KINEMATIC AND KINETIC EVENTS ON ROUGH SLIDING CRACK SURFACES IN CONTACT

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ABSTRACT

An elastic-plastic two-dimensional finite element technique has been developed to analyse contact problems associated with friction. A plane stress analysis was applied on a cantilever beam having a through-thickness crack along its neutral plane. Kinematic events such as crack tip and surface deformation were investigated for different crack lengths with coefficient of friction ranging from 0 to 1.6. Elastic and plastic deformation behaviors were compared. Kinetically, the technique enabled the computation of the intensity of the contact forces developed on the two crack surfaces. The results show the effect of friction on the beam stiffness, the strain energy release rate, the mode II stress intensity factor, the modes of crack tip displacement and the development of plastic deformation.

INTRODUCTION

Surface failure of machine elements due to the growth of a fatigue crack with rough-in-contact flanks is frequently observed. In such cases, shear mode crack tip displacement is involved [1]. On the shear mode crack surfaces, debris could be found along the crack line, e.g. [2], due to crack flanks rubbing. Thus, frictional forces exist between the crack surfaces and tribological aspects have contribution [3]. Friction has been always ignored in the analysis of rough crack surfaces in shear mode [4].

Large frictional forces act on the surfaces of mode II crack. The values of the corresponding stress intensity factor (SIF) given by linear elastic fracture mechanics (LEFM), K_{II}, are, thus, reduced compared to the zero friction cases [5], i.e. friction shields the crack tip from the applied mode II loading. Such a friction role was investigated in some fatigue crack growth (FCG) experiments. Friction along the crack flanks shifts the FCG rate versus ΔK_{II} curve to higher ΔK_{II} value [6]. However, experimental quantification of the friction contribution to mode II FCG is difficult [5,6]. Thus, numerical analyses are helpful in promoting the general understanding of the problem. For example, the finite element (FE) technique was used to compute ΔK_{II}, e.g. [7]. Obviously, the ΔK_{II} values obtained by the techniques that neglect the friction contribution are inaccurate. The frictional force is expected to depend on the load-friction-crack system [7].

In the present work, sliding crack surfaces are analysed that are completely or partially in contact. An in-house two-dimensional (2D) elastic-plastic FE program [8] was utilised. Kinetic and kinematic events possibly taking place both along the crack surfaces and around the crack tip were traced for the present work.

NUMERICAL WORK

A 2D body was considered having a curved crack with rough surfaces that were to be in contact on externally loading the body. The crack surfaces were allowed to move apart and to slide in plane. The body was assumed idealised for FE stress analysis with the sliding contact crack surfaces having identical nodal points with different numbers. A system of algebraic equations was generated in the well-known matrix form

$$[K] . [u] = [Q] \tag{1}$$

This equation was modified [8] such that its exactness and $[K]$ symmetry were ensured. The analysis started with initial undeformed body externally loaded by a sufficiently low dP value such that the resulting deformation was slight. The modified equation was iteratively solved for the displacement vector and the internal forces acting at the nodal points along the crack surfaces. The unknown forces between the crack surfaces were all initially assumed zero. In the iteration process, a maximum percentage error of 2% was allowed. In case of having the component of the force acting at a pair of contact nodes along the normal direction to the crack line be of a negative value, the corresponding nodes were allowed to move apart. The geometry of the deformed beam was the input geometry to the proceeding load increment. Thus, deformation, internal force and stress fields were traced in both the elastic and the plastic loading regimes.

The analysis was applied on a horizontal cantilever beam cracked along its span through its centroidal plane, see Fig.1 (a). The beam had the dimensions of span, $L = 70\ mm$, depth, $T = 1\ mm$ and height, $H = 20\ mm$. Twelve cracks of different lengths were individually analysed with the coefficient of friction $\mu = 0$, 0.4, 0.8, 1.2 and 1.6. A 2D plane-stress elastic-plastic previously developed FE analysis [8] was performed. The material properties were: elasticity modulus, $E = 206\ GPa$, Poisson's ratio, $\nu = 0.3$, yield stress $= 350\ MPa$ and strain hardening exponent $= 0.2$.

