criterion to predict the potential secondary tensile fracture. For shear fractures, the maximum shear stress theory is more convenient to predict fracturing. Figures 4(a) and (b) show the potential tensile fracture and shear fracture fields, respectively for both LL and LR modes. We take \( d \) equal to 0.1\( L \). The contour denotes the isoline with value of 1 for strain energy density in the case of the tensile cracks and for maximum shear stress in the case of shear cracks. Development of secondary tensile cracks is promoted in the staggered region for LL mode while secondary shear cracks develop in the staggered

Fig. 4. (a) The potential tensile fracture field for modes LL and LR \((d=0.1L\) and \(s=0)\), and (b) the potential shearing fracture field for modes LR and LL \((d=0.1L\) and \(s=0)\).
The Instability of En-echelon Cracks

region for LR mode. For LL mode, no secondary shear cracks develop between en-echelon cracks. For LR mode, no secondary tensile cracks develop in the staggered region, but secondary shear cracks develop.

2.2 Interaction and stability of two en-echelon cracks under pure shear loading

2.2.1 Interacting conditions and stability of two en-echelon cracks

In the previous section, we treat a problem of compressive loading. We will discuss a problem of pure shear loading in this section by using a series expansion of the stress intensity factor given by ISIDA (1970). We assume pure shear loading parallel to the direction of cracks at infinity $\sigma_{yy}$. Again a plane strain problem is considered. The interaction between the inner crack tips only will be discussed. When $s/L$ is smaller than $-1$, the stepping pattern changes from LR to LL or from LL to LR. Hence, we have $-1 < s/L < \infty$.

Let us consider first an effect of crack interaction on stress intensity factor at a crack tip. For the case of wide spacing, the stress intensity factors have been given by ISIDA (1970). By using his results, we calculate the ratio of $K_{2,A}$ to $K_i$ ($K_{2,A}$ denotes the shear mode stress intensity factor at the inner tip of a two-en-echelon-cracks system, and $K_i$ that at an isolated crack tip) as a function of $s/L$ and $d/L$ (Fig. 5). It is clearly shown from Fig. 5 that crack interaction is very strong when the distance between crack tips is small. When the ratio of $d$ to $L$ is greater than 2, there is almost no interaction. When the ratio of $d$ to $L$ is less than 0.5, strength of interaction increases obviously. On the other hand, when the ratio of $s$ to $L$ is greater than 2, there is, basically, no interaction. According to the results obtained from finite element analysis (Fig. 3), the strength of crack interaction is basically symmetric for $s > 0$ and $s < 0$. Therefore, crack interaction condition may be given by using

![Fig. 5. The ratio of the shear-mode stress intensity factor at the inner crack tip for two en-echelon cracks ($K_{2,A}$) to that at an isolated crack tip ($K_i$) as a function of $s/L$ and $d/L$.](image-url)
a combination of two parameters, $s/L$ and $d/L$ as follows:

1) Strongly interacting region: $D_S = \{ |s/L| < 0.5, \frac{d}{L} < 0.25 \}$
2) Weakly interacting region: $D_W = \{ -1 < s/L < 2, 0.25 \leq d/L < 2 \}$ or $\{ d/L < 2, 0.5 < |s/L| < 2 \} \text{ or } \{ -1 < s/L < -0.5 \}$
3) No interaction region: $D_N = \{ d/L \geq 2 \}$ or $\{ |s/L| \geq 2 \}$

