Analysis of Crack Coalescence in Rock Bridges Using Neural Networks

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ABSTRACT

Fractures, in the form of joints and micro-cracks, are commonly found in natural rocks, and their failure mechanism strongly depends on the crack coalescence pattern between pre-existing flaws. Determining the failure behavior of non-persistent joints is an engineering problem that involves several parameters such as mechanical properties of rock, normal stress and the ratio of joint surface area to the total shear surface area. To investigate the impact of such parameters on crack coalescence, the artificial neural networks can be applied. By this way, a number of networks of threshold logic units, facilitating with adjustable weights, have been tested. For training process, here the computational method was a back-propagation learning algorithm. In the present paper, the input data for crack coalescence consists of values of geomechanical and geometrical parameters. As an output, the network estimates the crack type coalescence (i.e. mode I, mode II or mixed mode III) that can be used to analyze the stability of geomechanical structures. The paper measures the network performance and then it compares the results with those acquired through an experimental method. The analysis shows that the most influential parameters on the crack coalescence are the joint coefficient (JC) i.e. the ratio of the joint surface to the total shear surface area, and normal stress.

Keywords: ANN; Back-propagation learning algorithm; Crack coalescence; Rock bridge; Non-persistent joint

1. INTRODUCTION

It is well known that the strength of rock mass is reduced mainly by the rock joints. However, the failure in the rock mass, some time, is limited to a single discontinuity alone. Generally, several discontinuities exist with different sizes that constitute a combined shear surface hence; the intact rocks located between neighboring discontinuities, called the rock bridges (RB) (see the definition in Fig. 1), are of a great significance for shear resistance of the failure surface (Eberhardt et al., 2002; Hatzor et al., 2004; Li et al., 2005).

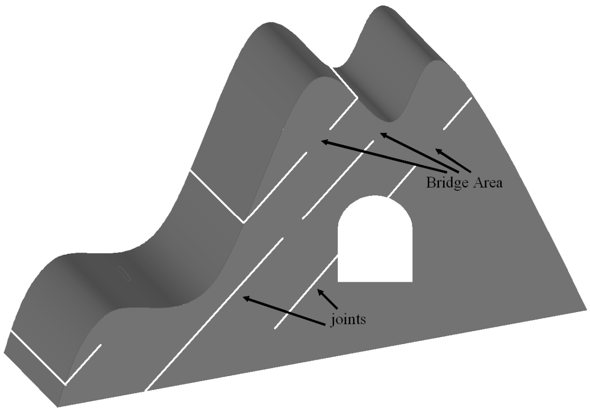

Fig. 1 - Rock bridges in non-persistent jointed rock

In hard rock formations, presence of a small percentage of intact rock bridges, in the joint-coplanar area, could provide internal or self-supporting load-carrying capacity which acts similar to the conventional support systems. This particular aspect of intact rock bridges has simply been ignored in various rock engineering problems such as foundation of dams, rock slopes and underground openings stability etc. As such, consideration of such an inherent support mechanism could not only lead to reduce support requirement rather it is safer and efficient technically-cum-economically for structural development. In Fig. 2a, the RB's tensile strength allows load transfer from normal to a wedge-bounding surface. This affords direct gravity support and increases the wedge stability. Fig.2b shows that the RB's shear strength increases the wedge stability i.e. tensile or shear-resistance along the co-planar joints in the given cases.

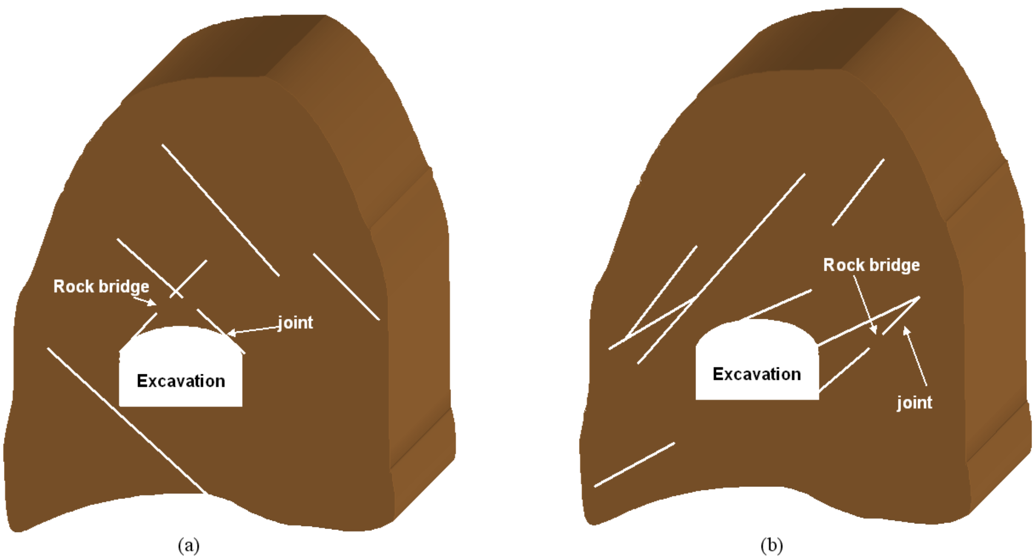

Fig. 2 - Cases of potential structural instability: a) tensile resistance due to rock bridges b) shear resistance due to rock bridges

Evidently, these internal support systems are responsible for enhancing the safety factor in geomechanical projects which, in turn, reduces the cost of the external support arrangements.

The coalescence of non-persistent joints acts as a critical factor in controlling the mechanical behavior of brittle rocks when the rock bridges are on the verge of failure. At the same time, crack propagation and coalescence processes could also lead to the rock failure in slopes, foundations and tunnels.

For example, in 1991, a large block of rock slide (about 2000 m^3) occurred at a quarry at Shau Kei Wan in Hong Kong. At the time of the incident, blasting had been taking place above a disused quarry for some time in conjunction with the site formation works for the construction of a new housing estate. The investigation report (GEO Landslide Studies, 1991) shows that the pre-existing parallel joints, dipping toward the rock slope surface, were not fully persistent before the slide occurred. It is likely that the crack initiation and growth at the tip of the joints may have been induced by the blasting vibration. Therefore, it is believed that crack coalescence was the cause of the rock slope failure. However, a comprehensive study on the shear failure behavior of jointed rock could provide a better understanding of both local and regional rock instabilities, leading to an improved design for rock engineering projects.

Using direct shear tests, few researches have so far been conducted on the coalescence pattern between the two parallel cracks in both modeling materials and natural rocks (Lajtai, 1969a, 1969b; Savilahti, 1988; Savilahti et al., 1990; Li et al., 1990.; Ghazvinian et al., 2008a). Also, a number of experimental studies have been carried out to investigate the crack initiation, propagation and coalescence in uniaxial or biaxial test conditions (Einstein et al., 1983; Reyes and Einstein, 1991; Shen et al., 1996; Bobet and Einstein, 1998; Wong et al., 1998, 2001; Sagong and Bobet, 2002; Mughieda and Khawaldeh, 2006).

The above researches have identified two types of crack patterns in the failure processes of rock bridges; namely wing cracks and secondary cracks. The failure typically starts with the wing cracks which are tensile and initiated at the tips of the joint and propagated in a curvilinear path in the direction of the applied axial load. Secondary cracks appear later and are generally described as shear cracks or shear zones (Fig. 3).