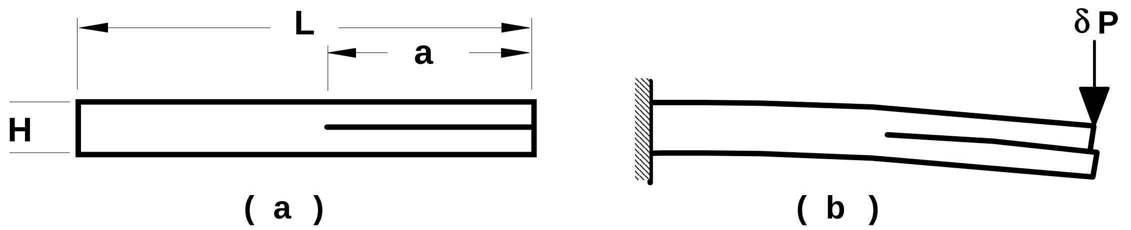

Fig. 1 The analysed cracked beam (a) General geometry ; (b) Schematic showing a general position of the deformed beam

The idealisations had 1064 triangular elements with a range of 1170 to 1214 degrees of freedom according to the crack length. A concentrated downward vertical load was applied at the top point of the free end. The analysis started with horizontal straight crack surfaces assumingly in contact. Fig.1 (b) shows a schematic of a general position of the deformed beam. Due to the displacement of the contact nodal points along the local tangential direction of the crack surface, nodal contact position was disturbed. A necessary modification was assumed by bringing each two nodal points previously in contact to their mid-position. To compute the slope of the tangent at a node, a circular arc was fitted for every three consecutive nodes on the crack line. When contact at a pair of contact nodes was abandoned, the last computation step was repeated with the new condition. The load increment in the elastic regime was $10\,N$, i.e. less than 5.5% of the load required to have the first element just plastically deformed within the beam having the longest smooth crack surfaces. In the plastic regime, the load increment was adjusted to have only one further plastic element.

RESULTS AND DISCUSSION

The vertical displacement of the loaded node, w , plotted against the applied load, P , for different crack-friction systems indicated that roughness of the crack surface lead to a stiffer beam. For the same w , P increased with increasing μ and/or decreasing a. In the case of $\mu = 0$, the beam stiffness was found generally decreasing with a. There was a crack length for each μ value below which the stiffness of the BEAM was not affected. Such a length increased with increasing μ .

There is an energy loss due to both cracking and crack surface roughness. The results relevant to the effect of μ on the variation of strain energy in the elastic regime due to cracking, ΔU , showed clearly the fact that part of the input energy was consumed in resisting the friction along the crack contact surfaces. Qualitatively, it is both well known and intuitively obvious that crack surface friction reduces the strain energy release rate, G . Quantitatively, G could be computed for a_L , $=a/L$, π 0.5 by partially differentiating ΔU per unit thickness with respect to a. The mode II stress intensity factor, K_{II}, was, then, computed, i.e. $K_{II}^2 = EG$ in the plane stress state. Fig. 2 shows a comparison of the only solution found in the literature for the present application due to Pook [9] and the present FE solution for smooth crack surfaces. The figure exhibits a maximum difference of 20%. However, the solution due to Pook [9] is approximate. There is an appreciable agreement in the short crack regime.

