THE HONG KONG POLYTECHNIC UNIVERSITY

RESEARCH DEGREE PROPOSAL

1 Title: The mechanical failure of 3D surface under compression and its application on undergrounds opening

2 Project Objectives

In nature, flaws commonly exist in rock mass in forms of joints, fissures, cracks and faults, etc. The length of flaws such as joint are varied form finite size to several kilometers. Fracture propagation and causing the brittle failure is an important research topic in rock mechanics fracture mechanics and damage mechanics.

When tectonic movement occurs, a active compression stress and shear stress will be induced which cause the fault plane to move and cause surface rupture. Since the failure mechanism of a rock mass containing flaws is totally different from an intact rock mass, the existing knowledge about how an intact rock mass rupture cannot be projected to the intact rock mass. It is known that under the applied loading, stress around the flaw top will increase, when the stress at tip exceeds its threshold value, (stress intensive factor). Crack is induced. The failure process is now understood to be due to the stable growth, interaction and coalescence of cracks. A number of studies had been done to investigate fracture propagation and brittle failure in 2D rock specimens containing a 2-D flaw.

Though different research carried out by many researchers, on of the crack propagation of rock mass containing one flaw is defined as “wing crack” and part of the mechanism under certain circumstance are addressed. In laboratory scale , it is found that tensile wing crack will initiate form the tips of inclined 2-D pre- existing flaw in brittle solids under far field compression. In a much larger geological scale, such tensile crack branching also manifests itself in faulting during large earthquakes. One Example is the surface rupture of the Fuyun earthquake of Xingjian, China, shown in with a series of tensile fractures trending NE form the lower Fuyun fault segment joining the upper segment.

Thus, it is reasonable to notice the area where the flaws tips located. If the earthquakes or tectonic movement occurs. Serious destruction may occurs in such area. Therefore, the mechanism of oblique crack propagation is an important topic and can help to reduce the hazard of the public and avoid structures constructed on the potential rupture zone. Since the same type of flaws also existing in the underground opening structures, for example, the column between the opening. In case of this, it is also very important to study the crack propagation.

There were many researches on crack growth in a specimen containing one or a group of two- dimensional (2-D) flaw under compression. However, a experiment with a 2-D flaw cannot reflect a real situation in the earth，since a result obtained from a sample containing a 2-D flaw is based on a assumption that the length of fault planes and joints is infinite. Hence, the results obtained in the past are not most reliable in the real situation.

For the case in the Chi-Chi earthquake in surface ruptures at the termination of fault appear in the form of an en echelon array of fractures between Fongyuan and Shiapolipu and become tensile fractrures from Shialipu to Shuanchi. This newly formed fault was named Shihkang – Shangchi fault zone. The rupture pattern of the Chelungpu fault is different from the wing crack pattern where the ruptures induced at the area of the stress under compression.

For the sake of explaining this phenomenon, based on the result obtained in 2-D experiment, 3-D experiments were carried out by many researchers in recent year. Wong at el (2004), anti wing crack[#] was reported, which has not been reported by researchers. From the past experience, a wing cracking are expected as a one of the phenomenon occurred when a rock mass containing a flaw is compressed. However, through this research, it is found that under certain circumstances, the anti wing cracking appears like the case in the Chi-Chi earthquake.

In order to determine the mechanism of anti wing cracking or wing cracking, Robina HC Wong carried out many researches on 3-D experiments and anit-wing cracking including different materials, gabbro, marble, sandstone, granite, PMMA etc.

Through reviewing the research and knowledge gained, it is concluding that there are many insufficiencies that are very important to whole of the theory behind such kind of crack propagation. Parts of the insufficiencies are in the following:

1 Most researches are carried out for study of a rock mass containing one flaw. Since, in nature, rock mass always contain multiple joint sets. In this case, the developed mechanism of crack propagation for rock with one pre-existing is not enough to interpret the cracking in nature.

2 From the past research, a formula is developed to describe how the stress varies under the loading in a rock mass containing a flaw. However, the equation only applies for homogenous material, PMMA. However, in nature, most rock mass are heterogeneous, for example granite, gabbro.