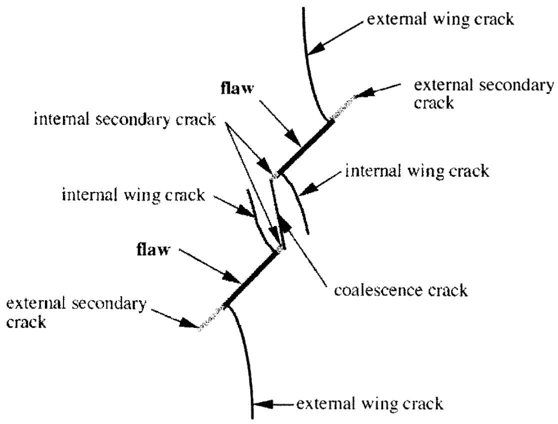

Fig. 3 - Crack patterns recognized in pre-cracked specimens of rock materials in uniaxial compression (Shen, 1995)

Most of the previous studies have focused on the effects of configuration such as length, orientation of rock bridges, orientation of joint segment and spacing between the joint sets on the mechanisms of crack initiation, propagation and coalescence in the rock bridge area. However, simultaneous effects of normal stresses, mechanical properties and the ratio of joint surface area to the total sheared area, on the pattern of crack coalescence, are not considered under the direct shear test. Since, such experimental tests are difficult to conduct due to all the above-mentioned considerations; the neural network has been duly adapted.

With the introduction of neural networks, scientists and engineers were attracted to apply this approach in their researches in the proposed area. This growing interest is stemming from the fact that the learning machines have an excellent performance in the issues related to non-linear function approximation, data classification, clustering and non-parametric regression or as simulations of the behavior of biological neurons and pattern recognition. The present study tries to investigate the validity by utilizing artificial neural networks in the prediction of the crack coalescence mode (i.e. tensile mode (Type I), the shear mode (Type II) and the mixed mode (Type III)) that can be applied to analyze the stability of geomechanical structures.

The study conducted by Jing (2003) and Jing and Hudson (2002) showed that all numerical modeling methods try to achieve one-to-one mechanism mapping. In other words, a one-to-one mechanism, occurring in reality, is modeled similar to a given stress–strain relationship. The term ‘one-to-one mapping’ refers to the direct modeling of geometry and physical mechanisms either specifically, or through equivalent properties. The neural network approach is a ‘non-one-to-one mapping’ method and can be termed as semi-direct. Since it provides prediction capabilities, this model has gained interest in the area of rock and soil mechanics.

From the artificial neural networks perspective, the approach to the problem of crack coalescence requires sophisticated modeling techniques, experience, and in-depth knowledge of engineering as well as a vast amount of experimental data.

The neural network modeling approach has already been applied to a variety of areas in rock and soil mechanics (Millar and Hudson, 1994; Sklavounos and Sakellariou, 1995; Goh, 1995a, b; Najjar and Basheer, 1996; Gangopadhyay et al., 1999; Deng and Lee, 2001; Yang and Rosenbaum, 2001; Chang et al., 2002; Pekcan et L., 2008, Yasrebi and Emami, 2008). Ghazvinian et al. (2008a), using neural network tools, have investigated the failure mode in rock bridges.

Whereas the investigation of the simultaneous effects of normal stresses, the mechanical properties of model material and the ratio of joint surface area to the total sheared area on the pattern of crack coalescence is difficult and problematic by experimental approach, therefore the neural network tool has been used to take into account triple effect on the crack coalescence mode.

2. EXPERIMENTAL STUDIES

The discussion of experimental studies is divided into four sections. The first section discusses the physical properties of a modeling material, the second section is describing the technique of preparing the jointed specimens, the third section is focused on the testing procedure in loading the jointed specimens and the fourth section considers the general experimental observations and discussions.

2.1 Modeling Material and its Physical Properties

Full scale testing on a rock mass containing a specified number of joints with predetermined configuration is seldom possible. The common procedure to the problem is to conduct experiments under conditions that are attainable, but the patterns of discontinuities involved in the prototype have to be preserved in the model experiments and the modeling material must behave similar to rock mass. The most comprehensive review on how to select a modeling material for rocks is probably by Stimpson (1970). Also there are number of modeling materials that can be considered as rock-like (Labuz et al., 1996; Momber and Kovacevic, 1997). The present investigation has used gypsum, a material used by Reyes and Einstein (1991), Takeuchi (1991), Shen et al. (1995), Bobet and Einstein (1998) and Ghazvinian et al. (2007) during their respective courses of studies. Gypsum is chosen because, in addition to behave same as a weak rock, is an ideal model material with which a wide range of brittle rocks can be represented (Nelson, 1968); second, all the previous experiences and results can be incorporated and the earlier findings can be compared with the new ones; third, it allows to prepare a large number of specimens easily; Forth, repeatability of results.

Here, five different admixtures with different mechanical properties have been used. Concurrent with the preparation of specimens and their testing, uniaxial compression and indirect tensile strengths of the intact material was also tested in order to control its variability. The uniaxial compressive strength (UCS) of the model material is measured on fabricated cylindrical specimens with 56 mm in diameter and 112 mm in length. The indirect tensile strength of the material is determined by the Brazilian test using fabricated solid discs of 56 mm in diameter and 28 mm in thickness. The testing procedure of Brazilian test and uniaxial compressive strength test complies with the ASTM C496-71 (1971) and ASTM D2938-86 (1986) codes respectively. Table 1 summarizes the mechanical properties of the material.

Table 1 - Mechanical properties of five different mixtures of gypsum material

Samples	Uniaxial compressive strength (σ_c) MPa	Tensile strength (σ_t) MPa	Young;s Modulus (E) MPa	Poisson's Ratio (υ)
Type I	4	0.5	690	0.14
Type II	6	0.8	1030	0.15
Type III	8	1	1370	0.16
Type IV	10	1.2	1710	0.17
Type V	14	1.5	3500	0.2

2.2 The Technique of Preparing the Jointed Specimens

The procedure developed by Bobet and Einstein (1998) for preparing open non-persistent joints was used in this research with some modifications. Following is a description of the procedure of making open coplanar non-persistent joints.

The material mixture is prepared by mixing water and gypsum in a blender; the mixture is then poured into a steel mold with internal dimension of 15×15×15 cm. The mold consist of four steel sheets, bolted together and of two PMMA plates 1/6 inch thick, which are placed at the top and bottom of the mold, as shown in Fig 4; the top plate has two rectangular openings used to fill the mold with the liquid gypsum mixture. The upper and the lower surfaces have slits cut into them. The opening of slits is 1 mm (0.02 inch) and their tract varies based on the width of the joints.

Through these slits, greased metallic shims are inserted through the thickness of the mold (to produce open joints) before pouring the gypsum. The mold with the fresh gypsum is vibrated and then stored at room temperature for 8 h afterward, the specimens un-molded and the metallic shims pulled out of the specimens; the grease on the shims prevents adhesion with the gypsum and facilitates the removal of the shims.

