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Interaction Effects Between Interfacial and Sub-Interfacial Cracks in Gravity Dam

S. Liamani, B. Bachir Bouiadjra, B. Serier and M. Belhouari

LMPM, Department of Mechanical Engineering,
University of Sidi Bel Abbes, BP 89 Cité Ben M'hidi, Sidi Bel Abbes, 2200, Algeria

Abstract: The aim of this study is to analyse by the finite element method the effects of interaction between a sub-interfacial crack and an interfacial crack in gravity dam under hydrostatic pressure. The effect of the presence of the interface rock/concrete on the behaviour of sub-interfacial crack is also studied. All these effects are analysed by the computation of the stress intensity factors at the cracks tips. The effect of the water high contained by the dam is highlighted. The obtained results show a mixed mode of cracks displacements. The presence of the interface increases the stress intensity at the tips of the sub-interfacial cracks and there is a compensation of the stress intensity between the interfacial and sub-interfacial cracks.

Key words: Gravity dam · Sub-interfacial crack · Interfacial crack · Stress intensity factors · Finite element method

INTRODUCTION

The interface between concrete dam and rock foundation is one of the most important region governing the strength and stability of gravity dams. The fundamental understanding of the fracture behaviour at the Rock-Concrete interface requires evaluation of fracture criteria such as stress intensity factor, energy release rate etc [1-7] Fracture mechanics concepts and theories have been successfully applied to study the cracking phenomena in dams [8-15]. However, not much work is reported regarding the crack at the interface of concrete dam/rock foundation, witch is one of potential sites of cracks initiation and propagation. The determination of the stress intensity factor at the crack tip is one the possible means to analyse the behaviour of interface cracks in gravity dam. It is known that the finite element method gives, with a great accuracy, the stress intensity factors at the crack tip. Among the author whom uses this method in fracture of dam we can quote: Chandra et al [16], Ayari and Saouma [17], Chandra [18] and Kojerban [19]. In this study the finite element method is applied to analyse the interaction effect between an interfacial and subinterfacial cracks in gravity dam by computing the stress intensity factor at the tips of the two cracks. First, the interaction between the interface rock/concrete and a subinterfacial crack is analysed. Secondly, the interaction effect between an interfacial cracks and a subinterfacial crack is analysed. The variation of mode I and II stress intensity factors at the interfacial and subinterfacial cracks tip according to the distance between the two cracks is plotted. The effects of hydrostatic pressure in all studied cases were highlighted.

Geometrical and Finite Element Models: The dam used for the analysis is a gravity dam type. It is 80 m high and 60 m width. The crest of the dam is 5 m width. The cross-section of the dam along with simplified dimensions is shown in Figure 1. The analysis was undertaken of the assumption of initially isotropic elastic materials for both concrete dam and rock foundation. The materials properties of rock and concrete are given in Table 1. The dam is subjected to the reservoir hydrostatic loads. Three cases of these loads are studied h=40, 60 and 80 m. where h is the high of water contained by the dam. The uplift pressure inside the interfacial crack is taken into account.

The geometrical model is idealised by a mesh having 2125 eight nodded elements using the finite element fracture code FRANC 2D by the cornell fracture groupe under direction of Pr A. Ingraffea [20]. This mesh is considered fine enough as further refinement did not significantly improve the results. The crack tip is modelled with the standard quarter-point elements. Figure 2 shows

Corresponding Author: S. Liamani, LMPM, Department of Mechanical Engineering, University of Sidi Bel Abbes, BP 89 Cité Ben M'hidi, Sidi Bel Abbes, 2200, Algeria.