Since the ratio $K_{2,A}/K_{2,B}$ becomes large when $|s/L| < 0.5$ and $d/L < 0.25$, a system of two en-echelon cracks in a strongly interacting region is in a more unstable state than a system of an isolated crack under the same loading level. Instability region may be expressed as follows:

$$D_{\text{instability}} = D_S = \{ |s/L| < 0.5, \frac{d}{L} < 0.25 \}$$

### 2.2.2 Stability and instability of a system of two en-echelon cracks in equilibrium state

The stress intensity factors at the inner and outer crack tips for the case of wide spacing have been given by Isida (1970) in the form of series. But the series is divergent when $\lambda = 2L/\sqrt{(s+2L)^2 + d^2}$ is greater than 1. Therefore, if $\lambda$ is greater than 1, we take $\varepsilon = 1/\lambda$ as the parameter of series expansion. The principle of continuity should be satisfied when $\lambda$ is equal to 1. Hence the stress intensity factor can be expressed as follows:

$$K_{2,A} = \begin{cases} \sigma/L \sum_{n=0}^{m} Q_n \lambda^n & \lambda < 1, \quad (s/L+2)^2 + (d/L)^2 > 4 \\ \sigma/L \sum_{n=0}^{m} Q_n' \varepsilon^n & \varepsilon = 1/\lambda < 1, \quad (s/L+2)^2 + (d/L)^2 < 4 \end{cases}$$

and

$$\sum_{n=0}^{m} Q_n = \sum_{n=0}^{m} Q_n' \quad \text{when} \quad \lambda = 1,$$

where $\sigma = \sigma_c - T_f$, $T_f$ is frictional resistance force on the crack surface, $Q_n, Q_n'$ ($n = 0, 1, \cdots, m$) are constants determined from the boundary conditions, and $m$ is the maximum term number of truncated series.

According to Nemati-Nasser et al. (1978, 1980), we consider total potential energy of the system and the first and second derivatives of the total potential energy of the system. We take the $x$-$y$ coordinate system as shown in Fig. 1(b). The equilibrium regime of the system of two en-echelon interacting cracks is:

$$K_{2,A} = K_c(s/2, d/2) \quad K_{2,B} = K_c(b, d/2) \quad K_{2,A'} = K_c(-s/2, -d/2) \quad K_{2,B'} = K_c(-b, -d/2)$$

where $K_{2,A}$ and $K_{2,B}$, respectively, indicate the shear mode stress intensity factors at the inner and outer tips of one of en-echelon cracks, and $K_{2,A'}$ and $K_{2,B'}$, those at the inner and outer tips of another crack, respectively, and $K_c(x, y)$, fracture toughness, and $b = 2L + s/2$.

(Please note that $L$ shows half crack-length.) Assuming that the crack propagates straight, we may obtain the criteria of stability expressed in terms of the geometrical factors $s$ and $d$:

(i) When $d$ is fixed, we have
The Instability of En-echelon Cracks

\[ > - \frac{\partial K_c(x, d/2)}{\partial x} \bigg|_{x=s/2} \] stable

\[ \frac{\partial K_{2,A}}{\partial s} = - \frac{\partial K_c(x, d/2)}{\partial x} \bigg|_{x=s/2} \] critical

\[ < - \frac{\partial K_c(x, d/2)}{\partial x} \bigg|_{x=s/2} \] unstable.

(ii) The effect of changing \( d \) on the stability of the system of two en-echelon cracks is equivalent to the effect of increasing the crack length on the stability of the system. Accordingly we have

\[ > - \frac{\partial K_c(s/2, y)}{\partial y} \bigg|_{y=d/2} \] stable

\[ \frac{\partial K_{2,A}}{\partial d} = - \frac{\partial K_c(s/2, y)}{\partial y} \bigg|_{y=d/2} \] critical

\[ < - \frac{\partial K_c(s/2, y)}{\partial y} \bigg|_{y=d/2} \] unstable.

For obtaining a qualitative insight into the stability of the system, we take the first two terms in Eq. (1) and apply relations (3) and (4) and obtain the following results:

1) For homogeneous, isotropic, elastic medium, we assume \( K_c(x, y) = \text{constant} \). Therefore, \( \partial K_c/\partial x = \partial K_c/\partial y = 0 \). If two en-echelon cracks are separated \( (s > 0) \), the system is

Fig. 6. Two assumed distributions of fracture toughness \( K_c(x, y) \). (a) Low \( K_c \) for cracks and high \( K_c \) in the staggered region and (b) \( K_c \) increases gradually from crack to the staggered region.
always in an unstable equilibrium state. When two en-echelon cracks are overlapped ($s < 0$), the matter may develop in two possible directions: the system will be unstable if $(s/L + 2)^2 + (d/L)^2 > 4$ and stable if $(s/L + 2)^2 + (d/L)^2 < 4$.