As the gypsum seated and hardened, each shim leaves in the specimen an open joint through the thickness and perpendicular to the front and back of the specimen. Immediately after removing the shims, the front and back faces of the specimens are polished and the specimen is stored in laboratory for 4 days. At the end of the curing process, the specimens are tested. It does not appear that the pull out of the shims produces any damage to the flaws. Since the aperture of joints is made to be 1 mm, the joint roughness does not have any effect on the rock bridge failure.

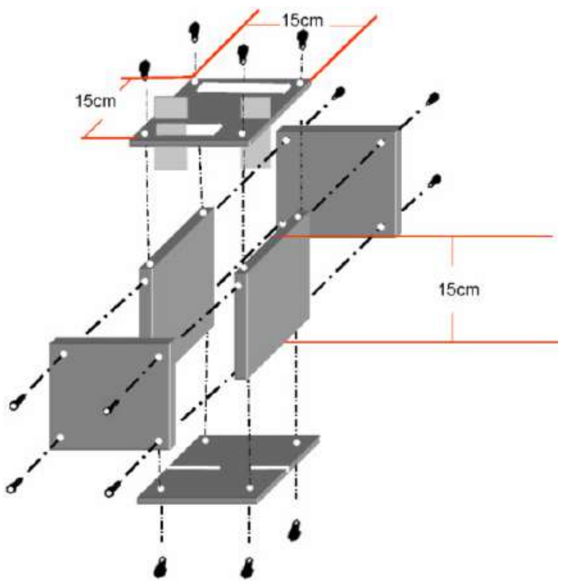

Fig 4 - The model used for fabrication of gypsum specimens

A total of 280 physical models consisting non-persistent joints with 15×15×15 cm dimensions have been prepared. The joints and rock bridges are simulated on the same plane (Fig. 5).

Fig.5 - Physical models consisting of non-persistent joints

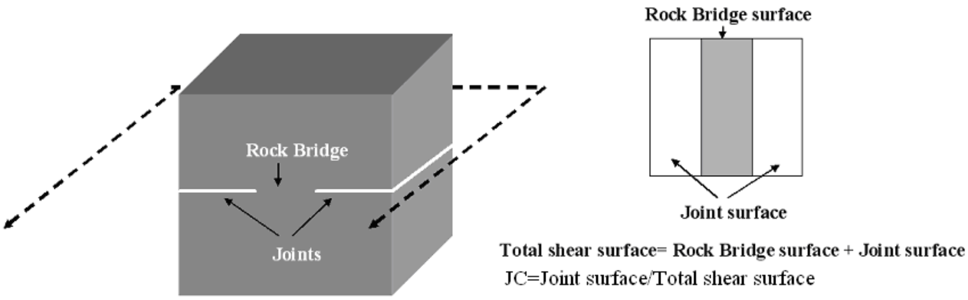

Fig.6 - Configuration of non-persistent joints

The rock bridges have occupied various areas of the total shear surfaces. Based on the change in the area of the rock bridges, it is possible to define the Jointing Coefficient (JC) as the ratio of joint surface to the total shear surface areas (Fig. 6).

From each mixture, 7 physical models with different JC (Jointing Coefficient varies from 0.05 to 0.65 with increments of 0.1) have been prepared. In order to study the complete failure behavior in the discontinuous joint, from each geometry, eight similar blocks were prepared and were tested under 8 different normal stresses (σ_n): $\sigma_c/16$ to $\sigma_c/2$ MPa with increments of $\sigma_c/16$ MPa (table 2).

Table 2 - Different conditions for direct shear tests

Uniaxial strength of models σ_c (MPa)	Jointing Coefficient (JC)	Normal stress σ_n (MPa)
	0.05	$\sigma_c/16$ to $\sigma_c/2$ with increments of $\sigma_c/16$ MPa
4	0.15	$\sigma_c/16$ to $\sigma_c/2$ with increments of $\sigma_c/16$ MPa
6	0.25	$\sigma_c/16$ to $\sigma_c/2$ with increments of $\sigma_c/16$ MPa
8	0.35	$\sigma_c/16$ to $\sigma_c/2$ with increments of $\sigma_c/16$ MPa
10	0.45	$\sigma_c/16$ to $\sigma_c/2$ with increments of $\sigma_c/16$ MPa
14	0.55	$\sigma_c/16$ to $\sigma_c/2$ with increments of $\sigma_c/16$ MPa
	0.65	$\sigma_c/16$ to $\sigma_c/2$ with increments of $\sigma_c/16$ MPa

2.3 Testing Program

Testing of the specimens is done in direct shear until failure. These tests have been performed in an especially designed shear machine which complies with the requirements that were found to be indispensable in conventional shearing devices. Consequently, the shear boxes were provided with a high stiffness and with only one degree of freedom for the lower shear box in the horizontal direction and for the upper one in the vertical direction, corresponding to a shear displacement or dilation, respectively. Unwanted rotations and uncontrolled loading conditions could be prevented this way. The second main requirement comprised the possibility to permanently observe the cracking process in the sheared specimens from the above view of the shear box. Figure 7 shows the direct shear set up that has been used in the present study.

A total of 280 direct shear tests have been performed on specimens with discontinuous joints. The tests are performed in such a way that the normal load was applied to the sample in advance and then the shear load is adopted. Loading is carried out using displacement control at a rate of 0.002 mm/s.

Fig.7 – General set-up of direct shear testing equipment

The vertical displacement, crack pattern and coalescence stress, are the basic measurements and observation made in this tests. From upper shear box, it was observed that the pre-existing joints remain open until the coalescence; immediately afterwards the joints close, at least partially. The shearing process of a discontinuous joint constellation begins, as one would expect, with the formation of new fractures which eventually transect the material bridges and lead to a through-going discontinuity.

2.4 Observations and Discussion of Experimental Results

By observing the failure surface during and after the tests, it is cleared that the crack pattern is always a combination of only two types of cracks: wing cracks and shear cracks. Wing cracks start at the tip of the joints and propagate in a curvilinear path as the load increases. Wing cracks are tensile cracks and they grow in a stable manner, since an increase in load is necessary to propagate the cracks. Shear cracks also initiate at tip of the joints or initiate at the edges of the samples and propagate in a stable manner.

In general, three main modes of crack coalescence have been observed which are: the wing tensile mode (Type I, Fig. 8a), the shear mode (Type II, Fig. 8b), and the shear cum tensile mixed mode (Type III, Fig. 8c).

While examining the wing crack surfaces, part of the surfaces was found to be smooth and clean with no trace of crushed or pulverized material and no evidence of shear displacement. These surface characteristics indicated that tensile stresses were responsible for the initiation and propagation of the wing cracks. The shear failure surface was in a wavy mode. The inspection of the surface of the shear cracks producing coalescence revealed the presence of many small kink steps, crushed gypsum and gypsum powder, which suggested coalescence through shearing. The shear-cum-tensile mixed mode of failure surface was exhibiting a combination of the both aforementioned characteristics.