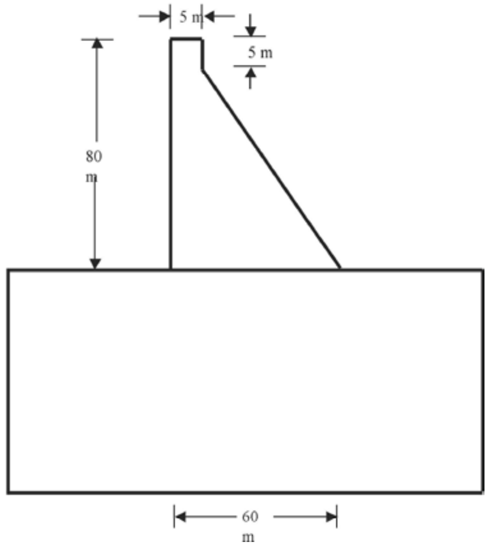

Fig. 1: Geometrical model

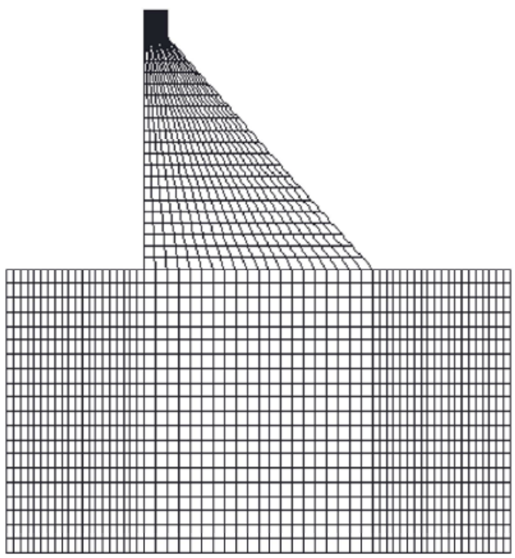

Fig. 2: Finite element mesh model

Table 1: Elastic properties of the rock and concrete

Elastic properties	Concrete	Rock
Young Modulus (Mpa)	$4{,}867.\ 10^6$	$3{,}952.\ 10^6$
Poisson ratio	0,255	0,165

typical mesh model of the total structure and near the crack tip. A linear elastic material model coupled to a linear elastic discrete fracture model was used in the analysis. The authors also explored the possibility of using an elastic-plastic material of the concrete which is available in the program, but for this massive concrete and rock structure for which linear fractures theory is considered reasonable. It was decided to restrict the analysis to the consideration of linear materials.

RESULTS

Interaction Effect Between Sub-interfacial and Interface Rock/Concrete: Before studying the interaction effect between an interfacial and sub-interfacial cracks, it was considered useful to analyse the interaction effect between the interface rock / concrete without crack and a sub-interfacial cracks located at a distance d from the interface as shown in Figure 3. The crack length is a=1 m. The origin for the distance d is chosen at the interface. Conventionally, the negative distance (d) is considered when the crack is located in the rock. The left tip of the crack is named “tip 1 and the right tip: "tip 2”.

Figure 4 presents the variation of the mode I stress intensity factor (K_I) at the tip 1 of the crack as a function of the ratio d/H (H is the height of the rock considered in the study) for the three height of water contained by the dam (h=40, 60 and 80 m). It can be seen that the applied pressure has a very significant effect on the SIF variation. Indeed, the stress intensity factor is multiplied by three between water high of 60 and 80 m. It can also be noted that, the maximum of the SIF is recorded for d/H=-0.5 when the crack is in the rock. In this last case, the curve presenting the SIF according to d/H takes an increasing form until d/H =-0.5, then decreases slightly when the crack approaches the interface rock/concrete. When the crack is in the concrete (d/H>0), the K_I increases with the increase of d/H until this ratio reaches the value 0.5. Beyond this value, the mode I stress intensity factor fall in a significant way toward a half of its maximum value. One can thus affirm that the mode I stress intensity factor (K_I) takes relatively significant values when the ratio d/H is included in the interval (-0.5, +0.5). This tendency shows that the presence of the interface rock / concrete influences clearly the opening energy at the crack tip. The fact the mode I stress intensity factor is maximum for d/H=0.5 can be interpreted as follow: The nature of loading, which is an hydrostatic pressure applied on the concrete, produces raised normal stresses in the interface vicinity located in the concrete.

Figure 5 presents the variation of the mode II stress intensity factor (K_{II}) at the tip 1 of the crack as a function of the ratio d/H determining the inter-distance between the crack and the interface for h=40,60and 80 m. It is noticed that the values of K_{II} are slightly lower than those of K_I. The difference is about 25%.. The applied pressure affects clearly the variation of the mode II stress intensity factor. It appears even proportionality between the K_{II} and the high of water h. By examining attentively the shapes of the curves of Figure 5, it can be noticed that the K_{II}