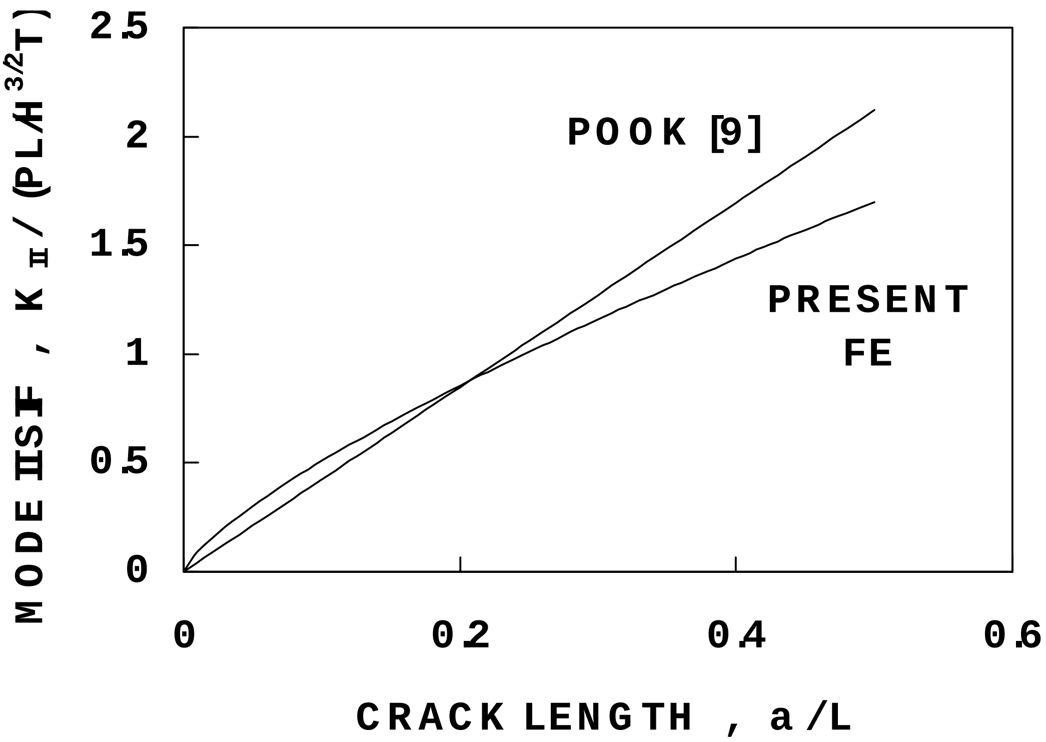

Fig. 2 Comparison of the present SIF solution and the solution due to Pook [9]

There was a crack length dependent on the value of μ below which the crack tip was completely shielded. The friction forces act along the mating crack surfaces. With respect to the crack flanks, those forces are eccentric thereby they generate normal axial forces and bending moment acting on each flank. This lead to a corresponding increase in the stress-strain field induced within the beam. Thus, an increase in μ caused a completely shielded longer crack. The effect of μ is to lower G for a specific crack at a given value of deflection. In terms of K_{II}, Fig.3 clarifies the influence of loading-friction-crack system on K_{II} / K_{II_o}. In this case, $K_{II} = K_{II_o}$ when $\mu = 0$.

The present FE results showed that the crack surfaces behind the crack tip were opened allowing the simultaneous operation of both mode I and mode II crack tip displacement. The extent of such separation of crack surfaces is shown in Fig. 4 for some crack-load-friction systems analysed in the present work. The length of the opened crack surfaces increased with an increase in both a and P and also with decreasing μ. As P increased, the local opening along the crack surfaces was, generally, found increasing with an increase in the ratio of the opening and the relative tangential displacements of the two crack surfaces measured at the node just behind the crack tip.

