Shear Strength and Cracking Process of Non-persistent Jointed Rocks: An Extensive Experimental Investigation

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Abstract In this paper, a number of artificial rock specimens with two parallel (stepped and coplanar) non-persistent joints were subjected to direct shearing. The effects of bridge length (\(L\)), bridge angle (\(\gamma\)), joint roughness coefficient (JRC) and normal stress (\(\sigma_n\)) on shear strength and cracking process of non-persistent jointed rock were studied extensively. The experimental program was designed based on Taguchi method, and the validity of the resulting data was assessed using analysis of variance. The results revealed that \(\sigma_n\) and \(\gamma\) have the maximum and minimum effects on shear strength, respectively. Also, increase in \(L\) from 10 to 60 mm led to decrease in shear strength where high level of JRC profile and \(\sigma_n\) led to the initiation of tensile cracks due to asperity interlocking. Such tensile cracks are known as “interlocking cracks” which normally initiate from the asperity and then propagate toward the specimen boundaries. Finally, the cracking process of specimens was classified into three categories, namely tensile cracking, shear cracking and combination of tension and shear or mixed mode tensile–shear cracking.

Keywords Artificial rock specimen · Non-persistent joint · Joint roughness coefficient (JRC) · Direct shear test

List of symbols

\(\theta\) Joint angle with horizon
\(\gamma\) Bridge angle
\(L\) Bridge length
JRC Joint roughness coefficient
\(\sigma_n\) Normal stress
UCS Uniaxial compressive strength of intact specimen
\(E\) Young’s modulus of intact specimen
\(\sigma_t\) Tensile strength of intact specimen
\(\tau\) Shear stress
\(\tau_n\) Shear strength of non-persistent jointed specimen
ANOVA Analysis of variance
DoE Design of experiment
OA Orthogonal array

1 Introduction

Rock mass consists of two components, namely intact rock and discontinuities. Understanding the behavior of each component is important for accurate characterization of rock mass. In many instances, rock mass mostly consists of different types of discontinuities such as joints, fissures and cracks whose mechanical behavior is mainly controlled by these discontinuities (Brady and Brown 2006). Persistent and non-persistent joints are the most common types of discontinuities in rock masses. Persistency of joints is known to have a significant impact on the behavior of rock mass, particularly on its shear behavior (ISRM 2007). Assessing the degree of joint persistency is important to identify the level of contribution of intact rock to the final failure of rock mass where some examples include rock slopes, tunnels, bridge piers, high walls and dams (Bahaaddini et al. 2016a).
A substantial number of investigations have focused on mechanical behavior of persistent jointed rocks (Amadei and Goodman 1981; Asadollahi et al. 2010; Bahaaddini et al. 2013a, 2014b, 2015, 2016b; Einstein et al. 1983; Grasselli 2006; Jade and Sitharam 2003; Lajtai 1996a; Li et al. 2016, 2017; Mas Ivars et al. 2011; Saeb and Amadei 1992; Serrano et al. 2014; Sherpa et al. 2013; Wang and Huang 2009; Zhang 2010) while according to Bahaaddini et al. (2016a), non-persistent jointed rocks have received less attention mainly due to complex interaction between intact rock bridges and joints.


Lajtai (1969b) was first who conducted a very limited experimental study on non-persistent jointed rock having only two cracks in a slab-shaped specimen. Gehle and Kutter (2003) performed a large number of shear experiments on non-persistent jointed slab-shaped specimens made of artificial rock material gypsum. Gehle and Kutter (2003) made only one row of parallel cracks inside a number of artificial specimens to represent non-persistent joints where the angle of joints was a variable parameter. Gehle and Kutter (2003) demonstrated that based on the direction of the initial cracks, the wing cracks grow either toward the distant tip of the adjacent initial cracks which can form some asperities at the end of the test or directly toward the tip of the neighboring cracks. Prudencio and Van-Sint-Jan (2007) improved the testing condition of non-persistent jointed specimens compared to that employed by Gehle and Kutter (2003) where instead of having only one row of parallel cracks, more than one row was utilized. The finding by Prudencio and Van-Sint-Jan (2007) was consistent to that reported by Gehle and Kutter (2003). Ghazvinian et al. (2012) on the other hand designed and made a number of slab-shaped specimens with only two cracks at the boundary of specimens in a form of notch to represent non-persistent joints. The focus of their study was on change in the bridge length through alteration of crack lengths. Ghazvinian et al. (2012) then generated and ran some numerical models based on Particle Flow Coding (PFC) and finally compared their experimental data against the numerical results. Sarfarazi et al. (2014) employed a similar experimental approach to that applied by Ghazvinian et al. (2012) for testing program while instead of only changing the length of cracks, the location and the length of the cracks were variable. Sarfarazi et al. (2014) then performed some numerical models using PFC.