2) For heterogeneous elastic medium, the conditions of instability depend not only on the geometry of cracks, but also on the distribution of fracture toughness $K_c(x, y)$.

Case 1: We assume that the distribution of the fracture toughness $K_c(x, y)$ is as shown in Fig. 6(a). In this case, the medium between the two cracks is homogeneous. Therefore, from the results obtained above, the system will be stable if the inequality $(s/L + 2)^2 + (d/L)^2 < 4$ is satisfied.

Case 2: We assume that the distribution of $K_c(x, y)$ is as shown in Fig. 6(b). The negative slope is given by $k = (C_1 - C_0)/(s/2)$ ($C_1$ and $C_0$ are constants). When the inequality $(s/L + 2)^2 + (d/L)^2 > 4$ is satisfied, it is unstable. When $(s/L + 2)^2 + (d/L)^2 < 4$, the stability condition is:

$$2kL\sqrt{(s+2L)^2 + d^2} < \sigma_0 \sqrt{L(s+2L)Q_1'},$$

where $Q_1'$ is a positive constant shown in Eq. (1). It is shown that the smaller the slope $k$ is, the more stable the system is.

### 2.3 Interaction and stability of two en-echelon cracks under compressive loading

In fracture mechanics, a number of works have been done on the extension of an isolated crack under tensile loading (Goldstein and Salganik, 1974; Wu, 1978a, b; Lo, 1978; Cotterell and Rice, 1980; Hayashi and Nemat-Nasser, 1981a, b, c). Du and Ma (1987) studied the behavior of an isolated crack under compressive loading by introducing a parameter $\xi$ called the lateral tension coefficient, and gave an expression for the stress intensity factor at an isolated crack tip. $\xi$ is a material constant and it is related to Poisson's ratio (Du and Ma, 1987). Here we assume that an infinite homogeneous, isotropic, elastic solid plate with two en-echelon cracks, is subject to biaxial compressive loading at infinity. The far-field principal stresses $\sigma_1$ and $\sigma_2$ are given as $\sigma_1 = -\sigma$ ($\sigma > 0$) and $\sigma_2 = -t\sigma$ ($t > 1$), where $t$ is the loading factor. The angle between $\sigma_2$ and the direction of the crack is denoted by $\alpha$. The geometrical factors and the $x$-$y$ coordinate system are the same as above, and we also introduce $r$ and $\theta$, the polar coordinates (Fig. 1(b)). In the $x$-$y$ coordinate system, far-field normal stresses $\sigma_x$, $\sigma_y$ and shear stress $T_{xy}$ are given as:

$$\sigma_x = -\frac{1}{2} \sigma [(t+1) + (t-1) \cos(2\alpha)]$$

$$\sigma_y = -\frac{1}{2} \sigma [(t+1) - (t-1) \cos(2\alpha)]$$

$$T_{xy} = \frac{1}{2} \sigma (t-1) \sin(2\alpha).$$

On the basis of the results for an isolated crack under compressive loading and for two en-echelon cracks under pure shear loading, the stress intensity factors for mode I, $K_{1,A}$ and for mode II, $K_{2,A}$ under biaxial compressive loading are given as follows:
The Instability of En-echelon Cracks

\[ K_{1,A} = \begin{cases} \frac{1}{2} g_1(t, \xi, \alpha) \sigma \sqrt{L f_1^{(A)}(\lambda)} & \lambda < 1 \\ \frac{1}{2} g_1(t, \xi, \alpha) \sigma \sqrt{L f_1^{(A)}(1/\lambda)} & \lambda > 1 \end{cases} \] (6)