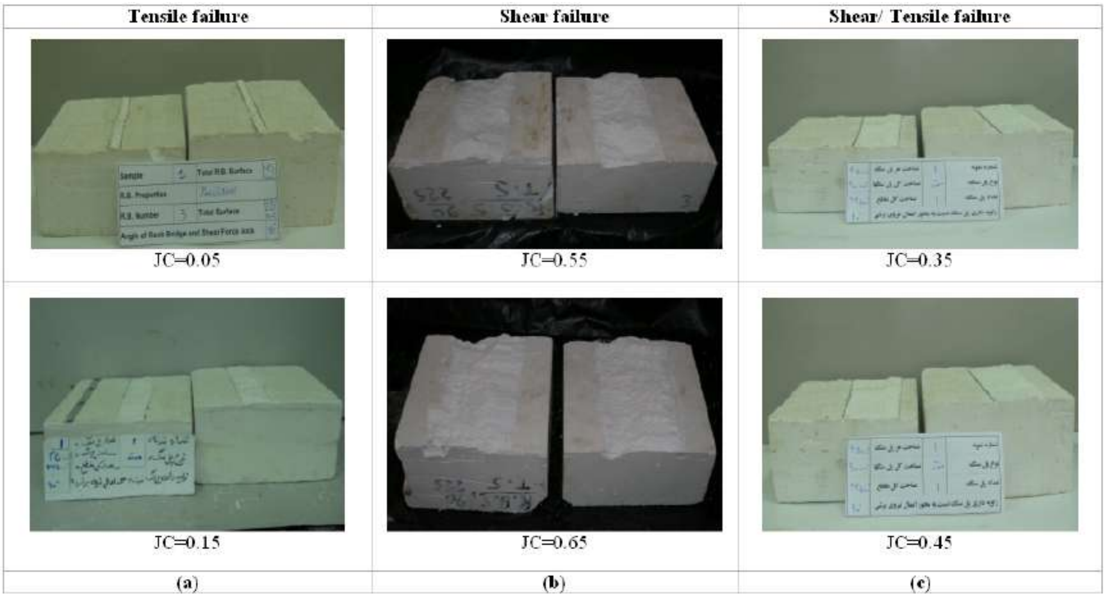

Fig. 8 - Failure modes in rock bridges; (a) shear failure, (b) tensile failure, (c) shear cum tensile failure

It is to be noted that the type of failure can be specified from vertical displacement so that when tensile crack propagates through the rock bridge, there is dilation in model during the test. But propagation of shear crack cannot lead to any vertical displacement in the broken rock bridge. The further comments on the failure mechanism of rock bridge have been presented by Ghazvinian et al. (2007) and Ghazvinian et al. (2008b).

Table 3 indicates the type of crack coalescence modes and its relative percentage value for each combination of JC, σ_n and σ_c respectively.

Table 3 - The percentage value of crack coalescence types for each combination of JC, σ_n and σ_c

Normal stress	JC						
	0.05	0.15	0.25	0.35	0.45	0.55	0.65
$\sigma_n \leq \frac{\sigma_c}{6}$	III (100%)	III (100%)	I (28%) III (72%)	I (50%) II (50%)	I (78%) III (22%)	I (100%)	I (100%)
$\frac{\sigma_c}{6} < \sigma_n < \frac{\sigma_c}{4}$	II (25%) III (75%)	II (12%) III (88%)	II (12%) III (88%)	III (100%)	III (100%)	I (37 %) III (62%)	I (100%)
$\frac{\sigma_c}{4} \leq \sigma_n \leq \frac{\sigma_c}{2}$	II (100%)	II (100%)	II (95%) III (5%)	II (90%) III (10%)	II (90%) III (10%)	II (86%) III (14%)	I (22%) II (72%) III (6%)

The shear experimental results revealed that the mechanical properties of the material, normal stress and jointing coefficient are factors influencing the crack coalescence mode. It is worth noting that the fracture toughness has an important effect on the crack coalescence mode as its effect is governed by uniaxial and tensile strengths of material on the rock bridge failure mode (Ghazvinian et al. 2007 and Ghazvinian et al. 2009). It can thus be said that there exists a linear and direct relationship between fracture toughness and the mechanical properties of rocks (Zhang, 2002). Since, the fracture toughness was not incorporated in the ANN analysis, a further analysis can be undertaken to explore the effect of the toughness parameters carefully.

It is problematic to scrutinize the experimental results; therefore it needs to use the neural network tools for investigation of simultaneous effect of these parameters on the crack coalescence mode. The tests results are used for training, validation and testing of the Neural Network.

The discussion of neural network studies is divided into four sections. The first section discusses the Artificial Neural Networks (ANN), the second section is describing the ANN architecture, the third section is focused on the analyzing the network and the fourth section considers the results and discussion.

3. ARTIFICIAL NEURAL NETWORKS (ANN)

ANNs seek to simulate human brain behavior by processing data on a trial-and-error basis as well as learning as how to avoid an error the next time a similar situation occurs. Recently, numerous advances have been made in developing intelligence, particularly those in which, functioning is based on biological neural networks. During the 1970s, the application of ANNs was very limited and models were unable to handle many problems then proposed. Researches resumed following a study by Hopfield (1982) which showed the relationship between physical systems and auto-associative recurrent neural networks. Thereafter, Rumelhart (1986) proposed a multiple-layer perceptron (MLP) model and based on enhancing the perceptron (proposed by Rosenblatt, 1958), MLP neurons are organized in layers including data input and output, as well as hidden layers as shown in Fig. 9. Hidden layers are important because they are largely needed for mathematical adjustment operations. According to Flood and Kartan (1994), MLPs with at least two hidden layers provide the extra flexibility required for modeling complex systems.

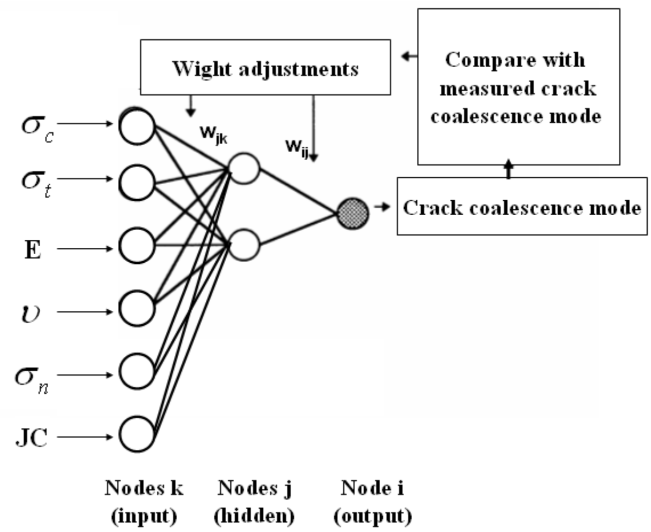

Fig. 9 - Diagram illustrating typical MLP

During the training processes, inputs are inserted and outputs determined whereas error between predicted and actual values are calculated. Based on this error, weights are adjusted right from the output layer to the input one, which is known as back propagation. Using an independent term is a common practice, nowadays, in summing weights and inputs to each neuron in order to lend more stability to the network and particularly to enhance its generalization. A constant '1' enters each neuron as an input and is multiplied by a scalar bias, which is similar to a weight for this input and is modified, as are the other weights (Haykin, 1994). Certain tools are used to accelerate the back-propagation algorithm as well as to reduce the incidence of local minima. It is worth mentioning that much more effective results may be obtained by treating MLP network input and output data. In order to obtain values with uniform amplitudes, data normalization, considerably, enhances the network performance. This is probably due to a more homogeneous distribution of data as highlighted in Figure 10. Many researchers have adopted this procedure (e.g. Flood and Kartan, 1994).