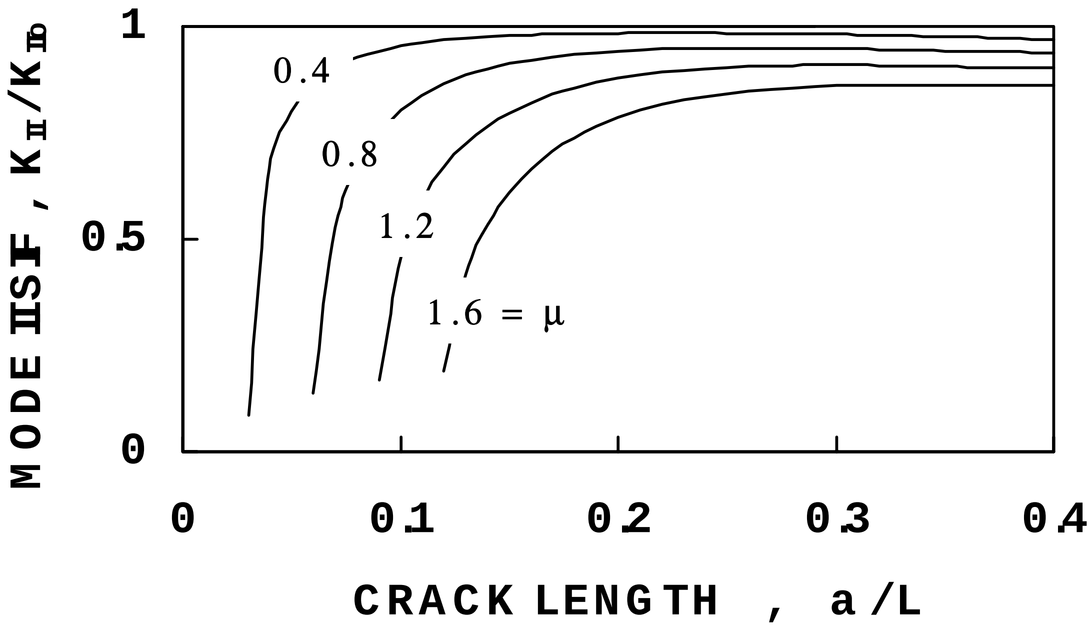

Fig. 3 Mode II SIF for different crack-friction systems

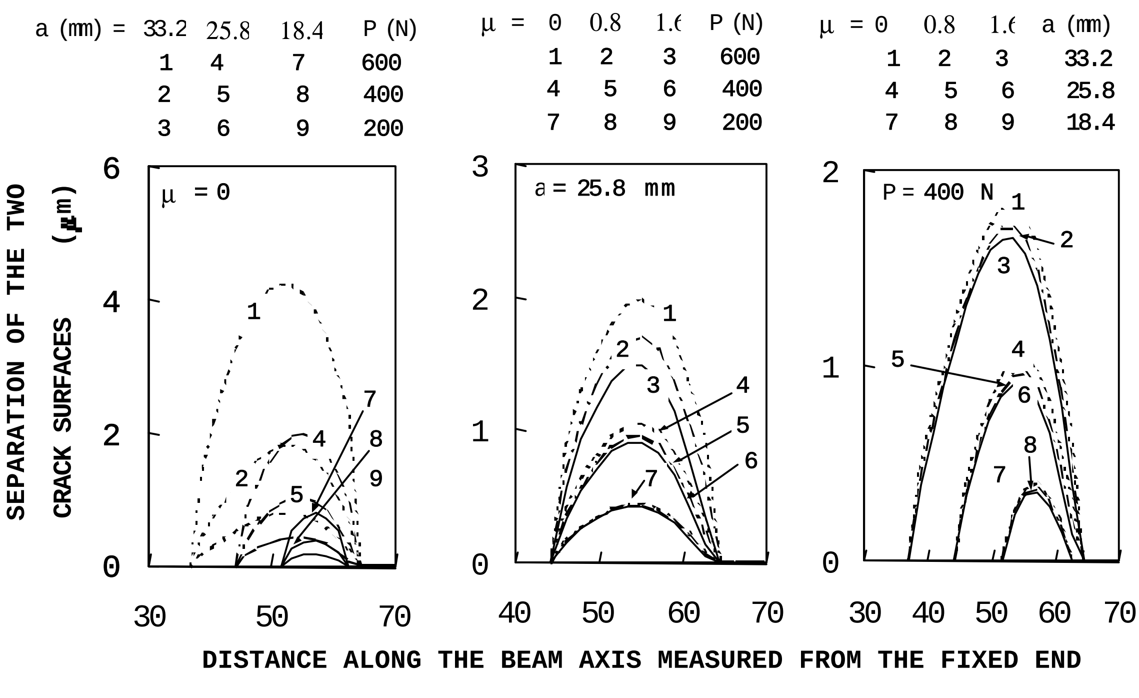

Fig. 4 Separation of the crack surfaces for different crack-load-friction systems

