3. Rheological heterogeneities, crack arrest and healing phenomena

3.1. Introduction to Chapter 3

The configurations chosen in the previous Chapter refer to a non confined rupture, in the sense that the crack develops without limit. This is an idealization, because in this way there would be an infinite total seismic moment, as the fractured area is unbounded. What is more, we have shown in previous Chapter that the cohesive zone shrinks as the rupture enlarges, but because the characteristic distance have to be constant, the peak slip velocity have to increase (see Appendix A). Such a shrinking have two consequences: the first one is that, in order to resolve the cohesive zone (in terms of breakdown zone time and breakdown zone size) we would have an arbitrary small temporal and spatial discretizations (see Appendix C). The second consequence is that the peak slip velocity would be also unbounded.

In this Chapter we will show numerical simulations with a more physical situation, in which the crack is arrested. This is accomplished by introducing frictional heterogeneities in the spatial distributions of the constitutive parameters, both of the slip – weakening law and of the rate – and state – dependent friction laws (see Chapter 1 for an intensive review).

We will also show different type of healing phenomena, arising from a crack arrest and from a particular choice of the constitutive models. The topics of this Chapter are an essential improvement of the frictional model analyzed in the past two decades and demonstrate that and how frictional models can be used to model real – world events. We will show in Chapter 4 a fully 3 – D, heterogeneous multi – faults model, that can be regarded as the end of such a generalization.

3.2. The crack model and the arrest models

3.2.1. The barrier – healing

Both the BIE and the FD numerical procedures described in Chapter 2 have been implemented to use spatial heterogeneous distributions of the constitutive parameters for a slip – weakening law (prestress t_0, upper yield stress t_u, kinetic frictinal level t_f and characteristic distance d_0). The use of homogeneous distribution of constitutive parameters implies a constant fracture energy G that does not allow to completely model the spontaneous rupture growth (Andrews, 1985). In this section we will compare the two methods by discussing the results of several simulations of a crack propagation obeying to a SW law for a line source having spatially variable distribution of dynamic parameters.

The first heterogeneous model consists of a barrier (low prestress and high yield stress on finite extended patch) located in the middle of the fault (see Figure 3.1): t_0 and t_u are equal to 1 and 1.8 everywhere except that in the region $13 \le x_1 \le 17.2$, where they are 0.1 and 11, respectively. The kinetic level

t_f and the characteristic length d_0 are uniform and fixed as 0 and 2.094, respectively. In Figure 3.1 we show the spatio – temporal evolution of the slip velocity obtained by the two numerical approaches. It is evident the abrupt arrest of crack propagation, when the rupture front reaches the barrier caused by the high strength value ($S = 109$) in this region. This simulation allows us to model the rupture arrest. The two methods provide similar results, although the FD is slightly more noisy. Both the solutions point out an healing front back - propagating from the barrier. Although both the methods provide similar results, we point out that the BIE solution is more stable.

In a second simulation we have modeled the rupture propagation on a line source having a heterogeneous distribution of the frictional stress (t_f): the kinetic stress is 3 everywhere, except in the section $5.6 \le x_1 \le 12.2$, where it is null. The initial shear stress t_u and d_0 are 4, 4.8 and 1.309 everywhere along the entire fault line. Figure 3.2 shows the results of this simulation obtained with the two methods. It is evident the sharp increase of rupture velocity when the crack enters in the region with low strength (S): the crack speed jumps suddenly to the P - wave velocity in both the solutions. The spatio – temporal behavior of these solutions is quite similar and points out the same general features discussed above. The most striking difference between the two solutions concerns the traction behavior during the acceleration phase. The total traction suddenly decreases to the kinetic value in few time steps for the BIE solution, while the FD one still shows a more complex behavior that includes an initial acceleration at nearly constant traction before the subsequent traction decrease.

3.2.2. The self – healing

In the previous section we have discussed several simulations in order to compare the behaviors obtained with the BIE and the FD numerical methods by applying the SW governing equation with heterogeneous distribution of constitutive parameters. In particular, we have examined a model where the rupture is arrested by a barrier and a healing phase is back – propagating along the fractured zone (Figures 3.1 and 3.2). This behavior has been defined as barrier – healing.

In this section we aim to present some simulations calculated by using the FD method and heterogeneous spatial distributions of constitutive parameters for the Dieterich – Ruina (DR) law. In particular we discuss the inference on the rupture arrest resulting from using rate – and state – dependent constitutive laws emphasizing the effects of rupture heterogeneities.

