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Behaviour of Limestone Rock with Opening under Confining Pressures

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ABSTRACT

Many factors may affect the stability of rock mass in terms of strength and deformability. Such factors are the loading conditions, presence of natural weakening features and manmade openings. In the present study, an evaluation of stresses and deformations is carried out through experimental and numerical analyses for plane-strain and plane-stress conditions. The study includes the effect of circular opening on strength, deformation and failure mode of limestone rock under various confining pressures (σ_3=0, 1, 2 and 3 MPa).

The results show that the opening causes a reduction in strength of rock but the effect of the presence of the opening reduces with the increasing the confining pressure from 1MPa to 3MPa. Samples tested under plane-strain condition give strength higher than those tested under plane-stress condition. The differences between both cases reduce under high confining pressure 3MPa. Failure pattern showed splitting type failure in an unconfined case (σ_3=0) and changes to shear type associated with cracks inclined at 15°-30° in solid sample; while cracks inclined at 45° in sample with opening as the confining pressure increases. The presence of opening resulted in an increase in the deformation of the sample. The deformation of opening increases with increasing confining pressure to 1MPa, thereafter, it reduces. Numerical analysis gives higher results than experimental tests.

Keywords: Biaxial test; Confining pressure; Plane-strain; Plane-stress; Rock mass; Opening

1. INTRODUCTION

The instability conditions of structures founded in/on rock may be affected by many factors such as rock mass strength, in-situ stresses, presence of opening ,nature of ground condition and others. The stress conditions play an important role in the governing the behaviour of rock mass and in turn the stability of surrounding structures. Many previous studies have investigated the behaviour of rock strength, deformation and failure types in form of disc or ring with opening (Hoskins, 1969; Hudson, 1969; Gay, 1976). The fractures in quartz rock with square opening initiated from corners as contours different from that occurred in elliptical opening. In both cases, a reduction in strength associated with the opening (Hoek, 1966).

Liu et al. (1972) tested a planar specimen (127mm×127mm×12.7mm) of concrete material and found that the biaxial compressive strength is 20% more than the uniaxial value. Brown (1974) recorded 15% difference for marble rock prism (76mm×76mm×25mm).

Labuz et al. (1996) subjected a biaxial stress mode on a sandstone rock prism. The rupture zone may be associated with a fracture in the transition from splitting to shearing failure and the failure plane was not fully formed at the peak. The strength drops from 204kN to 194kN due to the presence of circular opening in sample.

Fakhimi et al. (2002) performed a biaxial compression test on a sandstone specimen (100mmx100mmx40mm) with a circular opening of 14mm diameter to simulate a load-type failure around an underground excavation in brittle rock. It has been shown that the damage within the rock is associated with microcraking inclined at an angle between 50° and 70° with stresses concentrated on the periphery of opening. In addition, a numerical analysis carried out using PFC-2D package to investigate the fractures pattern. The fractures extended from the opening vertically towards the boundary of samples similar to that observed in experiments.

Kulatilake et al. (2006) studied the failure modes and strength of rock-like material. Both intact as well as jointed blocks of size (356mmx78mmx25mm) having different joint configurations were tested under biaxial compressive loadings. The main finding is that the intermediate principle stress plays an important role on rock mass strength and failure pattern. The splitting failure associated either with a low confining pressure or without, while the shear failure is accompanied with medium confinement. A combined failure is observed along with high confinement. Similar findings have been reported by Noferesti and Rao (2010), they observed a tensile splitting fracture under low confining pressure (less than 3.1 MPa) and with increasing the confining pressure, the shear cracks occurred.

Alobaydi et al. (2009) showed a reduction in strength and modulus of elasticity of rock samples with increasing size of opening and the maximum effect of opening is when the ratio of the opening size to diameter of sample is in range of 0.2-0.25. The sandstone rock is significantly affected by the opening comparing with limestone and gypsum rocks.