3 In the past, computer simulation were used to model a rock mass containing flaw are compressed and how the cracking occurs. It is believed that, with visualization and numerical simulation in computer, researchers can have a clear picture on it for their research related to the crack propagation. By reviewing the result of using computer simulation Wong al et, it is very concluded that the aid of computer can enhance whole of the base of the mechanism

3.1 Scope of Research

Based on the finding in previous research, this project is an extension of Robina HC Wong et al's study (2004), which recommended further experimental and theoretical investigation on crack propagation as follows:

(1) Experimental: The rock mass containing multiple will be investigated so that the failure mechanism and theory of the crack propagation for rock mass containing multiple joint sets can be developed, which is more consistent to the real rock in nature.

(2) Theoretical: Based on the observation from the experiment, theoretical crack model will be estimated to explain the observations and to estimate the mechanism qualitatively.

(3) Numerical: Computer programs will be used to predict the evolution of stress distribution and its relation to the process of fracture propagation.

The present study is with academic value as well as of practical value. The results of this project will advance our understanding of three-dimensional rock fracturing under compression, and will lead prediction of areas having probability of surface rupture induced by earthquakes.

3.2 Background of Research

Review of anti- wing crack study form 2-D surface flaws in rock

In the early stage, various researches were conducted to investigate the cracking mechanism in a material containing a single crack or multiple cracks.

Hoek and Bieniawski (1965), Pan and Johnson (1972) and Krartz (1979)
The research found that when a specimen containing group of flaws was under compression, the cracks initiated and coalesced.

Fairhurst and Cook (1966) showed that when the rock was under uniaxial compression, tension cracks, which were named as wing cracks, would initiate form the flaw and propagate parallel to the compression axis. The cracks were opened by two opposite forces disjointing

Germanovich et al. (1995) calculated the tensile stress opening the wing crack in his study and surprisingly found that the results were in agreement with Fairhurst and Cook's study.

Wong and Chau (1998) undertook a research on rock-like materials containing two flaws. The study showed that the cracks coalesced the two flaws by three modes, viz: shear, tensile and mixed under uniaxial compression. The mode of coalescence depended on the position and the distance the two flaws.

Though the researches listed above, failure criteria of rock mass containing an existing flaw and related mechanism of crack propagation are identified. Apart from this, the occurrences of anti wing crack during tectonic movement also are noticed in field of rock propagation. However, all results obtained by researches listed above only can be projected to a rock mass with infinite length of flaw since the researches studying 2D cracks is based on the assumption that the length of pre-existing flaw is infinite. For the sake of developing further understanding of real situation, 3-D researches were carried out.

Review of anti- wing crack study form 3-D surface flaws in rock

In case of different nature of 3-D and 2-D pre-existing flaws, specimens containing a 3-D pre-existing flaws were carried by many researchers.

The significance of the three-dimensional nature of the problem was already recognizd in a number of earlier studies (Adam and Sines , 1978 ; Dyshin andSalganik, 1987; Germanovich etal, 1994 ‘ Arcady etal, 1999; Wong etal, 2002)

Uniaxial compression test Adam and Sines on PMMA sample with inclined disk –like crack made by cutting semi-circular slots into the two halves of the sample and then gluing the sample back together. They report that, two primary crack (wing crack or tensile cracks) initiate from the tips of a crack and branch towards the axis of the compression . In the lateral direction, two set of small additional petal microcrack appeared close to the lateral part of the initial crack contour. As the load increase , large ‘fish-fin’ contour initiate after the primary cracks and formed near the centre of the flaw surface towards the compression direction.

Wong et al (2004) investigated crack propagation in rock. Anti wing crack[#] was reported, which has not been reported by researchers. From the past experience, a wing cracking are expected as a one of the phenomenon occurred when a rock mass containing a flaw is compressed. However, through this research, it is found that under certain circumstances, the anti wing cracking appears.