It is evident that to date, almost all the experimental studies on non-persistent jointed rocks have only utilized the discontinuities with smooth surfaces while the need for physical modeling of discontinuities having rough surfaces is important. Barton (1973) incorporated this unique characteristic of the discontinuities in his well-known Barton (1973) shear strength model through introducing joint roughness coefficient (JRC) profiles (Barton and Choubey 1977). Thus, the design and conduction of an extensive experimental work on non-persistent jointed rocks having rough joint surfaces are essential for more accurate replication of the field scenario in the laboratory. The experimental results from such a study can boost the reliability of the numerical modeling works where instead of only simulating non-persistent joints with smooth surfaces those with rough surfaces can be simulated with high accuracy.

As a result, in this paper for the first time a number of slab-shaped specimens with non-persistent joints having rough surfaces were designed and developed to extensively investigate their shear behavior. A range of rough surfaces was selected and created with the aid of 3D printing technology. The effects of some geometrical parameters such as bridge length \( L \) and bridge angle \( \gamma \) on the shear strength \( \tau_s \) of non-persistent jointed rocks were examined along with the impacts of JRC and normal stress \( \sigma_n \) (see Fig. 1).

This is followed by a comprehensive analysis of cracking process of non-persistent jointed rocks based on Wong and Einstein (2009) study. For the testing program, a number of artificial specimens with two parallel (stepped and coplanar) non-persistent joints were subjected to direct shearing. To obtain an efficient number of experiments and statistically sound understanding of the impact of each parameter on the shear strength of non-persistent jointed rocks, a statistical analysis was conducted.
method based on Taguchi approach (Taguchi and Konishi 1987) was implemented, and finally, the validity of the resulting data was evaluated based on analysis of variance (ANOVA).

2 Testing Material and Equipment

2.1 Artificial Rock Specimen

A number of slab-shaped artificial rock specimens with dimensions of 300 × 300 × 120 mm were casted consisting of plaster (48%), cement (24%) and water (28%). The dimensions of the specimens were selected according to Barton (1973) who suggested minimum 100 mm length of joint for shear testing in the laboratory environment. Therefore, in the plane of 300 × 300 mm two coplaner joints along each other can be fit with total length of 200 mm and the remaining 100 mm is important to minimize the boundary effects during the experiments. The results of the laboratory scale experiments, however, can be extrapolated to field condition using appropriate scale correction functions (Bahaaddini et al. 2014a; Bandis 1980, 1990).

The artificial specimens were brittle having relatively long curing time which was suitable for making non-persistent joints inside the specimens. The final product was achieved by trial and error (Asadizadeh et al. 2016) having the average uniaxial compressive strength (UCS) of 22.97 MPa, mean Young’s modulus (E) of 3.78 GPa and tensile strength (σt) of 3.43 MPa (Asadizadeh et al. 2017). Such an artificial rock with these mechanical properties can be classified into weak rock type according to Brady and Brown (2006). The curing time was 14 days, and all the casting processes were conducted at room temperature (20–25 °C). The UCS and E were extracted from the uniaxial compressive tests on five slab-shaped specimens (see Fig. 2). A servo-controlled loading frame with the maximum loading capacity of 400 ton was used for testing program. Two-millimeter-thick Teflon sheets were placed between the loading platen and the end surfaces of the slab-shaped specimens to minimize the frictional effects during the compressive test.