Sagong et al. (2011) investigated the behaviour of rock-like material containing joints with a circular opening under biaxial compression through experimental and numerical analyses. The dip of joints was 30°, 45° and 60° to the horizontal. Under the biaxial condition, tensile crack initiation and propagation occurs around the hole in a low joint dip angle (i.e. 30° dip with horizontal), while the failure of mode in shear occurs in a sample with joint dipping 60°; and a combined failure of tensile and shear is exhibited in sample with joint dip 45°. Similar findings were reported in numerical and experimental studies of (Lee et al., 2012; Mughieda, 2012). The transition of the failure pattern from splitting to shear depends on lateral stress (Liu, 2012).

Wang and Huang (2013) performed a numerical study using FLAC-code on rock samples containing joints with different dips and circular opening at their center. The shear strength and failure pattern depends on the dip angle of joint and the maximum strength of 2.75MPa is without joint and the lowest strength of 2.2MPa is in case of dip angle of 45°.
Reliable evaluation of stresses and displacements is an essential aspect in the analysis and design of foundation and excavation in rock mass. Such problems are associated in geotechnical engineering in case of tunnels, caverns and foundation resting on rock. Various techniques have been proposed and developed to estimate stresses, but approach to the actual value is not an easy task. Hence, all existing methods suffer from certain deficiencies and limitations. A true stress path that generated in the field must be followed during experimental and theoretical analyses. In the present study both numerical and experimental analyses have been carried out to evaluate the strength, deformation and failure type of limestone rock under various confining pressures.

2. EXPERIMENTAL WORKS

2.1 Material Properties

A limestone rock was used in this study selected from Nineveh province. The mechanical properties of the rock were, dry density of 1840kg/m^3, saturated density of 2000kg/m^3. The shear strength parameters (c and ϕ) of the rock were obtained from triaxial compression test which gives a cohesion value of 6.5MPa and an angle of internal friction of 36°. The unconfined compressive strength is 11.2MPa.

2.2 Sample Preparation

The size of rock sample governs the demand load capacity of the test equipment. Prismatic rock sample was (100mmx100mmx200mm) solid and having a circular opening (12.5mm diameter) at the center of sample and represented the plane strain condition, while a (200mmx200mmx50mm) solid prism having an opening (25mm) at its center represented plane stress condition as shown in Fig. 1.

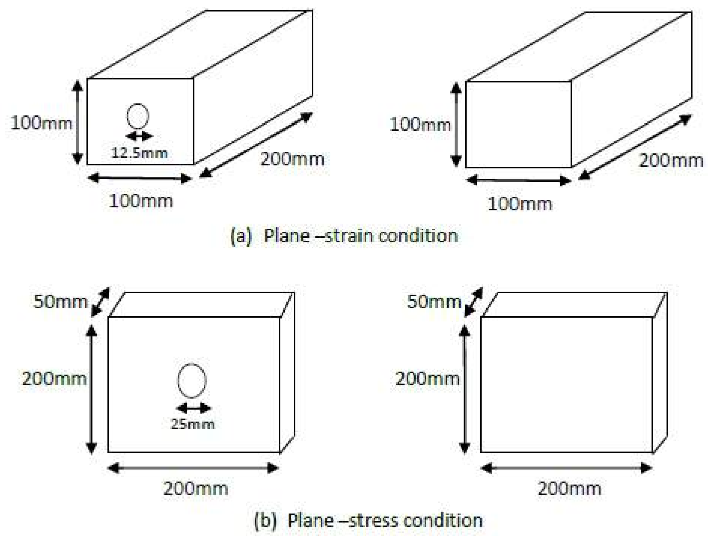

Fig. 1 - Samples size with and without opening

2.3 Testing Procedures

The uniaxial and biaxial compression tests on prismatic rock samples were performed using the hydraulic type biaxial frame (Fig. 2a), designed and fabricated at the University of Mosul. The lateral load was applied manually through oil pressure pump in system shown in Fig. 2b. The axial and lateral loads were applied in a sequence manner. Both increased sequentially in a stepwise manner up to a required lateral pressure which kept constant through the experiment. Then, the axial load increased with a constant loading rate at 1mm/min until the sample failed. Different lateral pressures were selected as 0, 1, 2 and 3 MPa. An LVDT was used to monitor the axial compression of the sample alongwith TME type strain gauges fixed on crown and sidewall of opening to monitor the closure of opening.