Robina HC Wong (2005) investigated antiwing crack propagation in different rock and make a conclusion for a different rock containing a 3-D flaw. The following two tables are the summar. It is found that anti –wing crack initiated only in rock with high **σ_c/σ_t** ratio such as granite, gabbro and sandstone. For Marble with intermediate **σ_c/σ_t**, there is no a clear d/t for occurrence of the anti-wing crack.

Table Crack growth in materials with d/t 0.27

Rock Type	**σ_c/σ_t**	**Changing parameters**	**Primary crack**		**Secondary crack**	**Other crack**
			Wing Crack	**Anti wing Crack**		
PMMA	2.73	α =30−80°	100%	-	-	Petal crack
Plaster	6	α =15−75°	100%	-	-	-
Marble	12.99	α =15−75°	50%	50%	Oblique crack or wing crack	Petal crack
			(no clear d/t to initiate anit-wing crack)			
Gabbro	17.67	α =15−80°	-	100%	Wing crack or compressive crack	Petal crack
Granite	20.92	α =45°	-	100%	-	-
Sandstone	22.43	α =35−75°	-	100%	Wing crack or compressive crack	-

Another summaries listed below show the critical d/t for anit wing crack of different material, this conclusion reveal that d/t ratio is one of the important parameters controlling the occurrence of wing cracking or anti-wing cracking.

Table The effect of d/t on crack propagation in granite, gabbro and sandstone

Rock type	Total no of testing	Critical d/t for anti wing crack initiation
Granite	7	d/t =< 0.27
Gabbro	8	d/t =< 0.6
Sandstaone	5	d/t =< 0.4

By concluding the finding from Wong et al, it is found that anti wing cracking is depend on d/t and $\boldsymbol{\sigma_{c}/\sigma_{t}}$. Based on the mechanism and result gained, it is a useful background for this proposed research.

4 Research plan and methodology

The proposed research is divided into 4 parts, the estimated time is show as follows

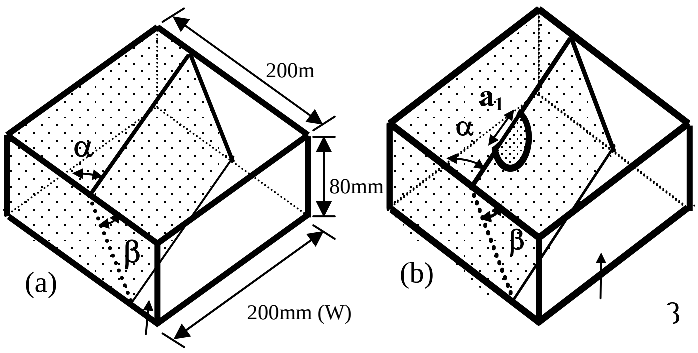
The estimated time –frame is as follows:

Component of work	1^{st} Year	2^{nd} Year
1. Experiments of 3-D surface fracture growth for Theoretical study for rock mass with one flaws	←→	
2. Theoretical study for rock mass with one flaws	←→	
3. Numerical simulation analysis	←→	←→
4. Experiments of 3-D surface fracture growth of rock containing multiple joints	←→	←→
Paper and thesis writing	←→	←→

1. **Experiments of 3-D surface fracture growth for Theoretical study for rock mass with one flaws.**

Based on the experiments carried out by Wong at el before, granite is chosen for the theoretical study and numerical simulation. There are two reasons why the granite is chosen to develop the empirical formula. Firstly, there has been theoretical study of homogenous material PMMA. However, the theory behind the heterogeneous material like granite has not been developed. Since, most rock mass are heterogeneous in nature, it is a reasonable to investigate in this aspect. Secondly, by comparing the other material used in other research like sandstone, it is very difficult to carry out AE measurement in the experiment, since the signal received is very weak.

The sample are bock shape with dimensions of 200mm x 120mm x 15mm(Fig4).The specimens are cured so that the loading area is smooth and compressive stress distributed evenly. Then, a cutting blade material is used to form a fault. Fault geometry will be fixed as semi-circular with fixed length a1 and orientation α. The inclined angle of fault plane is β under a uniaxial compressive stress and 3 conditions. Acoustic emission sensors are attached on the rock surface to investigate the acoustic emission activities during fracture propagation.