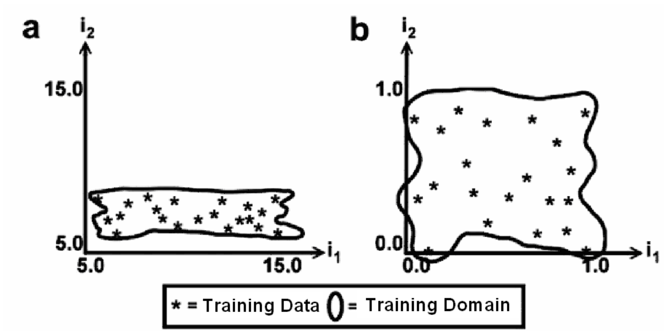

Fig. 10 - Influence of data normalization on distribution homogeneity; (a) not-normalized domain; (b) normalized domain (After Flood and Kartan, 1994)

4. ANN ARCHITECTURE

The main scope of the current research is to implement the ANN architecture in the proposed problem of crack coalescence pattern prediction. In this way it is possible to investigate the effect of the material properties, joint coefficient and normal load on the failure mechanism of specimens. That is difficult to do with experimental tests.

The experimental results will help identify the suitable input parameters for training as well as to test the ANN after it is trained.

The ANN model consists of six input parameters: uniaxial strength (σ_c), tensile strength (σ_t), Young's modulus (E), Poisson's ratio (υ), normal stress (σ_n) and joint coefficient (JC). The experimental data are divided into training, validation, and test sets. The validation set is used to ensure that there is no over-fitting in the final results. The test set provides an independent measure of how well the network can be expected to perform on data. Out of 280 data sets, 240 were picked randomly from the original data to train the network, 25 were taken to validate the network, and they were tested by the remaining 15 data set.

The well-known feed forward neural network learning by back propagation (BP) algorithm written in MATLAB has been used and its ability to predict the crack coalescence mode has been studied by training and testing the ANN for various cases of inputs and comparing its performance for various input conditions.

Trying to achieve the best network's performance, several networks were developed with different architectures using all the possible variations of the back-propagation algorithms available in MATLAB v.7.0. Following are the specifications of the artificial neural network used during the course of study:

- Number of input nodes in the input layer: 6 (σ_c, σ_t, E, υ, σ_n and JC).
- Number of output nodes in the output layer: 1.
- Number of hidden layers: 3 with 29, 20 and 15 nodes, respectively.
- Training algorithm used: back propagation.
- Transfer Function of layers: tansig.
- Back propagation network training function: traingdm.
- Back propagation weight/bias learning function: learngdm.
- Performance function: MSE.
- The learning rate was set to lr = 0.005 and the error goal (EG) was set to EG = 4×10^{-4}.
- The output of the neural network is the crack coalescence mode.

Here, the crack coalescence mode is considered as discrete values of 0, 1 or -1, which symbolize the mix mode, the shear mode and the tensile mode of failure, respectively. Figure 11 depicts the simulation of the network architecture, using the SIMULINK, module of MATLAB v. 7.0.

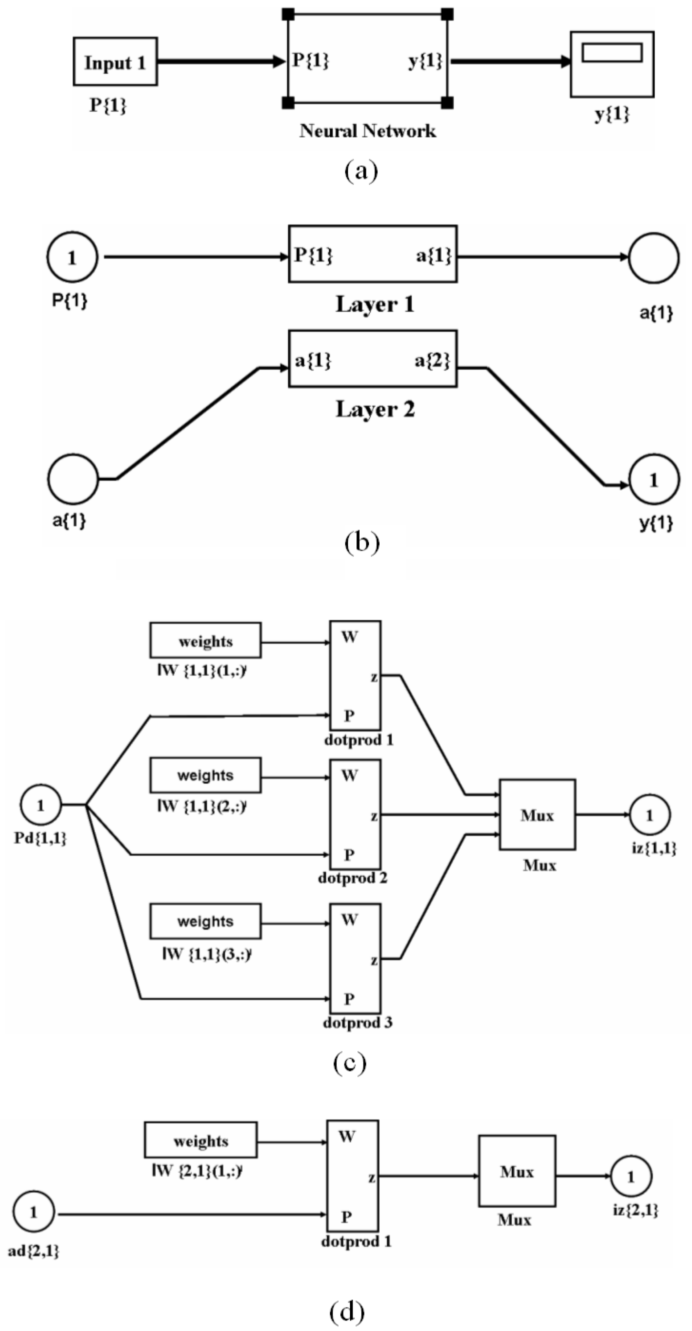

Fig. 11 - Neural network architecture visualized by SIMULINK; (a): Input-hidden-output layers, (b): Neural network architecture, layer 1: input, layer 2: output, (c): Schematic representation of input layer and weights from the input to hidden layer, (d): Schematic representation of the second layer and weights from the hidden to output layer

5. ANALYZING THE NETWORK

The discussion of analyzing the network is divided into two sections. The first section discusses the progress of training by pre-existing data and the second section is describing the verification of network by new experimental data.

5.1 Progress of Training by Pre-Existing Data

To cross check the progress of training, Figure 12 represents the plot of the training, validation, and test errors for the ANN model of crack coalescence modes. The results acquired from 200 data sets are reasonable since the test set and the validation set errors possess similar characteristics without any significant over-fitting.

As mentioned before, 15 experimental data sets were used for testing the network. Figure 13 depicts the network outputs for these data test sets and their corresponding targets in order to provide a deeper understanding of the prediction capabilities of the employed ANN model. The horizontal axis represents the sample number and the vertical axis is the crack coalescence mode. Solid rectangles on this plot show the output of the neural net; whereas, the hollow circles represent the actual crack coalescence mode (the values of 0, 1 or -1 are representing the mix mode, the shear mode and the tensile mode of failure respectively). As it can be inferred from Figure 13, the network has predicted values close to the measured ones.