(a) (b)

Fig. 2 - Test of samples under biaxial loading condition (a) hydraulic type biaxial frame (b) oil pressure pump system

3. NUMERICAL MODELLING

3.1 Model Properties

The properties of the rock model are presented in Table 1. The parameters are directly or indirectly obtained from laboratory tests that were used for numerical analyses. The Young's modulus was estimated using a tangent modulus of stress-strain curves of the uniaxial compression test at the 50% of the failure stress level. The Poisson's ratio was estimated to be 0.25. The effect of dilatancy was not considered in the present study, i.e., ψ=0.

Table 1 - Rock properties in numerical analysis

Properties	Units	Material Rock
Model	--	Mohr-Coulomb and Elastic Linear
γ_d	kN/m^3	18.4
γ_{sat}	kN/m^3	20
E	MPa	500
μ	-	0.25
c	MPa	6.5
□	degree	36
ψ	degree	0

3.2 Numerical Simulation

In order to simulate the experiment, a two dimensional finite element method was used. Two types of modelling were prepared, one with dimensions of 100mmx100mm and the other of 200mmx200mm for plane-strain and plane-stress respectively. A numerical test on a sample without and with a circular hole was performed as shown in Fig. 3.

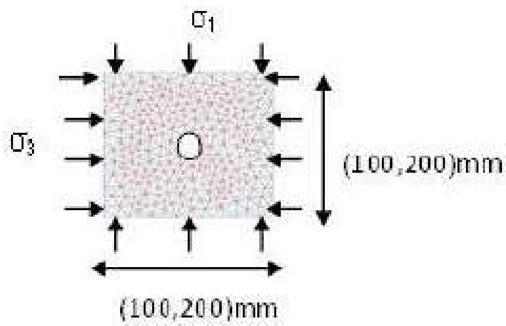

Fig. 3 - Numerical Modeling

4. RESULTS AND DISCUSSION

The present study investigated the behaviour of rock around an opening in a rock mass through experimental and numerical analyses. The study includes the effect of circular opening on strength, deformation and failure mode of limestone rock under various lateral confining pressures (σ_3=0, 1, 2 and 3MPa). The results are presented for plane-strain and plane-stress conditions and a comparison between numerical and experimental studies has been performed.

4.1 Variation of Strength with Confining Pressure

The experimental results displayed in Figures 4 and 5 show the increase in strength of sample with increasing lateral stress for both plane-strain and plane-stress respectively. The samples tested under plane-strain condition (Fig. 4) give higher strength than those displayed by plane-stress condition (Fig. 5). This may be attributed to the effect of buckling in plane stress, while the effect of intermediate stress is higher in plane-strain which causes an increase in modulus of elasticity and in turn the strength. Table 2 shows that the stresses at failure of an unconfined sample with opening in a plane-strain is higher by 1.57 times of those in plane-stress, while it is of order of 1.21 times when lateral pressure increased to 3MPa. The influence of opening and type of sample on strength reduced with lateral pressure.

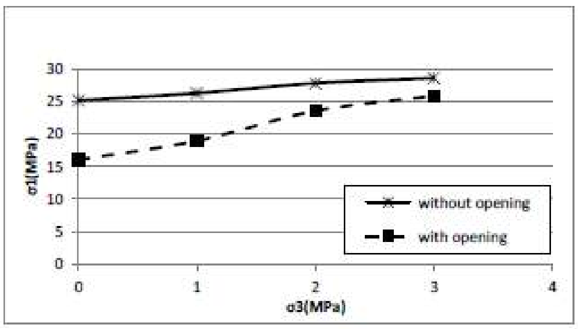

Fig. 4 - Variation of failure stress with confining pressure (Experiment - plane strain)