Geometric Setting-
Granite Specimens

There are some proposed variable factors of experiment used in the research in extension of Wong et al's study (2004), the parameters are proposed in the following:

1. Dip angle of the flaw α
2. Frictional coefficient along flaw
3. Rotation of the flaw β

Through changing the parameters listed above in the many sets of experiments, the parameters is used to fixed to develop a analytical model to output failure criteria and stress concentration at different location of the rock mass.

Table 1 Details of group 1 Experiment

Fault material	α (°)	β (°)	d/t	Shape of fault	Purpose of study
Group 1 None Group 2 The dust of granite#	0	75, 60, 45, 30, 15,	0.22-0.45 Increase 0.05 in each experiment	Semi-Circular	Vary fault geometry (length, shape, angle α and β), σ_3 and frictional coefficient of fault plane and σ_3

50 Granite Sample will be used in experiment group 1.

2. Theoretical study for rock mass with one flaws

Through the uniaxial compression adopted in the proposed experiment, it is hope that a theoretical crack model can be developed. The d/t, and β will be assumed as a two of the parameters of the experiment. By changing the d/t and β, the parameters will be fixed to develop a empirical formula so that certain coefficient can be developed.

3. Numerical simulation analysis

Ansys will be used in this part to simulate the mechanism at crack .The ANSYS® Multiphysics™ solution provides the analysis industry's most advanced coupled physics technology, combining structural, thermal, CFD, acoustic and electromagnetic simulation capabilities in a single software product. With the ANSYS Multiphysics solution, you are getting the core physics of the entire ANSYS simulation suite in one convenient package! Applications involve everything from rotating machines (motors and alternators), sensors and actuators, power generators and transformer systems, and Micro Electro Mechanical Systems (MEMS).

Through the ANSYS, whole of the rock sample can be divided many finite element and each element of rock are represented by nodes in the program. After input the geometric property, boundary condition, crack property and the governing equation, through an internal computer numerical analysis, whole of the mechanism can be displayed.

4. Experiments of 3-D surface fracture growth of rock containing multiple joints

Based on the experiments carried out by Wong at el before, mock rock sample were made to contain only one flaw. In extension to the Wong at el, two flaws will be used so that the more reliable mechanism of crack propagation can be obtained, since rock mass always contain multiple joins set in nature.

The sample are bock shape with dimensions of 200mm x 200mm x 80mm(Fig4).The specimens are cured so that the loading area is smooth and compressive stress distributed evenly. Then, a cutting blade material is used to form a fault. Fault geometry will be fixed as semi-circular with fixed length a1 and orientation α. The inclined angle of fault plane is β under a uniaxial compressive stress and 3 conditions. Acoustic emission sensors are attached on the rock surface to investigate the acoustic emission activities during fracture propagation.

Effect of variable factors of experiment on Crack Propagation

1. Dip angle of the flaw α
2. Frictional coefficient along flaw
3. Rotation of the flaw β

The following activities would be held so that

1 Locate the crack initiation and propagation by visual observation, strain and AE measurement under uniaxial compression,
2 Differentiate crack types ie compression tension or shear cracks
3 Determine the controlling factors for crack initiation and propagation
4 Deteremine the 3-D deformation when crack growth
5 Investigate the AE characteristics inconnection with crack propagration

Flaw Deformation in Relation to Crack initiation:

When sample were under compression, the samples would experience deformation. ie volume. Both axial and lateral strains were recorded by strain gauges and data loggers.

The data of strains obtained during compression and at the moment of cracking are used in the following purpose:

1 To verify that cracks would first appear at location where the maximum strains occurred, strain gauges were installed above, below and surrounding the flaw. A video camera was also installed to record the surface.