\[ K_{2,A} = \begin{cases} \frac{1}{2} g_2(t, \mu, \alpha) \sigma \sqrt{L f_2^{(A)}(\lambda)} & \lambda < 1 \\ \frac{1}{2} g_2(t, \mu, \alpha) \sigma \sqrt{L f_2^{(A)}(1/\lambda)} & \lambda > 1 \end{cases} \] (7)

where

\[ f_1^{(A)}(\lambda) = \sum_{n=0}^{m} P_n^{(A)} \lambda^n \quad f_1^{(A)}(1/\lambda) = \sum_{n=0}^{m} P_n^{(A)} (1/\lambda)^n \]

\[ f_2^{(A)}(\lambda) = \sum_{n=0}^{m} Q_n^{(A)} \lambda^n \quad f_2^{(A)}(1/\lambda) = \sum_{n=0}^{m} Q_n^{(A)} (1/\lambda)^n \]

\[ g_1(t, \xi, \alpha) = 2 \xi (t - 1) \cos(2\alpha) \]

\[ g_2(t, \mu, \alpha) = (t - 1)[\sin(2\alpha) + \mu \cos(2\alpha)] - \mu(t + 1) \]

\( \mu \) is the coefficient of friction; \( P_n, P_n^{(A)} (n = 0, 1, \ldots, m) \) are constants. Studying Eqs. (6) and (7), and comparing \( K_{1,A} \) and \( K_{2,A} \) with the stress intensity factor at an isolated crack tip, it is found that the loading conditions influence none of the interacting conditions, the loading instability, and equilibrium stability which are related to the geometrical factors \( s \) and \( d \). But the loading condition does influence the crack propagation.

For LL mode, the tensile cracks develop in the staggered region. Therefore, we apply the maximum tangential stress and minimum strain-energy-density criteria to predict the initial extension of the tensile crack. In the following we show the results obtained by applying the maximum tangential stress criterion. The initial extension angle \( \theta \) of the tensile crack may be determined by

\[ f_1(\lambda) g_1(t, \xi, \alpha) C_1(\theta) + f_2(\lambda) g_2(t, \mu, \alpha) C_2(\theta) = 0 \]
\[ f_2(\lambda) g_2(t, \mu, \alpha) C_3(\theta) - f_1(\lambda) g_1(t, \xi, \alpha) C_3(\theta) < 0 \] (9)

where

\[ C_1(\theta) = \sin \frac{\theta}{2} + \sin \frac{3}{2} \theta \]
\[ C_2(\theta) = \cos \frac{\theta}{2} + 3 \cos \frac{3}{2} \theta \] (10)
\[ C_3(\theta) = \sin \frac{\theta}{2} + 9 \sin \frac{3}{2} \theta . \]

From Eq. (9), we conclude that the initial extension angle (the angle between the directions of secondary tensile cracks and the original en-echelon cracks) is the function of not only \( t, \xi, \alpha, \) and \( \mu \), but also the geometrical factors \( s \) and \( d \). Some numerical results are given in
Fig. 7. The initial extension angle $\theta$ between the directions of secondary tensile cracks and original en-echelon cracks as a function of $s/L$ and $d/L$ for LL mode. (a) $\theta$ as a function of $d/L$ when $t=5$, $\xi=0.3$, $\mu=0$, and $s/L=0.1$, and (b) $\theta$ as a function of $s/L$ when $t=5$, $\xi=0.3$, $\mu=0$, and $d/L=0.05$.

Fig. 7. It is shown that the initial extension angle slightly increases with the increase of $d$ (Fig. 7(a)), and slightly decreases with the increase of $s$ (Fig. 7(b)).