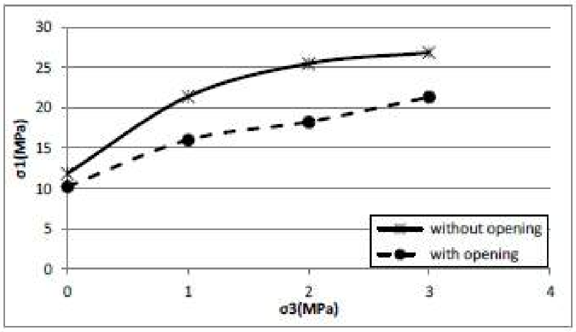

Fig. 5 - Variation of failure stress with confining pressure (Experiment - plane stress)

The results of numerical analyses presented in Fig. 6 and Table 2 show that the maximum reduction in strength due to the presence of opening in unconfined sample is 2.22 times than the solid one without opening. With increasing lateral stress, the effect of opening reduces and this behaviour coincided with the past experimental results. However, numerical the results are higher than those obtained from experiments. This may be due to possibility of presence of invisible stratification and micro-cracks and weak features in tested rock that are not implemented in the numerical analysis due to assuming the rock model as a continuum model.

4.2 Failure Pattern

Figures 7 and 8 presented the modes of failure under uniaxial and biaxial loading respectively. The unconfined (σ_3=0) intact rock sample exhibited a tensile splitting mode of failure through the rock material in direction normal to the direction of lateral axis for both plane-strain and plane-stress conditions as shown in Figure 7. For sample with an opening, the tensile cracks initiation and propagation occurs around the opening under uniaxial compression.

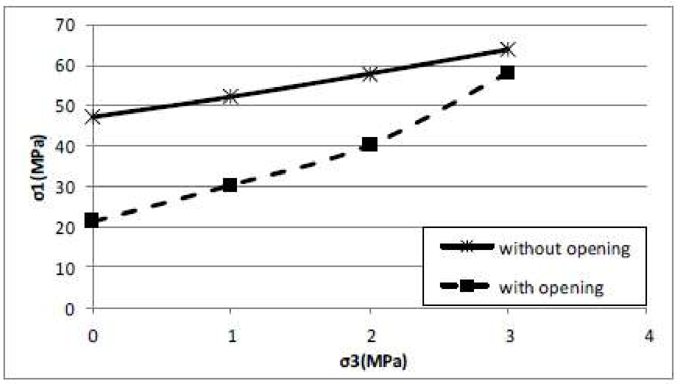

Fig. 6 - Variation of failure stress with confining pressure as per the numerical analysis

Table 2 - Experimental and numerical results of failure stress

σ_1 (MPa) at failure						
	Sample without opening			Sample with opening		
σ_3 (MPa)	Pane Strain	Plane Stress	FEM	Pane Strain	Plane Stress	FEM
0	25.10	11.83	47.20	16.02	10.20	21.23
1	26.22	21.37	52.20	18.91	16.00	30.31
2	27.75	25.47	57.93	23.50	18.25	40.24
3	28.53	26.83	63.69	25.80	21.30	58.18

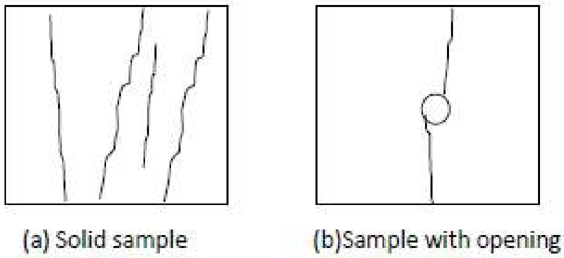

Fig. 7 - Mode of failure for solid and samples with opening (σ_3=0)

On the other hand, under biaxial compression, the cracks were inclined at 15°-30° with horizontal in solid sample (Fig. 8a), while in sample with opening the cracks were also initiated around the hole but the failure mode changes from splitting to shear type failure associated with cracks dipping at 45° from horizontal (Fig. 8b). Accordingly, it can be said that the failure transition from splitting type to shear type failure is observed with increasing confining pressure.