AE study of Crack Initiation and Propagation

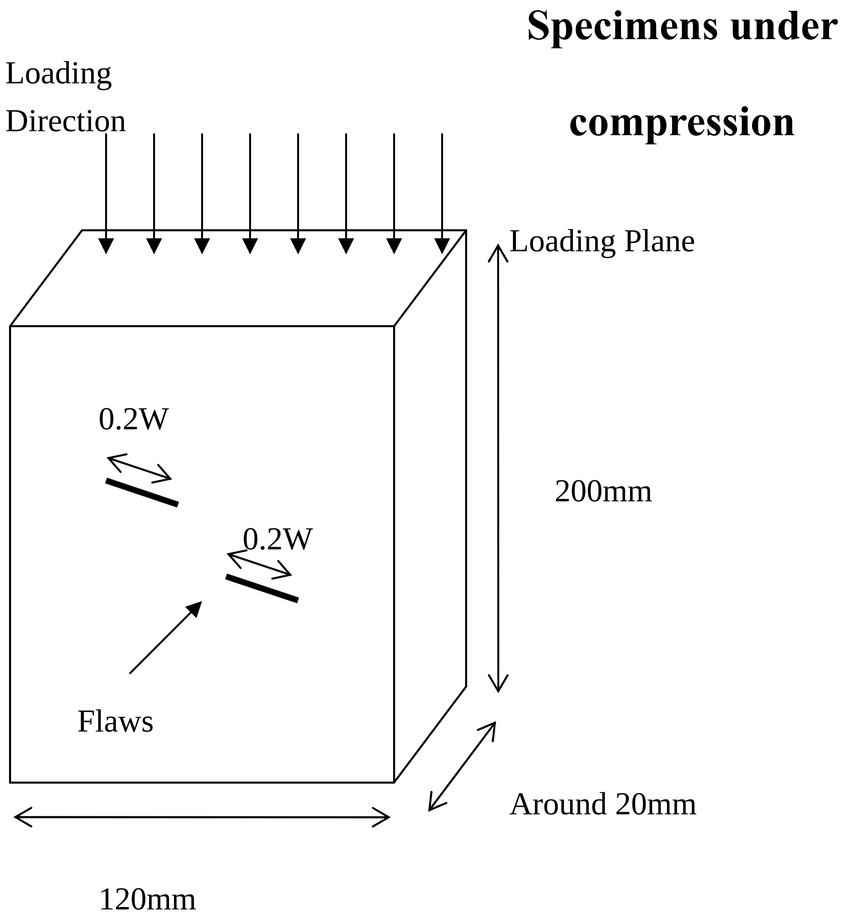
Unlike the research using the PMMA, the material like granite marble, are not transparent. With AE measurement equipment, cracking released AE signals were recorded to locate the crack locating. The crack location was compared with the video observations and the AE energy at different cracking stages ere used to determine the cracking mechanism.

Table 1 Details of group 4 Experiment

Fault material	α (°)	β (°)	Fault length a_1(mm)	Shape of fault	Purpose of study
Group 1 None	75, 60, 45, 30, 15,	75, 60, 45, 30, 15,	0.2W	Semi-Circular & square	Vary fault geometry (length, shape, angle α and β), σ_3 and frictional coefficient of fault plane and σ_3

25Granite Sample will be used in experiment group 4.

Pre-existing flaws setting



5 Project Significance

On Boxing Day 2004, a powerful earthquake off the Indonesian coast triggered a tsunami that reached the shores of three continents leading to the deaths of more than 200,000 people.

In fact, owing to continuous tectonic movement, nature changes continuously. Thus, our understanding of nature may become totally different from the past. Even worse, through review of the unfortunate disaster, it is not difficult to find out that our existing understanding of the nature is also not enough. Tsunami, earthquake such as the disaster in Indian, may occur more frequently on the earth. Even worse these may be not forecasted. Hereby, engineers are responsible to cope with these new challenges.

Thus, some uncertainty of crack propagation, eg anti-wing crack, found researchers need to address the variation of nature and improve the understanding of the crack propagation continuously.

In the proposed research, the main aim is to develop deeper understanding to how a rock cracks. Though this research, I hope I can contribute to the world by the finding and result.

Project Value

By comparing the previous research and existing research, three desired achievements are expected to make contribution to rock mechanics and Mining Sciences.