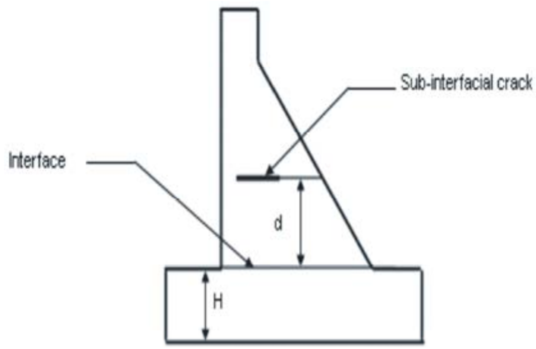

Fig. 3: Position of the sub-interfacial crack

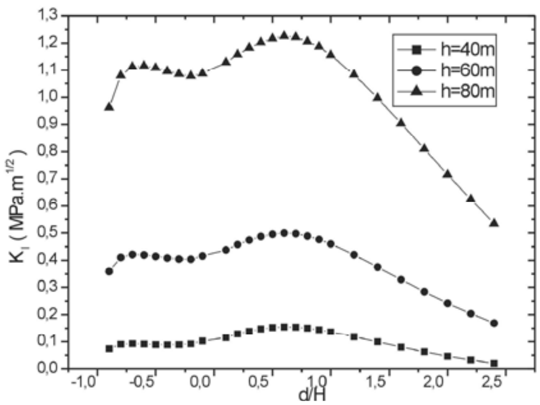

Fig. 4: Variation of the K_I at the tip 1

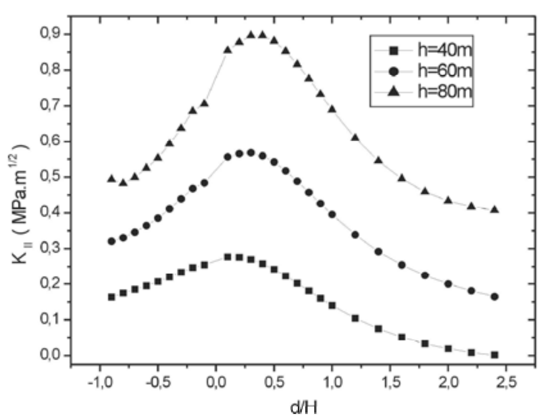

Fig. 5: Variation of the K_{II} at the tip 1

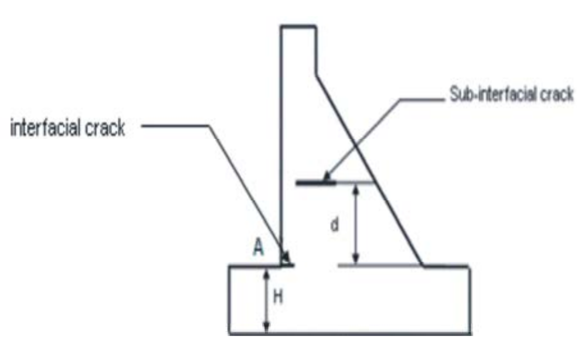

Fig. 6: Position of the interfacial and sub-interfacial cracks

increases as crack approaches the interface and pass by maximum beyond the interface. This maximum is reached for d/H=0.25 (position located in the concrete).

It should be noted that the maximum value of K_{II}, witch characterise the sliding mode, is reached at a position of the crack closer to the interface compared with the K_I, which characterise the opening mode. This is due to the fact that at the interface, the shear stresses are more significant, because of the difference between the Young modulus of the two joined materials (concrete and rock). It is known that the shear stresses are the causes of the sliding mode of the crack.

Interaction Effect Between an Interfacial and Sub-interfacial Cracks: In order to illustrate this effect, let consider an interfacial cracks with length 1 m initiated at the free edge of the interface located at the end of the loading line (point A of Figure 6). One also supposes also the existence of a sub-interfacial crack with same length. The left tip of this last crack is located on the prolongation of the tip of the interfacial crack. The distance between the two cracks is d. As taken in the previous paragraph, the origin for the distance d is chosen at the interface and the left tip of the crack is named “tip 1 and the right tip: "tip 2”.

The mode I and II stress intensity factors at the tips of the interfacial and sub-interfacial cracks are computed and plotted as a function of the ratio d/H characterising the inter-distance between the two cracks.

Stress Intensity Factors for the Interfacial Cracks: Figure 7 presents the variation of the mode I stress intensity factor at the interfacial crack as a function of the ratio d/H. According to this figure, it is observed that, when the sub-interfacial cracks approaches the interfacial one (the ratio d/H decreases in absolute value), the stress intensity factor increases. This increase is more significant when the applied pressure is higher. The interaction effect seems to depend not only on the inter-distance between the two cracks, but also nature of the cracked material. Indeed, the values of the mode I stress intensity factors (K_I) are note symmetric on both side of the interface. The values for the position located in the concrete are slightly higher. This is due to the difference in the young modulus for the two involved materials (concrete and rock). The crack in the most resistant materials presents a high mode I stress intensity factors. One can thus conclude that the presence of a sub-interfacial crack near the interfacial crack increases the opening energy at the tip of the interfacial crack.