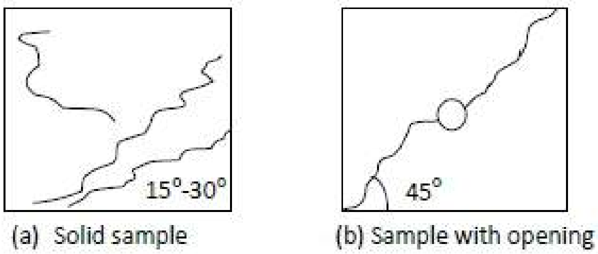

Fig. 8 - Mode of failure for solid and samples with opening (σ3>0)

4.3 Variation of Deformation with Lateral Pressure

The variation of deformation with confining pressure (σ_3) of rock samples tested experimentally in the plane-strain and plane-stress conditions are shown in Figs. 9 and 10 respectively. In case of plane-strain the deformation increases with increasing confining pressure up to σ_3=2MPa and then reduces (Fig. 9), while in plane-stress the deformation increases with confining pressure (Fig. 10). The maximum deformations recorded for plane-strain samples are 1mm and 0.4mm for samples with and without opening respectively. Under all confining pressures, the plane-strain deformations are higher than those observed in the plane-stress. The differences between the two cases are due to presence of opening which causes an increase in the deformation of samples.

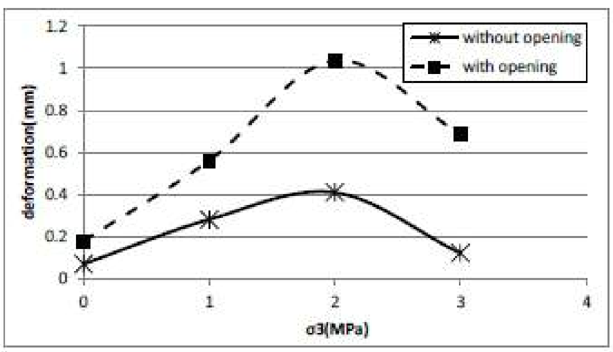

Fig. 9 - Variation of deformation with confining pressure (Experiment: plane-strain)

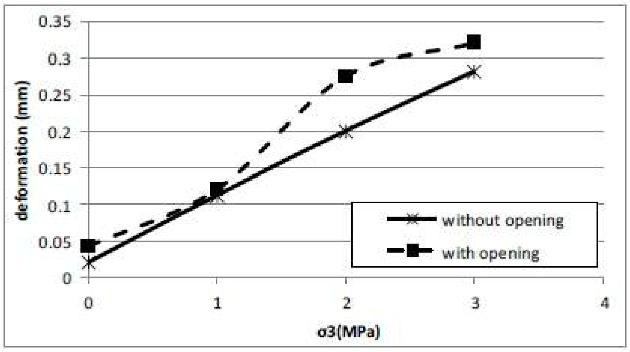

Fig. 10 - Variation of deformation with confining pressure (Experiment: plane-stress)

Figure 11 shows the variation of deformations with confining pressure obtained from the numerical analyses. Similar trends to that observed from the experimental tests of plane-stress condition are seen with approximately equal values.

The deformed shape of the opening has been obtained by measuring the vertical (δ_v) and horizontal (δ_h) deformations at crown and sidewall of opening respectively. Both vertical and horizontal deformations of opening increase with increasing confining pressure until 1MPa which show a reduction after that as shown in Figs. 12 and 13 alongwith Table 3. The maximum vertical deformations recorded for plane-strain and plane-stress are 0.043mm and 0.056mm respectively, and the horizontal deformations are 0.013mm and 0.009mm. Lower values are obtained from numerical analysis.