1 In extension to Robina HC Wong et al’s study, specimens used in the proposed research contain two flaws. In nature, multiple joints sets commonly exist in tectonic rock in forms of joints, faults. It is rare to observe only one flaws exist in rock mass. In the past research, the researchers rarely study a rock mass containing more than one flaw. Based on the existing knowledge gained in previous study, it is time to investigate how cracks propagate in rocks containing 2 flaws. It is also a first step to investigate rock containing multiple joints sets.

2 In order to develop a further understanding of crack propagation, some new parameters are used to find out variation of crack propagation in the proposed research. Through continuous trial and error, it is hoped that this can enhance the understanding of the crack propagation mechanism.

3 A formula is developed to describe how the stress varies under the loading in a rock mass containing a flaw. However, the equation only applies for homogenous material, PMMA. In the proposed research, more effort will be put to develop an empirical formula for heterogeneous material, for example granite, so that people can have an analytical/numerical method to study the crack propagation in the future.

4 Computer simulation will be used to model how a rock mass containing flaw are compressed and how the cracking occurs. It is believed that, with visualization and numerical simulation in computer, researchers can have a clear picture on it for their research related to the crack propagation.

Collaboration

For the sake of being familiar with using the AE measurement equipment, several visit to Institute of Geology, China Earthquake Administration had been held in department of Civil and Structural Engineering in Polytechnic University. Researchers Lau is a expert of using AE measurement equipment. In the Visit, Lau introduce a talk about how to use the AE measurement. In July, Dr Robina HC Wong (Department of Civil and Structural Engineering, The Hong Kong Polytechnic University) had a meeting with them. And several experiment had been held in the meeting. Through these visit and meeting, the collaboration with Institute of Geology China Earthquake Administration will continues.

7 Research Ethics/ Safety Approval

I confirm that approval is not required in the following area(s)

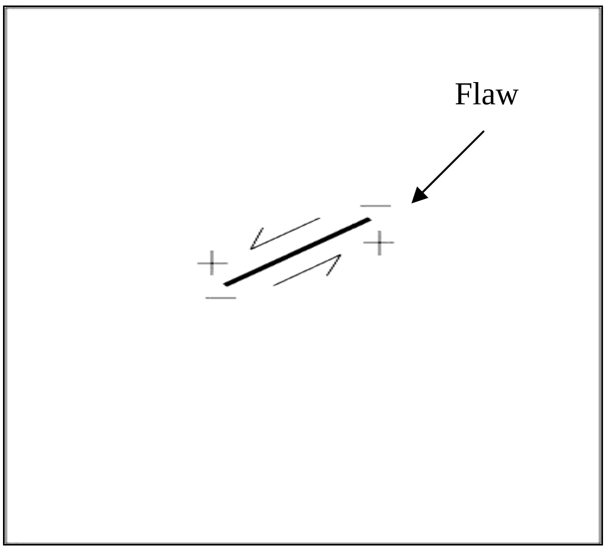
Human Research Ethics
Animal Research Ethics
Biological Safety
Chemical Safety
Ionizing Radiation Safety
Non-ionizing Radiation Safety.