One of the most important implications of barrier – healing models is that the slip duration is variable along the fault: this duration depends of the distance of the grid point from the barrier or the crack edge. The farther is the point larger slip durations are expected (an null duration at the crack edge). More recently, an alternative model has been proposed, which consists is a short and constant slip duration during the rupture growth, that has been called self – healing (Heaton, 1990). While the barrier – healing is simulated by classical crack model (Day, 1982; Das and Kostrov, 1983), the theoretical modeling of the self – healing process requires the use of more complex constitutive formulations. Several authors have proposed that, if particular regularizations of the rate – and state – constitutive laws are assumed to eliminate the singularity in the governing equation at the stationary contact (the slip velocity is zero, see Perrin et al., 1995; Roy and Marone, 1996; Zheng and Rice, 1998), the self – healing process can be easily modeled (Ben–Zion and Andrews, 1998; Cochard and Madariaga, 1996). In this study we propose that, even using the Dieterich – Ruina law without any regularization but assuming heterogeneous distributions of constitutive parameters, different healing mechanisms can be simulated.

We present the modeling results of three different configurations: the first is a homogeneous distribution of constitutive parameters; in the second one we assume that only the parameter L of the DR law is heterogeneous along the fault, while in the third configuration both the parameters a and b changes along the fault line, while L remains constant. We show the results of these simulations in Figure 3.3 by plotting the slip as a function of crack position as a superposition of snapshots at different time steps and in Figure 3.4 by 3 – D plots of the spatio – temporal evolution of slip velocity.

The first configuration allows to simulate a classical enlarging crack where the rupture arrest in not modeled (Figure 3.3a) and slip grows continuously as the crack advance along the line. We use this only as a reference model, since it is not of interest in this section. Figure 3.4a clearly shows the evolution of slip velocity for a barrier – healing model: slip in each grid point grows until the arrival of the back – propagating healing front. This behavior is also clear in Figure 3.3b which shows the snapshots of slip as a function of crack position. The barrier has been simulated using a greater value of the L parameter outside the rupturing region. The self – healing mechanism has been obtained for the heterogeneous distribution of a and b parameters (Figures 3.3c and 3.4b): the area where the nucleation occurs is velocity weakening and it is surrounded by a velocity strengthening area. Because these figures clearly point out the differences between barrier – healing and a self – healing models: in the latter the slip duration is nearly constant. To emphasize this result, we plot in Figure 3.5 the slip velocity time histories in four different grid points where it is clear the constant slip duration.

In the latter model it is quite evident that the rupture heals before that the rupture front, back – propagating from the velocity strengthening region, arrives at the specific grid point. We emphasize again that in this study we do not have introduced any analytical regularization of the constitutive relations to obtain both the barrier – healing and the self – healing. We have only assumed heterogeneous distributions of constitutive parameters.

3.3. The evolution law and the dynamic rupture growth

In the present section, we will use rate and state dependent constitutive laws to model the temporal evolution of slip velocity and dynamic traction during the propagation of a 2 - D in - plane crack. The goal is to understand the frictional control of slip weakening behavior and rupture healing. In the literature many different studies have discussed numerical simulations of dynamic slip on homogeneous faults showing either crack - like rupture mode or self-healing pulse propagation (Cochard and Madariaga, 1994, 1996; Perrin et al., 1995; Beeler and Tullis, 1996; Zheng and Rice, 1998). The healing of slip, leading to short slip durations or self-healing pulse propagation mode, has been related either to stress and/or strength (frictional) heterogeneity (see for instance Beroza and Mikumo, 1996, and Bizzarri et al., 2001). Self - healing ruptures have also been shown to appear in rupture propagation between dissimilar materials (Weertman 1980; Andrews and Ben-Zion, 1997; Cochard and Rice, 2000). In this study, we focus on the rupture propagation along homogeneous faults. In such a homogeneous configuration, healing mechanism and self - healing pulses are related to the friction law (Perrin et al., 1995; Cochard and Madariaga, 1996; Beeler and Tullis, 1996; Zheng and Rice, 1998). We review and discuss previous modeling results and interpret the physical mechanisms controlling the breakdown process and the slip acceleration in the framework of a rate and state constitutive formulation.