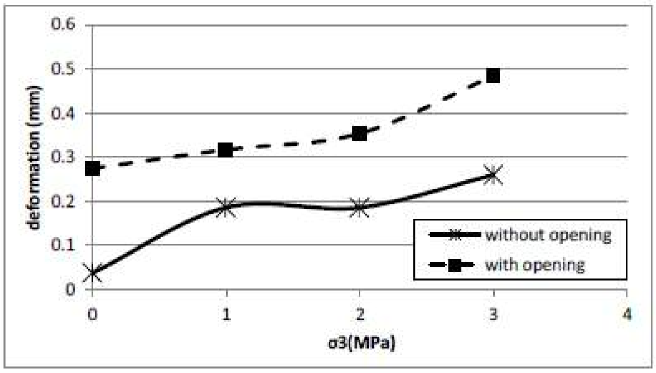

Fig. 11 - Variation of deformation with confining pressure as per numerical analysis

Table 3 - Vertical and horizontal deformations of the opening

Deformation of opening (mm)						
	At crown			At side wall		
σ_3 (MPa)	Pane Strain	Plane Stress	FEM	Pane Strain	Plane Stress	FEM
0	0.033	0.021	0.0195	0.006	0.0051	0.0047
1	0.056	0.043	0.0196	0.013	0.009	0.00481
2	0.044	0.031	0.0195	0.008	0.0056	0.00483
3	0.040	0.031	0.0195	0.007	0.0056	0.00483

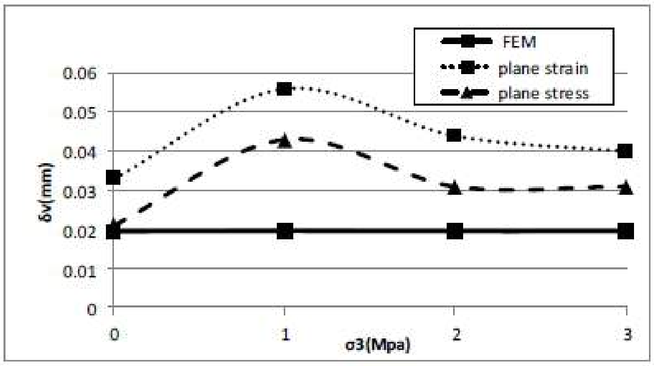

Fig. 12 - Variation of vertical deformation with confining pressure

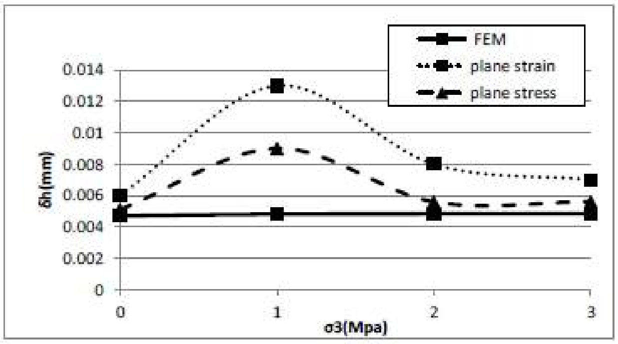

Fig. 13 - Variation of horizontal deformation with confining pressure pressure

5. CONCLUSIONS

From the results of experimental and numerical analyses, the following conclusions can be drawn:

- The presence of opening causes a reduction in strength of rock. The influence of opening on strength of the rock reduces with increasing confining pressures from 1MPa to 3MPa.
- Samples tested under plane-strain have strength higher than those tested under plane-stress condition. Biaxial strength is significantly more than the unconfined compressive strength.
- The difference in strength of samples tested under plane-strain and plane-stress reduces under higher confining pressure especially for solid sample.
- Failure pattern of solid sample showed splitting type failure in an unconfined case, while the cracks initiated at an angle of 15°-30) with horizontal in confined case.
- Failure pattern of sample with opening consists of cracks extended from opening boundary and the failure changes from splitting to shear type as confining pressure increases. The crack angle is about 45° from the horizontal.
- The deformations of plane-strain samples are higher than those exhibited by plane-stress samples and the differences are higher in the presence of opening.
- The presence of opening resulted in an increase in the deformation of sample.
- The deformation of opening increases with more confining pressure up to 1MPa and then reduces.
- Numerical analysis gives strength higher than that obtained from the experimental work.

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