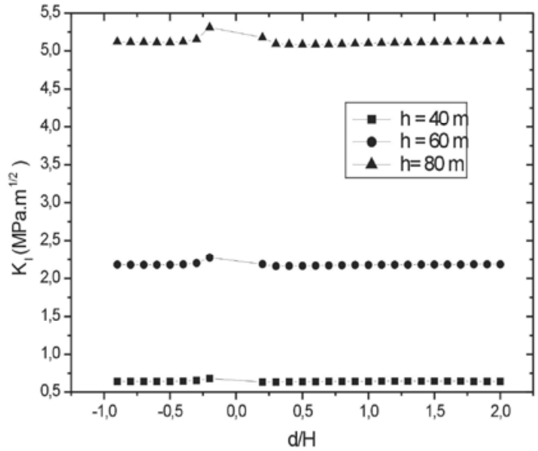

Fig. 7: Variation of the K_I at the interfacial crack

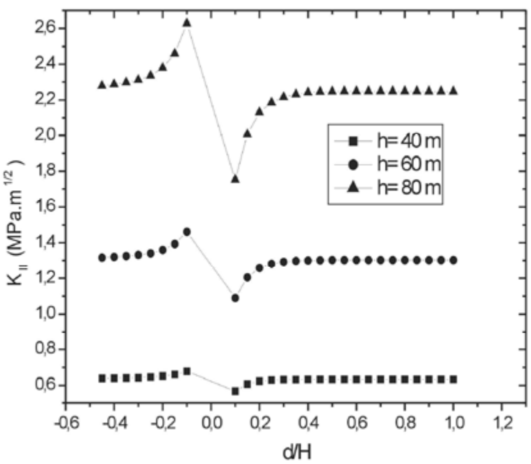

Fig. 8: Variation of the K_{II} at the interfacial crack

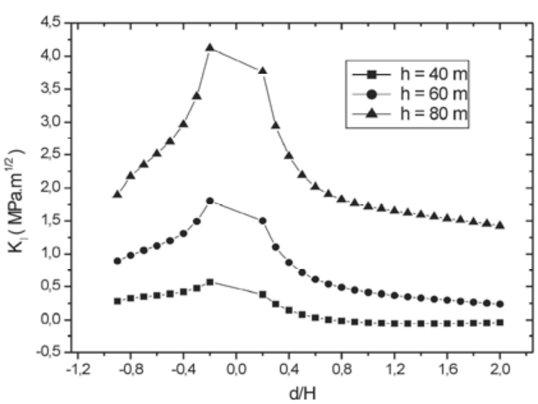

Fig. 9: Variation of the K_I at the tip 1 of the sub-interfacial crack

Figure 8 presents the variation of the mode II stress intensity factor (K_{II}) at the interface crack according to the ratio d/H for h=40, 60 and 80 m. It can be seen that the applied pressure has a significant effect on the K_{II} variation. For d/H<0 (sub-interfacial crack located in the rock), the K_{II} at interface crack tip increases when the ratio d/H tends toward 0 (the sub-interfacial cracks approaches the interfacial one). Inversely when the sub-interfacial crack is in the concrete, the K_{II} at the interface crack tip decreases as the d/H ratio tends toward 0. The sliding energy of the interfacial crack decreases if a sub-interfacial crack initiated in the rock is in its vicinity. This energy decreases if the sub-interfacial crack is in the concrete.

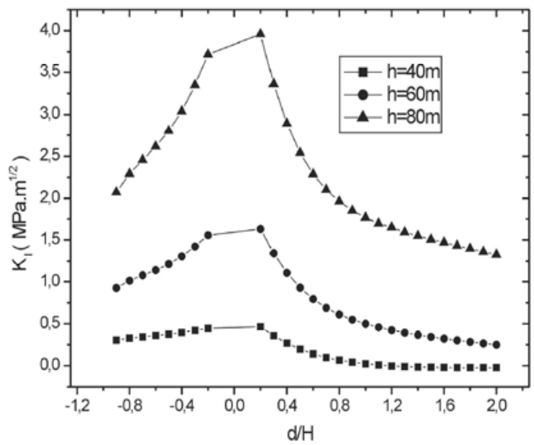

Fig. 10: Variation of the K_I at the tip 2 of the sub-interfacial crack

Stress Intensity Factors at the Tips of the Sub-interfacial Crack: In the previous paragraph, the effect of the sub-interfacial crack on the behaviour of the interfacial crack was analysed. In this paragraph, the opposite effect is studied; it's the effect of the influence of the interfacial crack on the stress intensity factors at the tips of the sub-interfacial defect.