In the Chapter 2 we have discussed the results of several simulations performed for a 2 - D in - plane crack obeying to a rate and state dependent law and using a slowness evolution equation. We have demonstrated that SW occurs within the breakdown zone and that the critical slip weakening distance is larger than the characteristic length scale parameter of the RandS formulation. We have concluded that the state variable evolution controls the weakening process and the consequent slip acceleration. Therefore, it is likely to expect that the analytical relation used for the evolution law can affect the SW behavior and the absorbed fracture energy. To test this finding, we have compared the SW curves resulting from numerical simulations performed by using the same constitutive and initial parameters for a slowness and a slip evolution laws. Figure 2.14 shows this comparison: Our simulations clearly show that the slip weakening curves resulting from these two evolution laws are very different and that the equivalent slip weakening distance for a slip law is much lower than that obtained for a slowness law (Bizzarri and Cocco, 2003). This result corroborates the idea that the state variable controls the weakening process, and it suggests that the analytical relation (4), which was established for the slowness law, is not valid for the slip law. The kinetic friction is the same because the steady state friction value is the same for the two laws and the yield stress does not substantially change with the evolution law.

We have also shown in previous calculations that the state variable evolution controls the time evolution of slip and therefore it should control the healing of slip. Several authors in fact suggested that the evolution law controls the healing mechanisms and the duration of dynamic slip. Our numerical results show that the slip velocity peaks resulting for a slip law are much larger than those simulated for a slowness evolution law. This is consistent with the shorter critical slip weakening distance that in turns results in a faster fracture energy release (as evidenced by the larger weakening rate) and a smaller cohesive zone size. According to Perrin et al. (1995) and Zheng and Rice (1998) we find that a slip or a slowness law do not yield self-healing or short slip duration, but the resulting solutions are always consistent with a crack-like rupture mode. In particular, Perrin et al. (1995) showed that no steady traveling pulse can occur if the constitutive law does not allow for restrengthening in truly stationary contact ($v = 0$). Here we generalize the definition of self-healing pulses, also considering slip velocity time histories for which the residual velocity is very small although not necessarily zero after arrest. We have to remark that in a homogeneous fault self-healing pulses can be generated either by modifying the fault constitutive law or by imposing an impulsive mode during rupture initiation, which is self-maintained during the dynamic rupture propagation (see Nielsen and Madariaga, 2002). We did not consider in this study the effect of stress and/or strength heterogeneity nor the effect of rupture propagation along a material interface. Our nucleation strategy does not prescribe the slip velocity pulse, because it is spontaneously induced by the state variable (see Bizzarri et al., 2001 for further details). Figure 6 shows the slip velocity dependence on time and space and the associated phase diagram: slip velocity does not return to zero and rupture healing does not occur. We remark again that while the slowness or slip evolution laws quantitatively describe the rupture initiation and propagation (see Lapusta and Rice, 2002) as well as the long term restrengthening (see Rice, 1993; Boatwright and Cocco, 1996), they cannot generate a self-healing rupture propagation model.

3.4. The direct effect of friction

Beeler and Tullis (1996) have proposed two distinct strength functions that can yield fast restrengthening and self-healing following the Heaton (1990) suggestion that negative slip rate dependence can yield healing of slip. The first function is based on a sequential function characterized by a linear dependence on slip followed by a dependence on slip rate. Our simulations allow us to exclude this class of strength functions because we have shown that slip- and velocity- weakening occur simultaneously and not sequentially. The second function proposed by Beeler and Tullis (1996) is based on the rate and state dependent formulation, quite similar to that described by equation (1). They proposed a governing equation where the dependence on slip rate is eliminated by assuming a constant term for the direct effect of friction, which is included in the reference friction value (τ_{kf}):

$$\begin{aligned} \tau &= \tau_{kf} + b\sigma_n \ln\Theta \\ \frac{d\Theta}{dt} &= \frac{1}{L}\left[\left(V + V_{BT}\right) - \Theta V\right] \end{aligned} \qquad (3.1)$$

where V_{BT} is an arbitrary slip velocity value. In this formulation, the state variable is adimensional. Following Beeler and Tullis (1996), we investigate in this study the role played by the direct effect of friction and the friction behavior at high slip rates by using a slowness evolution law.