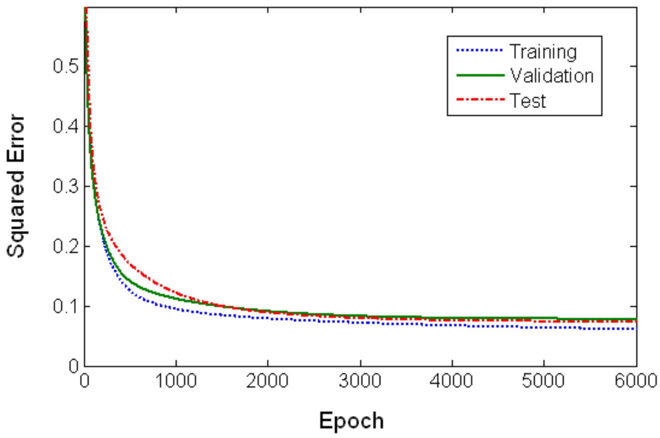

Fig. 12 - Network errors from testing ANN

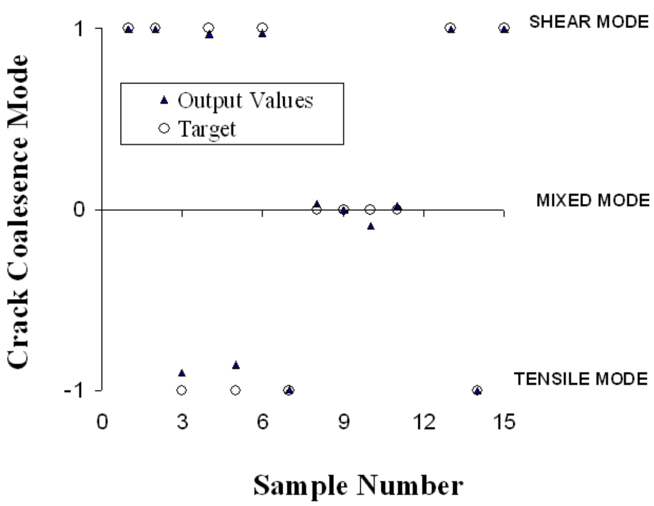

Fig. 13 - Network output and corresponding targets for 15 testing data set

The correlation coefficients between the respective values of experimentation and prediction were also calculated. As such, a correlation coefficient of 0.98 was deduced for the result of the ANN network (Fig. 14).

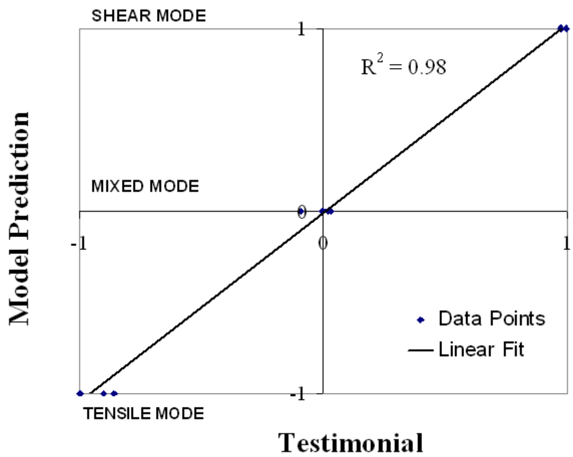

Fig. 14 - Scatter diagrams for crack coalescence mode

5.2 Verification of Network by New Experimental Data

In a research work in Graz University of Technology, some direct shear test performed on the planar non-persistent joint. The experimental results (crack coalescence mode) have been compared with network output.

The models have been prepared by combination of gypsum and anchor powder. The material properties from unconfined compression and tensile tests are as follows:

Average uniaxial compressive strength (σ_c):	7.0 MPa
Average Brazilian tensile strength (σ_t):	1.2 MPa
Average Young’s modulus compressive strength (σ_c):	1800.0 MPa
Average Poissons ratio:	0.2

Two similar model with JC=0.6 have been prepared and tested under two different normal loads (0.44 MPa (σ_c/16) and 1.75 MPa (σ_c/4)) by MTS machine. The tests procedure was the same as preceding case. Figure 15 shows the MTS machines used for carrying out the tests.

Fig. 15 - MTS machines used for direct shear, uniaxial and Brazilian tests

Figures 16 a & b show the crack coalescence mode in models under normal loads of 0.44 and 1.75 MPa respectively.

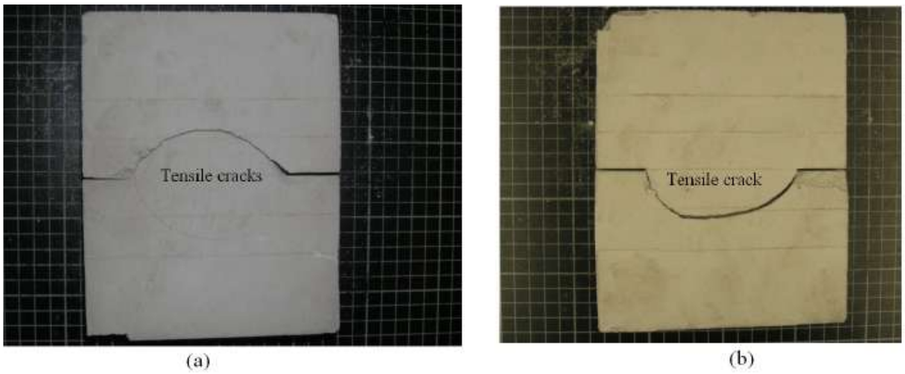

Fig. 16 - crack coalescence mode in models (JC=0.6), (a) Normal stress =0.44 MPa; (b) Normal stress =1.75 MPa

The failure surfaces were smooth and clean with no trace of crushed or pulverized material and no evidence of shear displacement. Also, there was dilation in the model during the tests. These surface characteristics indicated that tensile stresses were responsible for the initiation and propagation of the wing cracks. It is to be noted that when model is subjected to low normal stress (0.44 MPa), two tensile cracks appear in rock bridge (Fig. 16a) else the rock bridge failed by one tensile crack (Fig. 16b).

This data are used for reliability of trained network outputs. Figure 17 depicts the network outputs for these new data test sets and their corresponding targets. The horizontal axis represents normal load and the vertical axis is the crack coalescence mode. Solid rectangles on this plot show the output of the neural net; whereas, the hollow circles represent the actual crack coalescence mode. As it can be inferred from Figure 17, the network has predicted values similar to the measured ones.