3. Fracturing Process and Precursors of En-echelon Cracks

A series of rock experiments of en-echelon cracks with different geometries were designed to study the process of deformation and to examine the effect of geometrical factors. Gabbro samples were prepared in dimensions of $20 \times 18 \times 2$ cm$^3$, and 7-cm long and 0.12 cm-wide cracks were formed. The angle between the directions of crack and the axial loading is set to be $35^\circ$. The cracks were filled with gypsum for the sake of simulating the effect of fault gouge.

Figure 8 shows the pattern of propagating secondary cracks for some en-echelon crack models. The first row of Fig. 8 shows the patterns of LL en-echelon cracks. The value $d$ (step width between crack segments) is chosen to be 1.8 cm, and the values $s$ (separation distance between crack tips) are chosen to be $+1.8$, $0$, and $-1.8$ cm. These correspond to $d/L=0.51$ and $s/L=0.51$, $0$, $-0.51$. The second row shows the pattern of LR en-echelon cracks, where the same set of values for $d$ and $s$ are chosen. It is clearly shown that the pattern of propagating secondary cracks is controlled by the geometry of en-echelon cracks.

In order to investigate the process of fracturing in the staggered region and to find some precursors before the linking up of two en-echelon cracks, a detection system for acoustic emissions was prepared (Liu et al., 1986). Acoustic emission (AE) during fracturing was detected by four transducers each located at the four ends of the rock sample. The peak frequency of the transducers is 120 kHz. The received signals are amplified through preamplifier and main amplifier, and then supplied to two linear AE
locating units. The differences of arrival time between two transducers at the two opposite ends of the sample and the difference between other two transducers at the other two opposite ends are recorded by a digital printer. In addition, the energy of each AE event measured by a counter is also recorded by the printer. A new two-dimensional locating method called 'predemarcating and calibrating for acoustic emissions' was introduced (LIU, 1986). This method is applicable to the samples containing some complex structures. The positions of AE events are determined in this way and the isolines of event numbers are contoured in the fourth row of Fig. 9. The AE signals were also recorded by a 14-channel FM tape recorder with frequency range of 0-400 kHz. Accordingly, we could get the temporal sequence of AE events, which are shown in the fifth row of Fig. 9 as the logarithm of amplitude $\ln(A)$ versus time $t$ plot. Also, the ratio of the energy of the mainshock, $E_m$, to the energy of the foreshocks, $E_f$, is shown.

The displacement along the crack was measured by three strain gauges across the crack, whose positions are shown in the fourth row and fourth column of Fig. 9. The crack displacement during deformation is also shown in Fig. 9 by $D$ as a function of time $t$. Also, the orientation and magnitude of $\sigma_1$ and $\sigma_2$ in the staggered area were measured during the experiments and are shown in the seventh and eighth rows of Fig. 9.

Results shown in Fig. 9 are typical of the experiments. The main differences between modes LL and LR can be summarized as follows:

1) For mode LL the foreshocks swarm in the staggered area where the main fracture will take place, and migrate gradually toward the epicenter of the main fracture. On the contrary, the foreshocks for mode LR occur around the staggered area without migration toward the epicenter of the main fracture, and an AE gap is delineated in the center of the staggered area.

2) For mode LL, the foreshocks occur frequently and their magnitudes are large. The energy of the main fracture is about 10 times as large as the total energy of the foreshocks. For mode LR, the foreshocks are rare and the energy of the main fracture is about 100 times as large as the total energy of the foreshocks. The energy of the main
fracture for mode LR is one order of magnitude greater than that for mode LL.

3) The crack displacement of mode LL accelerated gradually and the acceleration becomes much larger just before the main rupture. Near the crack tip in the staggered region the acceleration is the largest. On the other hand the crack displacement rate for mode LR is almost constant in the whole process.

4) High tensile and weak shear stresses are induced in the staggered area for mode LL. As a result of microcracking, the axis of the principal stress rotates about $45^\circ$-$90^\circ$ in the staggered area just before the main rupture. At the same time, the value of the tensile stress decreases. On the contrary, high compressive and shear stresses are produced in the staggered area for mode LR. The principal stress axis does not change before the main shock, but the compressive stress increases violently.