Figure 3.6 shows the time histories of slip, slip velocity, dynamic traction and state variable (a) and the spatio-temporal evolution of slip velocity (b) for two simulations having different values of the parameter a (0.009 and 0.0115, respectively) and leaving all the other parameters unchanged. This figure shows that the peak slip velocity increases when a decreases and the crack propagation is faster (in this case, the simulation with the smaller a even shows a crack bifurcation and a jump in rupture velocity). The traction drop is faster when the direct effect of friction is reduced (small a). This result is physically reasonable and both simulations show a crack-like rupture propagation mode. We point out that we were unable to generate self-healing using a slowness constitutive law also reducing the contribution of the direct effect of friction by changing the value adopted for the parameter a. We have also studied the effect of different velocity cutoff in the governing equation at high slip rates, depicted for the steady state friction in panel (a) of Figure 3.7. We consider a governing equation (1) in which friction depends on slip rate when $V \ll V_{cut}$, while for $V \gg V_{cut}$ the direct term is frozen and taken constant. In this case, friction still depends on slip velocity through the evolution equation and the state variable. We show in Figure 3.7 the results of two simulations performed with two different values of the slip velocity cutoff (V_{cut}). The former calculations (shown in the left panels in Figure 3.7) have a cutoff very close to the initial velocity (therefore, the direct effect of friction is constant and independent of slip rate during most of the simulation). The latter (right panels in Figure 3.7) have a higher slip rate cutoff, so that the direct effect of friction is frozen only when $V>10^{-2}$ m/s. This figure shows that the direct effect of friction modifies the phase diagram reducing the velocity-hardening phase. In this case, the peak slip velocity occurs at the end of the weakening phase, when traction reaches the kinetic stress level and slip is equal to the critical distance (points C and D are now nearly coincident). When the velocity dependence of the direct effect of friction is eliminated, the phase diagrams display a nearly linear decay. On the contrary, if the slip rate controls the direct effect, the phase diagram is more elliptic and the velocity-hardening phase is more pronounced. We conclude however that in both cases we were unable to simulate self-healing pulse mode with a slowness evolution law.

It is important to point out that modifying the friction behavior at high slip rates affects the weakening processes within the cohesive zone. We show in Figure 3.8 the slip weakening curves resulting from the simulations performed with different velocity cutoff and we compare them with the reference model.

This figure emphasizes that the direct effect of friction and the friction behavior at high slip rates largely control the kinetic stress level and the yield stress, while the weakening rate is only slightly modified.

3.5. The evolution law and the healing mechanisms

We have discussed in the previous sections how the evolution law controls the dynamic rupture growth and the slip weakening behavior within the cohesive zone. We have also remarked that different modifications of the evolution law have been proposed to generate a self-healing or impulsive slip propagation mode. These attempts confirm our finding that the evolution law, peculiar of the rate and state formulation, play a dominant role in controlling the breakdown process and the temporal and spatial evolution of dynamic traction and slip velocity. The motivation to modify the evolution law for modeling short slip duration or self-healing consists in the impossibility to have such behaviors using slowness or slip constitutive laws (defined in equations 1 and 2).

In this section, we present and discuss several simulations performed by using two other constitutive laws, which have been modified to have a fast restrengthening leading to the healing of slip. We start with the constitutive law proposed by Perrin et al. (1995) who suggested to modify the rate and state dependent laws used above to allow rapid restrengthening in truly stationary contact. These authors correctly emphasized that not all constitutive models allow for steady traveling wave pulses, and concluded that for the slowness and slip constitutive laws used above steady pulse solutions do not exist. We believe that the observational constraints for steady pulse or constant rise time during real earthquakes are quite weak. In this study we attempt to model short rise times (that is, a slip duration much shorter than rupture duration which is independent of fault position) that are not expected with a crack–like rupture propagation mode. Perrin et al. (1995) proposed the following constitutive law:

$$\tau = \left[\mu_* + a\ln\left(\frac{V+V_P}{V+V_*}\right) + b\ln\left(\frac{\Theta(V_* - V_P)}{L} + 1\right)\right]\sigma_n^{eff}$$
$$\frac{d\Theta}{dt} = 1 - \frac{\Theta(V+V_P)}{L} \tag{3.2}$$