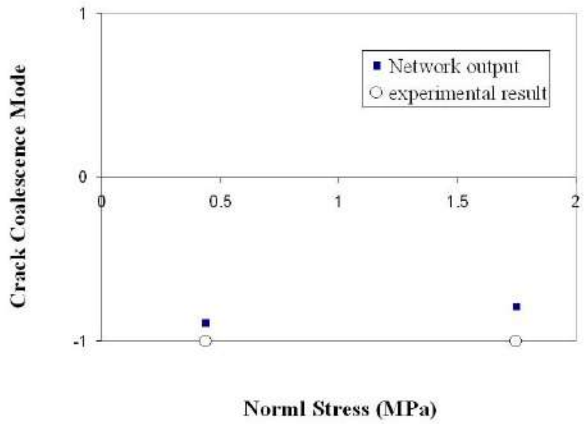

Fig 17 - Network outputs for new data test sets

6. RESULTS AND DISCUSSION

To identify the status of fracture mode and investigate the relative importance of the parameters involved in crack coalescence, the study has tried to investigate the problem of crack coalescence in the rock bridge from the ANN perspective.

Consequently, using all the possible variations of the back-propagation algorithms, a series of ANNs were created with different architectures. After introducing each group of data to the network individually, the performance of the networks was estimated. Finally, to predict the crack coalescence mode, the networks were analysed and the better one was chosen.

Figure 13 showed that the ANN model had predicted the fracture mode closer to the experimental ones. The correlation coefficients between experimental and predicted failure modes are 0.98 (Fig.14). The findings indicate that the network has successfully captured the relationship between input and output parameters, hence; the ANN model is an ultimate choice, so far as to predict the crack coalescence mode.

Further, the sensitivity analyses of the proposed aspect proved to be consistent and satisfactory that also enabled to verify the effect of certain parameters on crack coalescence mode. Sensitivity analyses were performed by changing the desired parameter while the other parameters were kept intact. The desired parameter was varied in between the minimum and maximum values of the data set. Figure 18a represents the sensitivity analysis of uniaxial strength of material on the failure pattern of non-persistent joint with JC= 0.45, normal load of 1 MPa and five equidistant points (σ_c = 4-14 MPa) were used to predict the crack coalescence mode.

The mixed mode coalescence appears for all of the uniaxial strengths values indicating that the crack coalescence mode is not sensitive to uniaxial strength of materials in this data range.

Figure 18b shows the effect of tensile strength of materials on the failure pattern of a non-persistent joint with a JC= 0.45, normal load of 1 MPa and five equidistant points (σ_t

= 0.5, 0.8, 1, 1.2 and 1.5 MPa) used to predict the crack coalescence mode. The mix mode coalescence appears for all of the tensile strength values, indicating that the crack coalescence mode is not sensitive to tensile strength of material in this data range.

Figure 18c depicts the crack coalescence mode versus joint coefficient (JC) variation. Seven equidistant points (JC= 0.05 - 0.65 with increments of 0.1) were used to predict the crack coalescence mode under the following conditions: σ_n=1 MPa (normal load), σ_c=4 MPa, σ_t=0.5 MPa, E=690 MPa and Poisson's ratio= 0.15.

The results found that the crack coalescence mode is sensitive to the JC and as such an increase in JC would change the mix mode of failure to the tensile failure.

Finally, Fig. 18d shows the crack coalescence versus normal stress (σ_n). Eight equidistant points (σ_n = 0.25-2MPa with increments of 0.25 MPa) were used to predict the failure pattern of non-persistent joint with JC= 0.45, σ_c=4 MPa, σ_t =0.5 MPa, E=690 MPa and Poisson's ratio = 0.15. This figure illustrates that the crack coalescence mode is sensitive to normal stress. It is evident that the increase in normal stress would result in the transformation of the mix mode of failure to the shear mode of failure.

The sensitivity analysis clearly shows that the most effective parameters on the crack coalescence are the JC and the normal stress (σ_n). In other word, the failure mode in rock bridges changes with the JC and the normal stress.

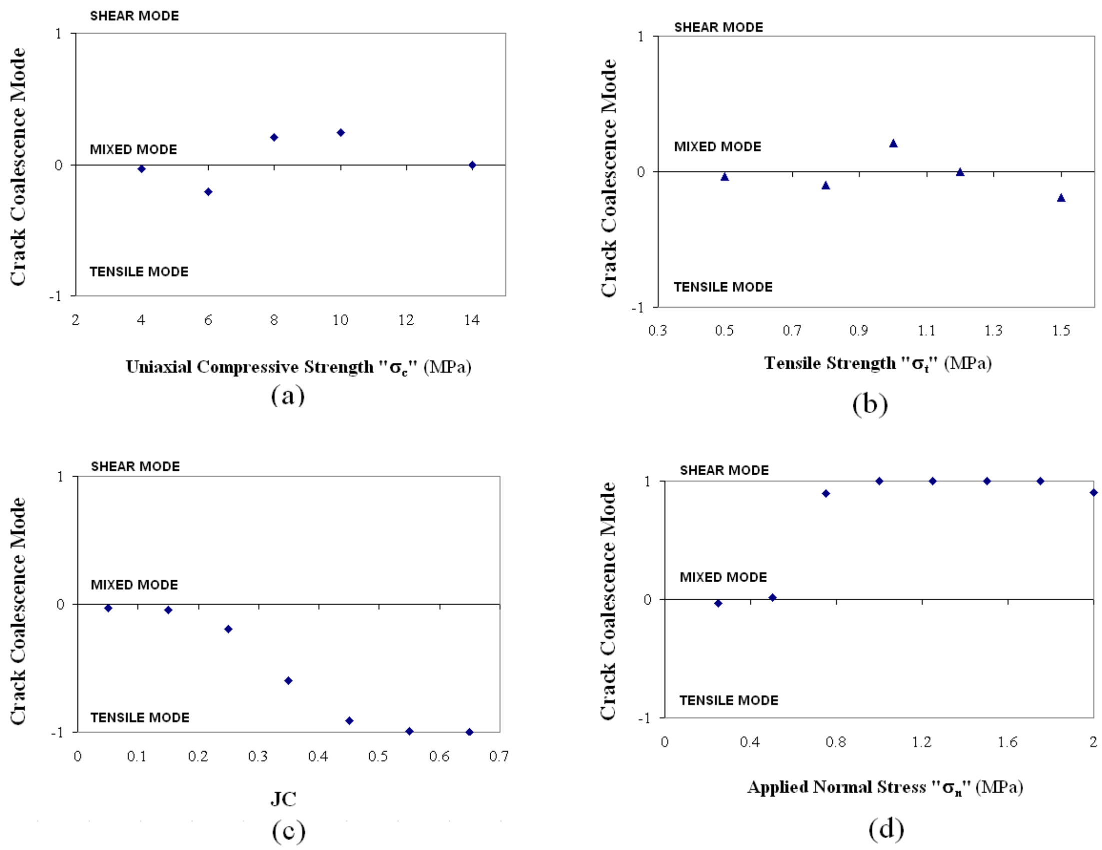

Fig. 18 - Sensitivity analysis of mode of fracturing versus (a) uniaxial strength (σ_c); (b) tensile strength (σ_t); (c) joint coefficient (JC); (d) normal stress (σ_n)

In order to study the simultaneous effect of normal stresses, the mechanical properties of model material and JC on the pattern of crack coalescence, the trained network is used for prediction of failure mode in the further extent of normal stress, uniaxial strength and JC.

Figure 19 shows the effects of the uniaxial strength of material on the failure mode of rock bridge in further ranges of uniaxial strength, JC and σ_n/σ_c (the ratio of normal stress to uniaxial strength). Variations of Uniaxial strength, JC and σ_n/σ_c are 4 to 150 MPa, 0.05 to 0.95 and 0.05 to 0.45, respectively.