The results mentioned above show that the sequence of the AE activity and the possible precursors are different owing to the difference in the direction of shearing relative to stepping, and the geometrical parameters $s$ and $d$ of en-echelon cracks.

Fig. 9. The difference of modes LL and LR during a precursory process prior to the main rupture.
4. Application

4.1 The geometrical configuration of the Xian-Shui-He fracture zone

According to the recent study of the Xian-Shui-He fracture zone, this left-lateral shear fracture zone is found to consist of several segments (Fig. 10(a)). Seismicity is obviously different in different segments. In the Dao-Fu region there exists strong seismicity. Several moderate and large earthquakes have occurred there. In the Qian-Ning region, we observe weak seismicity, and no large earthquake has ever occurred. Qian-Ning basin is formed in the region of potential tensile fracture shown in Fig. 4(a). Also, in the Ta-Gong region, no large earthquake has occurred, but small earthquakes in this region occur more frequently than those in the Dao-Fu and Qian-Ning regions. In the Dao-Fu region, faults are right stepping and the stepping pattern belongs to type LR. The fault geometries, i.e., $s/L = 0.4$ and $d/L = 0.04$ satisfy the condition for the strong interaction. Thus the faults are in an unstable equilibrium state. In the Qian-Ning region, faults also are right stepping and of type LR. The geometries $s/L = 0.23$ and $d/L = 0.18$ satisfy the condition for the strong interaction. Thus the faults are also in an unstable equilibrium state. In the Ta-Gong region, faults are left stepping (type LL) and overlapping. The geometries $-s/L = 0.46$ and $d/L = 0.14$ satisfy the inequality $(s/L + 2)^2 + (d/L)^2 < 4$. Hence the Ta-Gong region belongs

Fig. 10. (a) The geometrical configuration of the Xian-Shui-He fracture zone, (b) the surface deformation associated with an earthquake rupture at Lao Shankou in the Koukoutouhai-Ertai fault zone. (1, depression; 2, epicenters; 3, normal fault scraps; 4, zone of uplift; 5, strike-slip fault; 6, cracked zone.)
to the strong interaction region and is in a stable equilibrium state.

4.2 The fracture field of an earthquake in the Koukoutouhai-Ertai fault zone in Xinjiang Province

Figure 10(b) shows the surface deformations associated with an earthquake rupture at Lao Shankou in the Koukoutouhai-Ertai fault zone. Both the right and left stepping occurred on the right lateral shear fault. A close examination reveals that each fault segment also consists of a series of right lateral shear and left step en-echelon faults with $d$ of generally about 1 m and with $s$ of about zero. Tensile cracks extend out of the fault strike, but terminate rapidly.

In the staggered region of the type-LR stepping faults, the stress state appears to be compressive and zones of uplift appeared. The long axis of the uplifted zones is N40°E. The angle between the direction of the zones and the main faults (trending N20°W) is 60°. This is a result of non-brittle deformation. A shear fault or compressive thrust fault would be formed if brittle deformation occurred. In the region between the type-LL stepping faults, nearly parallel tensile cracks and depressions appeared. The angle between the directions of the tensile cracks and the main en-echelon faults is found to be 60°–70°. The initial extension angle $\theta$, predicted from the angle $\alpha$, between the directions of regional compressive principal stress (about N20°E) and main en-echelon faults (N20°W) is 65°–71° (see Fig. 7). The calculation agrees with the observed result.

Summing up the above mentioned results, we may conclude that the geometrical factors of en-echelon cracks influence the interaction and stability of faults and the nature of precursors of the main rupture. Therefore, the fracture zone may have different behavior due to different fault geometry. For a better understanding of faulting and seismicity, it is very important to study fault geometry in the field and to accurately map the fault geometry in detail.

REFERENCES