where the velocity V_P represents a low velocity cut-off with no weakening at slip rates $V << V_P$ (see also Zheng and Rice, 1998). This version of the slowness evolution law allows for truly stationary contact (V = 0) and gives an upper limit to a contact time $\Theta \leq L/V_C$. Perrin et al. (1995) have shown that, using the constitutive law defined in (3.2), the spontaneous rupture propagation will occur either in the self-healing slip pulse mode (although not generally a steady pulse) or in the classical enlarging crack-like mode depending on the values of the adopted constitutive parameters. We show in Figure 3.9 the spatio-temporal evolution of slip velocity simulated using our 2-D algorithm, the constitutive law defined in (3.2), and our set of constitutive parameters listed in Table 3.1. This figure emphasizes that slip velocity becomes very small and healing of slip clearly occurs. Slip duration is short and it is not associated to a steady pulse traveling along the fault. Figure 11 shows the time histories of state variable, slip, slip velocity and total dynamic traction and it points out again that the state variable drives the evolution of dynamic traction and the slip acceleration. The time window used in Figure 3.10 is too small to show the total duration of slip, but this is required to compare the different time histories. However, the comparison between the time histories shown in this figure with those shown in Figure 3.6 reveals the rapid increase of dynamic traction immediately after the end of the weakening phase, which is due to the fast restrengthening causing the healing of slip. This is even more evident in Figure 3.11 where we have plotted the slip weakening curve and the phase diagram resulting from the constitutive law defined in (3.2). The dynamic traction shows an evident slip-hardening phase preceding the slip weakening (which is in general more pronounced than that obtained with the constitutive models previously discussed) and the kinetic friction level is maintained only for a short time because the rapid restrengthening causes the dynamic traction increase. The phase diagram is also peculiar since the dynamic system, after an evident velocity hardening and weakening phases, does not follow the steady state friction, which means that the state variable is not constant or at the steady state. The rapid restrengthening is so fast that during the time window of the dynamic propagation the rupture re-nucleates, or re-accelerates if the arrest is not actually completed (see Figure 3.10).

The constitutive law (3.2), proposed by Perrin et al. (1995), includes a modification of the slowness constitutive relation (1) motivated by the physical requirement to allow stationary contact. Many different modifications of the rate and state constitutive laws have been proposed in the literature to attempt to explain self-healing or other dynamic processes, but only few of them are based on physical requirements. Nielsen and Carlson (2000) proposed a state dependent friction law that incorporates rate weakening and a characteristic time for healing. In this study, we have used a constitutive law where the governing equation is the same as the one used in (1) but the evolution law is that proposed by Nielsen et al. (2000) and Nielsen and Carlson (2000). This constitutive model has the form:

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\dfrac{V_*}{V} + 1 \right) + b \ln\left(\dfrac{\Phi V_*}{L} + 1 \right) \right] \sigma_n^{eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t}\Phi = \dfrac{\gamma - \Phi}{t_{fh}} - \dfrac{\Phi V}{L} \end{cases} \tag{3.3}$$

where γ has the dimensions of seconds and is taken equal to 1 and t_{fh} is the characteristic time for healing. The constitutive model described in (3.3) is different from that used by Nielsen and Carlson (2000) because we used a lab-derived governing equation in which we assign appropriate values to the parameters *a* and *b*. Moreover, we performed simulations with a dimensional data set that we will discuss in the following.

We have performed several simulations using the constitutive model (3.3) with the same set of parameters used in previous figures (listed in Table 5.1) and changing the value of the characteristic time t_{fh}. Our simulations show that if the characteristic time is appropriately chosen the solutions show a slip-pulse propagation mode with a nearly constant rise time. Values of the characteristic time larger than 0.1 s yield temporal evolution of slip velocity and dynamic traction very similar to the reference model. The healing of slip occurs when t_{fh} becomes smaller than 5 10^{-3} s. Figure 3.12 shows the results of a simulation performed using the values of parameters listed in Table 5.1 and a value of the characteristic time for healing (t_{fh}) of 3.9 10^{-3} s: slip velocity behavior shows a nearly constant duration and its peak increases as the crack advances, accordingly to the interpretation of Bizzarri et al. (2001). Figure 3.13b shows a 3-D plot with the traction dependence on slip and slip velocity. This figure shows a phase diagram quite similar to those previously discussed and a rapid increase of dynamic traction (restrengthening) immediately following the slip weakening phase that generates the healing of slip. Figure 3.13 shows a comparison between the 3-D phase trajectories resulting from the constitutive models (3.2) and (3.3), which are very similar. The results of our simulations are summarized in Figure 3.14 where we plot the superposition of slip profiles calculated at different times for three different constitutive models. The top panel shows the slip behavior resulting from the classical slowness law defined in (1) and it reveals that no healing occurs and the rupture propagates in the enlarging crack-like mode. The other two panels show the slip behavior resulting from the Nielsen and Carlson (2000) and the Perrin et al. (1995) constitutive models defined in equations (3.3) and (3.2), respectively. These models show short slip durations resembling a self-healing propagation mode.