In Figure 9 it is presented the variation of the mode I stress intensity factor at the 1 of the sub-interfacial crack as a function of the ratio d/H and for h=40, 60 and 80 m. It is observed that whatever the site of the initiation of the crack, the K_I at the tip 1 increases when the sub-interfacial crack approaches the interface crack (d/H tends toward 0). This increase is more significant when the structure is strongly loaded (h=80 m). The values of the stress intensity factor resulting from cracks initiated in the rock are slightly higher than those obtained for cracks initiated in the concrete. An inverse behaviour was announced in the case of the interface crack. It can be deduced than the interaction effect between the two cracks results from a compensation of the stress intensity between the two cracks.

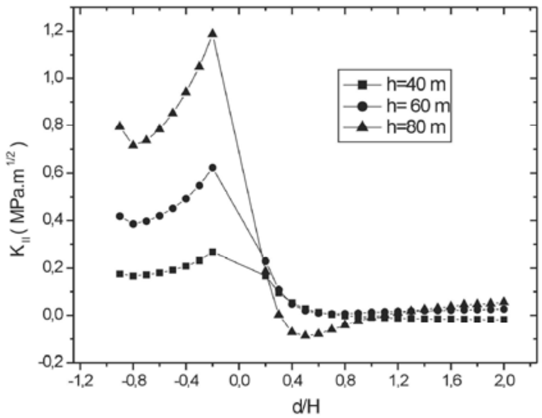

Fig. 11: Variation of the K_{II} at the tip 1 of the sub-interfacial crack

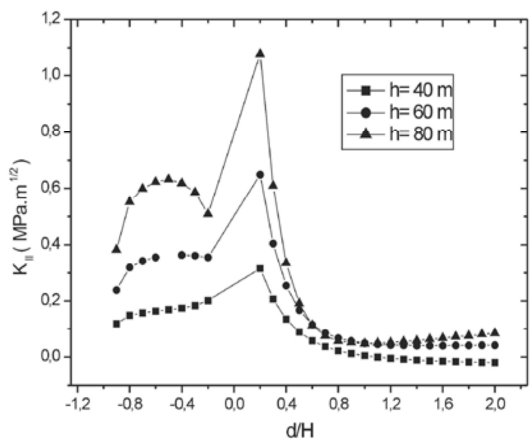

Fig. 12: Variation of the K_{II} at the tip 2 of the sub-interfacial crack

Figure 10 presents the variation of the mode II stress intensity factor at the second tip of the sub-interfacial crack (tip 2) for h=40; 60 and 80 m. The same tendency as the tip 1 is observed, except that the values of K_I for the tip 2 are slightly lower. The difference is about 6%.

Figure 11 presents the variation of the mode II stress intensity at the tip 1 of the sub-interfacial crack factor according to the inter-distance ratio d/H for the three high of water contained by the dam (h =40,60 and 80 m). When d/H <0 (the sub-interface crack is in the rock), the K_{II} decreases as the crack approaches the interface. Inversely, in the concrete, the K_{II} decreases when the ratio d/H decreases. This tendency is opposite to the case of the interface crack where the inverse behaviour was observed. These results confirm the compensation effect of the stress intensity between the two cracks announced previously.

Figure 12 shows the variation at the tip 2 of the sub-interfacial crack for h=40, 60 and 80 m. The same behaviour is also observed by comparison with the tip 1. The difference in the mode II stress intensity factor between the two tips is about 8%.

CONCLUSIONS

This study was carried out with an aim of studying by the finite element method the interaction effect between sub-interfacial cracks and: on one hand the interface rock/concrete and on the other hand an interfacial crack in a gravity dam. The obtained results allow us to deduce the following conclusions:

- The conditions of loading (applied water pressure) and the difference between the elastic properties of concrete and rock involve mixed modes of displacements of the cracks
- The applied pressure has an important effect on the variation of both mode I and II stress intensity factors.
- Near the interface rock / concrete, the stress intensity factors in mode I and II of a crack sub-interfacial increase.
- The presence of a sub-interfacial crack near the interfacial crack increases the opening energy at the tip of the interfacial crack
- The sliding energy of the interfacial crack decreases if a sub-interfacial crack initiated in the rock is in its vicinity. This energy decreases if the sub-interfacial crack is in the concrete.
- The interaction effect between the interfacial and sub-interfacial cracks results from a compensation of the stress intensity between the two cracks.
- The stress intensity at the tip 1 of the sub-interfacial cracks is higher than that of tip 2.

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