For a short crack at a small load, the crack surfaces were completely closed. When P increased in this case, the sliding displacement of the upper crack surface at the beam free end towards the crack tip relative to the underneath lower crack surface increased. To have this type of deformation continuously increased as P increased, the two nodes just behind the crack tip had to move apart. With increasing P, the crack tip further opened and the contact of more adjacent was released. Thus, the site of maximum crack opening displacement was found shifted away from the crack tip as P increased. That deformation pattern was pronounced as a increased as well as μ decreased. For example, the relative sliding displacement at the free end was $0.05mm$ whilst the maximum opening displacement behind the crack tip was $0.31\ mm$ in the case of $\mu = 0$, $a = 40.5\ mm$ and $P = 871N$.

In Fig.5 is a plot showing the intensity of the force normal to the deflected surfaces, f, in N/mm^2 for different crack-load-friction systems. The value of f continuously decreased from the highest value at the crack mouth along the crack surfaces towards the crack tip and vanished when the two crack surfaces commenced to displace apart. For a certain crack-friction system, the local value of f increased as P increased. For the same load-friction system, increases in a lead to an increase in f near the crack mouth and a decrease in f near the crack tip. The ratio of the resultant of such distributed forces and P was approximately constant for the same crack length independent of P and changed from about 0.35 for very short cracks to about 0.55 for long cracks. For all the analysed crack-load systems, the effect of μ on both f and its resultant was insignificant.

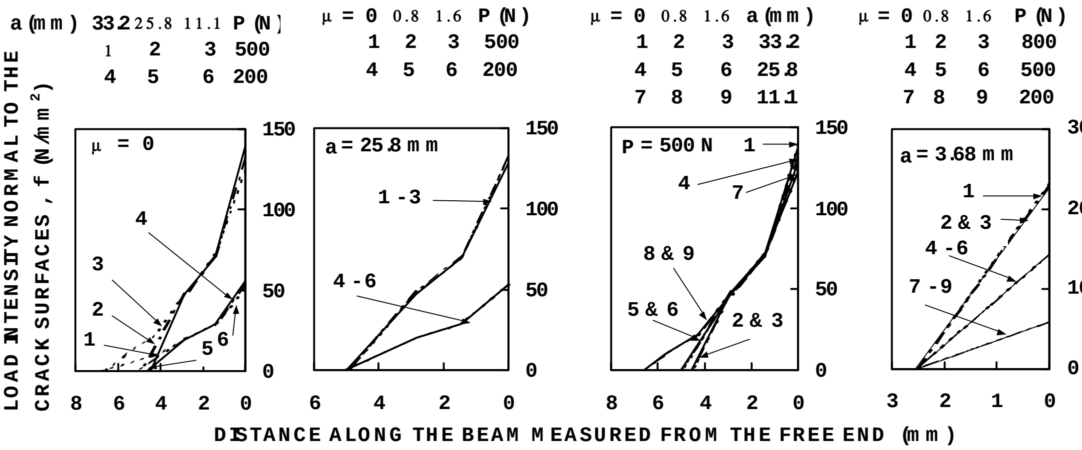

Fig. 5 Intensity of normal forces acting on the crack surfaces for different crack-load-friction systems

The shear deformation, ϕ, accommodated at the crack tip was indicated by the change in the angle measured between two perpendicular crack tip lines originally marked ahead of that tip such that one of them coincided with the undeformed crack surfaces. A typical result is presented in Fig.6 (a) for the case of $a = 40.5\ mm$, $P = 650N$ and $\mu = 0$. In that figure, the deformation-taking place for the two crack surfaces near the crack tip is hardly illustrated. The relative magnification used for the local horizontal displacement in Fig.6 (b) enabled the clarification of the variation of the geometry of the deformed lines for different crack-load-friction systems. As expected, ϕ increased with the increase in P, a and μ. However, the influence of μ was found insignificant. It is clear that the separation of the two crack surfaces due to the applied load has an effect on the crack tip shear deformation.