These results confirm that appropriate modifications of the evolution law can lead to self-healing slip propagation mode, but this requires the introduction of other characteristic parameters (a velocity cutoff in (3.2), or a characteristic time in (3.3)) that must be chosen without objective constraints. This implies that healing occurs with these constitutive laws only for particular set of the initial and constitutive parameters.

3.6. Discussion

We have demonstrated in this study that, in the framework of a rate and state formulation, appropriate modifications of the evolution law allow us to simulate spontaneous ruptures propagating as a slip velocity pulse with short rise times, thus including self-healing. These constitutive models are characterized by a rapid restrengthening occurring immediately after the end of the weakening stage. However, these constitutive laws have never been tested to simulate the whole seismic cycle or the quasi-static earthquake nucleation. Therefore, we point out that the modeling of self-healing rupture mode, which implies a fast restrengthening, might not be appropriate to simulate the fault behavior during the interseismic period or the quasi-static nucleation. This raises the question on the reliability of these analytical modifications of lab-derived constitutive laws to explain short slip durations, even when motivated by physical arguments. Certainly, the ambitious perspective of dynamic modeling investigations is the simulation of fault behavior during the entire seismic cycle. This requires us to describe the earthquake nucleation, the dynamic rupture propagation and arrest during individual earthquakes (accurately describing the breakdown processes and the healing of slip) and the long term restrengthening during the interseismic period, which yields to repeated dynamic failure episodes on the same fault. To this goal, it is important to look for a unified constitutive law describing most of these features. We have demonstrated that rate and state formulation is able to provide a reliable physical description of individual earthquake ruptures, and we have discussed in this paper some of these features, but it also allows the modeling of repeated dynamic failure episodes. However, it has to be kept in mind that different competing natural mechanisms contribute to the understanding of earthquake mechanics. Physical models are very useful to separate their effects. By adopting the rate and state dependent laws, we try to incorporate the dependence of the friction coefficient on time as well as on the properties and roughness of the fault surface. However, other factors such as thermal pressurization and pore fluid lubrication (see Brodsky and Kanamori, 2001; Andrews, 2003) can affect the effective normal stress, thus modifying the friction law ($\tau = \mu\sigma_n^{eff}$). Moreover, heterogeneities of constitutive parameters and complexities of fault geometry and earth structure should be considered in our modeling attempts. Short slip durations can be easily explained in terms of stress or strength heterogeneities (see Beroza and Mikumo, 1996; Bizzarri et al., 2001 among different others) or rupture propagation between dissimilar materials (Andrews and Ben Zion, 1997; Cochard and Rice, 2000). These phenomena might explain short slip durations without modifying the constitutive law. Lapusta and Rice (2002) propose a similar reasoning to explain the earthquake nucleation and the early seismic propagation as well as the scaling of nucleation patch dimension with the size of the impending earthquake. Although appropriate modification of the evolution law allows the modeling of self-healing ruptures and the propagation of slip velocity pulses, we believe that heterogeneities of constitutive parameters and fault complexities can explain short slip durations without modifying the constitutive model.

Despite the existing limitations to assemble and to describe all the competing processes affecting earthquake mechanics, efforts to propose a unified constitutive law are very important to achieve a reliable physical description of the dynamic rupture growth. We believe that rate and state formulation is a suitable tool to this purpose, although further investigations and laboratory experiments are needed to explain the friction behavior at high slip rates or to include the effects of normal stress variations in the constitutive model (see Linker and Dieterich, 1992). The goal of our study is well below these tasks. We aim to identify and model those mechanisms occurring in the cohesive zone, which are controlled by the constitutive law. According to our results, we can interpret the breakdown process in terms of the roughness and the properties of the contact surface, which evolves during sliding. Thus, in this context, we extend the physical interpretation of the state variable evolution, proposed to describe the nucleation and the long term restrengthening, to interpret the dynamic failure episode during the crack propagation (i.e., the breakdown process). The important conclusion of our study is that slip weakening should not be considered as an alternative description of the breakdown process, as pointed out by Cocco and Bizzarri (2002) and Bizzarri and Cocco (2003). We propose that the state variable evolution controls slip weakening, because in the framework of a rate and state constitutive formulation it governs the weakening mechanisms and the slip acceleration. We have to remind here, however, that complementary interpretations of the state variable and its evolution law exist: Segal and Rice (1995) and Sleep (1997) proposed to relate the state variable to the porosity within the fault zone, thus accounting for the effects of dilatancy and pore compaction. Therefore, while we have shown that the evolution law governs the breakdown process, the physical interpretation of the state variable is not uniquely defined, because it depends on different competing mechanisms.