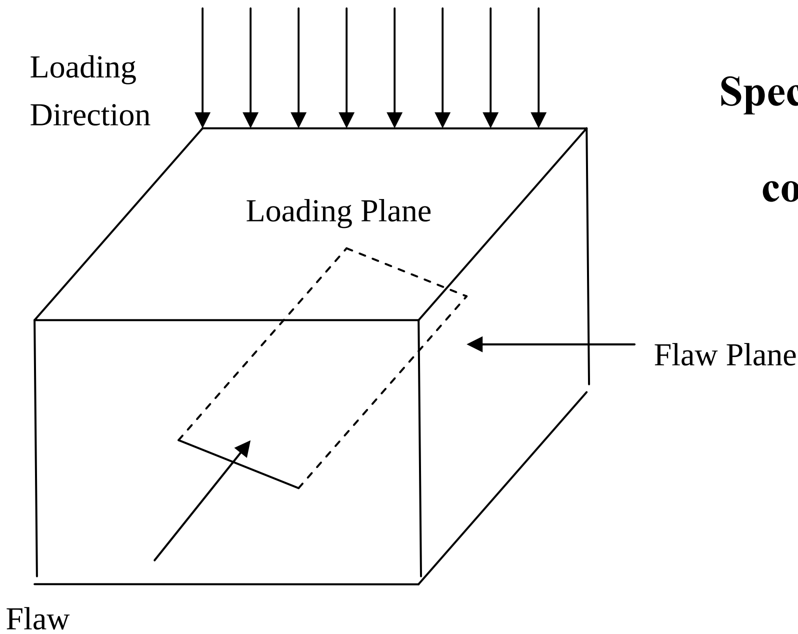
Appendix 1A

Apart from the parameters used in previous in result, new proposed result will be used in the proposed research.

1 Area and projected area of the flaw plane

The projected area is the area of flaw plane project to the plane of loading.

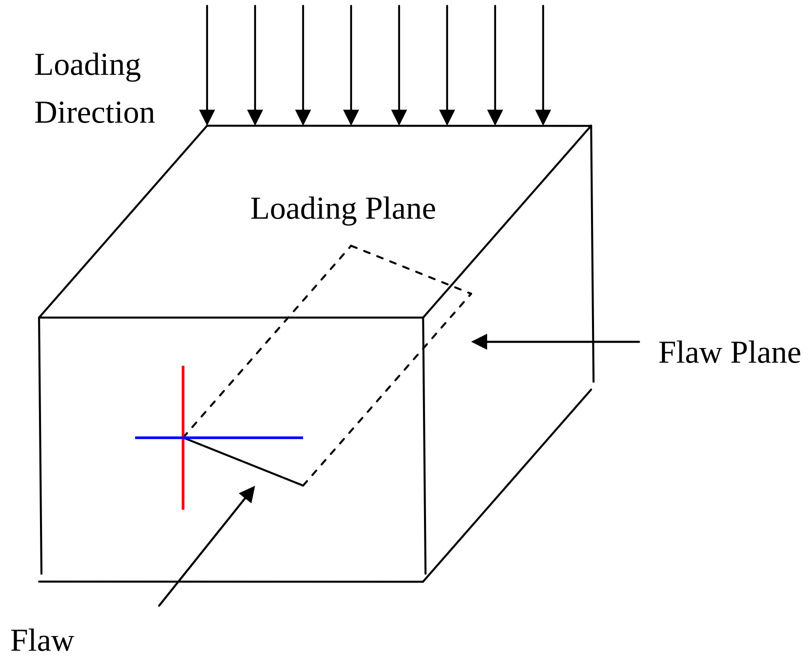




Specimens under compression

Appendix 1B

First Moment of inertia, Second moment of inertia of the flaw plane



As the Blue line and the Red line show above, Firstly, we define the red line as a y axis and blue line as a x axis. By taking moment at two line, we define the first moment of inertia and second moment inertia of the flaw plane. It is assumed that the moment of intertia is one of the parameters affect whole of the mechanism of anti cracking.

Reference

Wong Robina H. C. Guo Y.S.H., Chau K.T. Zhu W.S. and Li S.C. Anti-wing crack study from 3-D surface flaw in real rock.

Murakami, Y. and Natsume, H. 2002. Stress singularity at the corner point of 3-D surface crack under mode II loading, JSME Int. J. A-Solid Mech., 45(2), 161-169.

Bazant, Z.P. and Estenssoro, L.F. 1979. Surface singularity and crack propagation, Int. J. of Solids and Structures 15, 405-426.

Wong, T.F., Wong,R.H.C., Jiao,M.R., Chau, K.T. and Tang, C.A. 2004. Micromechanics and Rock Failure Process Analysis, Key Eng. Materials, 261-263,39-44.

Wong Robina H. C, Huang ML Jiao MR Tang CA and Zhu W The Mehcanisms of crack propagation form surface 3-D fracture under uniaxial compression