Fig.7 depicts the development of the monotonic plasticity within the beam for different load-crack-friction systems. Plastic deformation commenced in the un-cracked beam at the two upper and lower outer surface elements adjacent to the fixed end. As the applied load increased, plasticity was developed towards the free end and the centre line of the beam with a higher development rate along the former direction. With load increase, the upper and lower plastic zones met to continue the plasticity development with a lagging central front. Irrespective of the value of m, the beam with a short crack behaved in a very similar manner with no plastic deformation accommodated at the crack tip.

The behaviour was different in the case of a longer crack. The first plastic deformation took place at one of the crack tip elements at a load decreasing with a. The progress of the plastically deformed zone within the loaded beam was as follows. While the plastic zone was growing around the crack tip, two plastic zones were formed adjacent to the fixed end behaving in a similar manner as those found in the case of the uncracked beam. Plasticity development continued with loading to have two further plastic zones formed at the two outer surfaces of the beam just above and below the crack tip. The two latter zones joined the crack tip plastic zone first followed by joining the fixed end plastic zones. At a sufficiently high load, the above plastic zones joined to have one front progressing. Generally, friction retarded the development of plasticity.

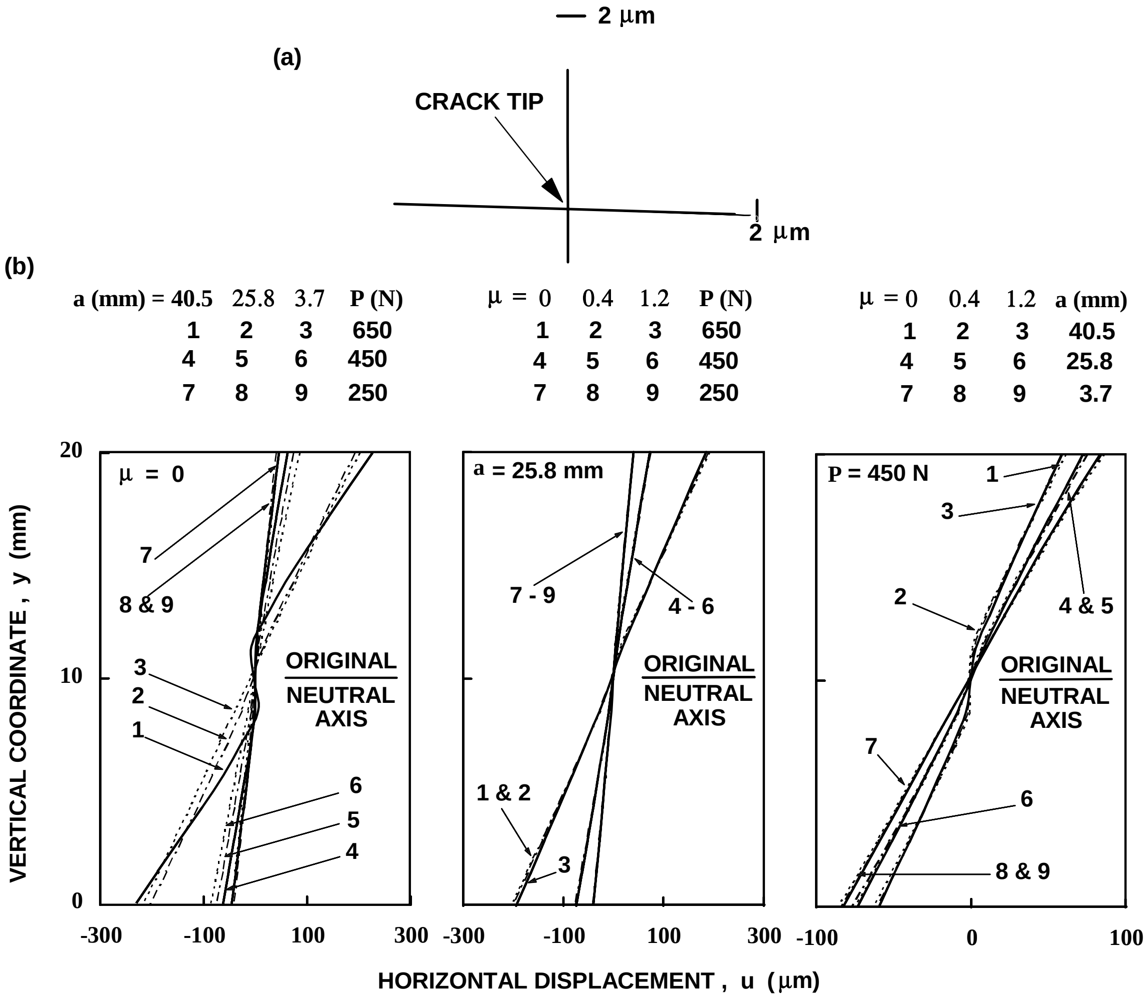

Fig. 6 Crack tip shear deformation for different crack-load-friction systems

In service, crack surface friction changes as repeated sliding takes place. One would expect the surface to become progressively smoother as wear and abrasion takes place, thus, reducing the effective coefficient of friction. Furthermore, if liquids are present, the friction may be reduced.

Both halves of the cracked part of the analysed beam were eccentrically subjected to the frictional forces. Thus, the height of the beam, H , should have a contribution on the influence of friction. One would expect that an increase in H has a qualitatively similar effect as increasing μ .

CONCLUSIONS

Friction should be taken into account in mode II crack tip displacement studies. Friction between crack surfaces affects the component stiffness, the strain energy release rate, the mode II stress intensity factor, the modes of crack tip displacement, the development of plastic deformation and the crack tip shear deformation.

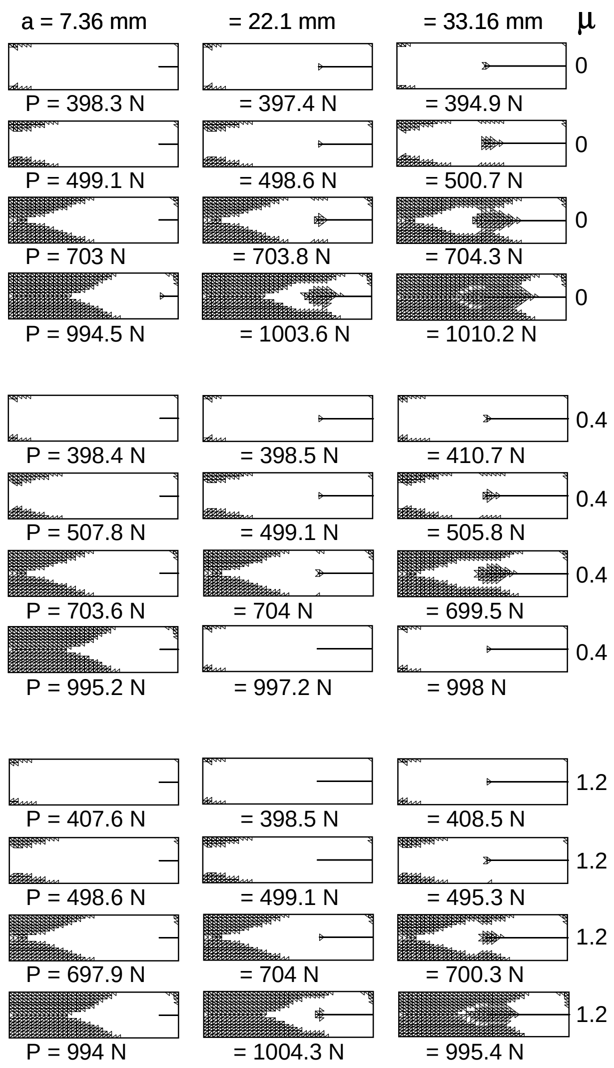

Fig. 7 Plasticity development for different crack-load-friction systems

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