In fixed values of JC and σ_n/σ_c, the crack coalescence mode is unchanged with increasing in uniaxial strength of material. For example when σ_n/σ_c=0.45, the shear failure occurs in rock bridge for JC=0.55 in through range of uniaxial strength. In the same way, for JC=0.75 with increasing the uniaxial strength the mixed mode of failure is unchangeable in rock bridge. This pattern is true for JC=0.95 while tensile failure occurs for all of the uniaxal strength.

From above finding, it is clear that while crack coalescence mode changes with both, the coefficients of JC and σ_n/σ_c, the uniaxial strength of material dose not have any effect on the rock bridge failure mode.

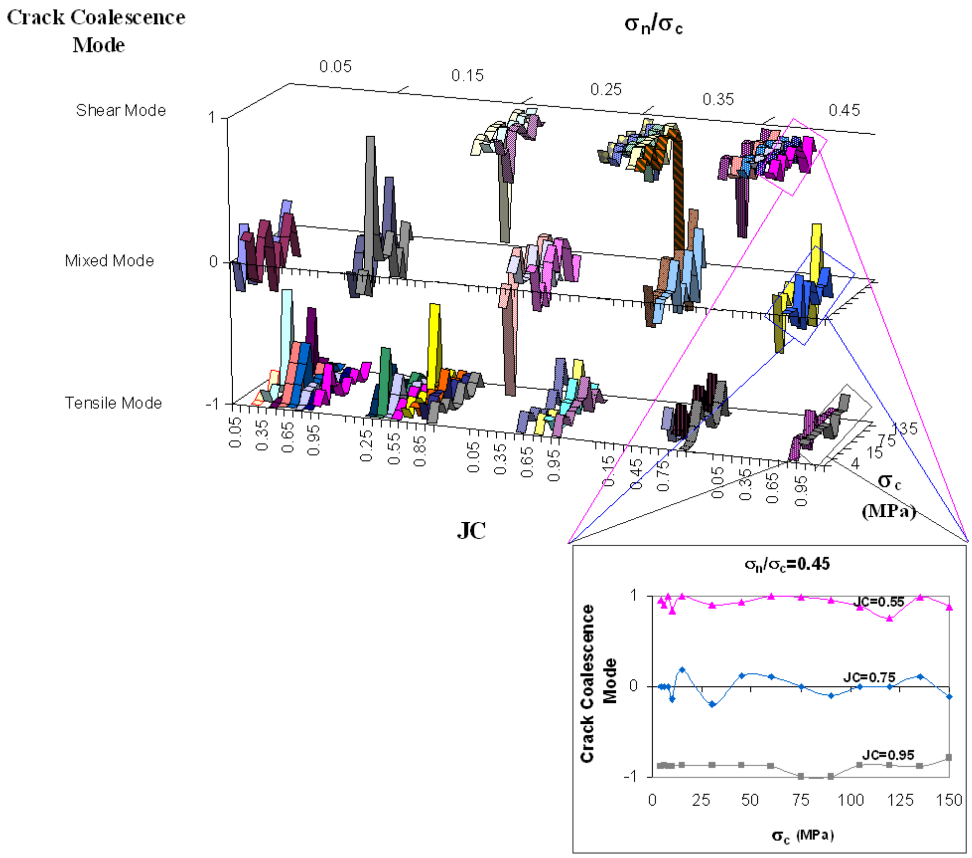

Fig 19 - Effects of the uniaxial strength of material on the failure mode of rock bridge in various range of JC and σ_n/σ_c

For further scrutinizing, Fig. 20 shows the combined effects of JC and σ_n/σ_c on the failure mode of rock bridge. The coefficient of JC varies from 0.05 to 0.95 with increments of 0.1 while the ratio of σ_n/σ_c varies from 0.05 to 0.5 with increments of 0.05.

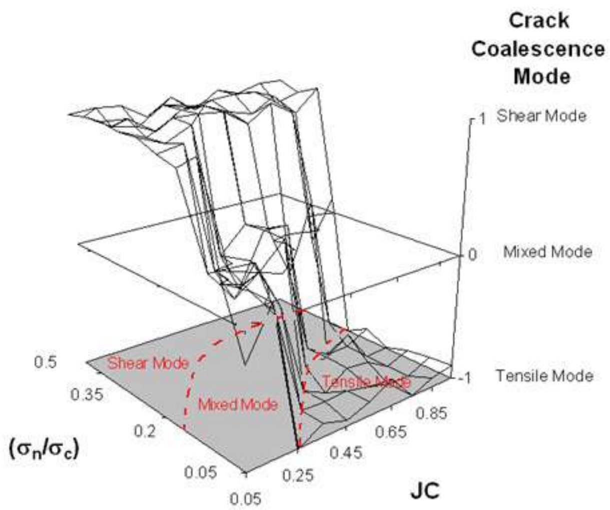

Fig 20 - Combination effects of JC and σ_n/σ_c on the failure mode of rock bridge.

The extension of three type of failures has been specified with dotted line in Fig. 20. It is clear that, in low values of JC, with increasing in the σ_n/σ_c, the mixed mode of failure change to shear failure mode while in high value of JC, the tensile failure mode change to shear failure mode with increasing in the σ_n/σ_c. Also in low values of σ_n/σ_c, with increasing in JC, the mixed mode of failure change to tensile failure mode while in high value of σ_n/σ_c, JC has not any effect on the crack coalescence mode so that the shear failure occurs in rock bridge.

7. CONCLUSIONS

Considering the above discussion, it can be said that the neural network is a suitable and useful approach to the problems of rock engineering wherein the mechanism is complex. In this study, an ANN model was developed that can be used for determining the crack coalescence mode. To this end, actual experimental results were used. The developed ANN model incorporates six input parameters (uniaxial strength, tensile strength, Young's modulus, Poisson's ratio, normal stress and joint coefficient). Although two modes of fracture toughness have an important effect on the crack coalescence, it is assumed that their effect on the crack initiation mode is similar to the effect of the mechanical properties of materials on the rock bridge failure mode. Therefore, fracture toughness did not enter these analyses.

The best adjustment was obtained from a designed network topology of three hidden layers of 29 neurons in the first layer, 20 in the second layer, and 15 neurons in the third layer. The learning rate was 0.005. The correlation coefficient between the respective values of observations and prediction values for crack coalescence mode based on the ANN model were calculated and found to be 0.98 for the networks. This correlation coefficient strongly supports the reliability. The sensitivity analyses were also found to be appropriate and proved useful in verifying the effects of certain parameters on the crack coalescence mode. These analyses indicated that the joint coefficient (JC) and the normal load are decisive and have significant impacts on the crack coalescence mode.

Further studies on the network outputs show that:

- The uniaxial strength of material dose not has any effect on the crack coalescence mode.
- In low values of JC, the mixed mode of failure change to shear failure mode with increasing the σ_n/σ_c.
- In high value of JC, the tensile failure mode change to shear failure mode with increasing the σ_n/σ_c.
- In low values of σ_n/σ_c, the mixed mode of failure changes to tensile failure mode with increasing the JC.
- In high value of σ_n/σ_c, JC has not any effect on the crack coalescence mode so that the shear failure occurs in rock bridge.

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