A number of uniaxial compressive tests were also performed on the cylindrical artificial rock specimens according to International Society for Rock Mechanics (ISRM 2007) suggested methods. The UCS and E of the cylindrical specimens were 23.70 MPa and 10.53 GPa, respectively (Asadizadeh et al. 2017). The change in UCS and E from the cylindrical to slab-shaped specimens can be associated with size- and shape-dependent behavior of brittle materials (Masoumi 2013; Masoumi et al. 2016). The tensile strength was obtained from the Brazilian tests conducted on a number of cylindrical specimens according to ISRM (2007).

2.2 JRC Profiles

Different physical JRC profiles sheets with dimensions of 150 × 100 × 1 mm (see Fig. 3) were designed and made using 3D printing technology. All the JRC sheets were made of VeroGray (RGD850) material.

2.3 Non-persistent Jointed Specimens

A specific mold was designed and fabricated (see Fig. 4) with the same dimensions as that explained for slab-shaped specimens to cast a number of non-persistent jointed artificial rocks as the final product for the experimental study.
Fig. 4 Schematic representation of the mold and its different parts used to cast non-persistent jointed specimens: (1) main box for casting the specimen, (2) sliding rail for controlling the joint angle with horizon \( \theta \), (3) steel rod for linking upper and lower platforms, (4) protractor for controlling the bridge angle \( \gamma \), (5) T segment for controlling the bridge length \( L \), (6) head of L segment, (7) sliding rail of L segment for controlling its movement along X and Y directions, (8) JRC 3D printing sheet holders, (9) JRC 3D printing sheet

The mold had three main parts: a main frame for casting the specimen, a T-shaped segment held by upper platform which was connected to L-shaped segments and a pair of L-shaped segments for holding the 3D printing JRC sheets.

For the casting of the jointed specimens, initially, the 3D printing JRC sheets were placed at the center of the mold where they were covered by a layer of Selefon (see Fig. 5). Once, the JRC sheets were fixed at the bottom of the mold, the artificial rock mixture was then gently poured into the mold. It is noteworthy that the pouring process was conducted slowly from the corners of the mold with a little normal load on JRC sheet. Hence, the mixture was continuously blended for approximately 12 min, and during the gelation process the JRC sheets were carefully removed. Example of a specimen with two parallel non-persistent joints is shown in Fig. 5.

2.4 Testing Procedure

A number of direct shear tests were performed on the specimens described above using an axial loading frame with maximum capacity of 400 ton under servo-controlled testing system. The shear displacement rate was constant at 0.005 mm/s. Some modifications were included to the loading frame along with a design and fabrication of two new shear box frames for shear testing. Figure 6 illustrates the detailed design of the shear boxes which can bear and transfer normal and shear loads. A 35-mm gap was considered on the shearing side of one box to account for displacement of the specimen with stepped joints. For another box, such a gap was 10 mm to test specimens with coplanar joints (see Fig. 6). To minimize the frictional effect, the L-shaped support shown in Fig. 6 was linked to the main box through a roller. The loading conditions of a shear test are shown in Fig. 7.

3 Experimental Program

In this study, the effects of four parameters including \( L \), \( \gamma \), JRC and \( \sigma_0 \) on shear strength of non-persistent jointed rocks are investigated. For clear understanding of the impact of
each individual parameter on shear strength statistically, an extensive parametric study is needed to assess the contributing weight of each individual parameter. Increase in the number of influential parameters leads to increase in the number of required experiments exponentially because of natural variability of each parameter. On the other hand, reduction in the number of experiments for each parameter can result in misleading understanding of their effects due to potential disregarding of the accurate weighting contribution of each individual parameter. Therefore, in here, to define an optimum number of tests which reflect a clear understanding of the effect of each parameter on the final product (e.g., shear strength in this study) statistically, the design-of-experiment (DoE) technique was employed.

The aim of DoE is to define a logical methodology to accurately and efficiently relate the input and output of a process with optimum number of experiments. In this study, \( L \), \( \gamma \), JRC and \( \sigma_n \) are the inputs and the shear strength \( (\tau_w) \) of non-persistent jointed rocks is an output. Taguchi technique (Taguchi and Konishi 1987) offers a robust DoE approach which has been used in rock engineering (Bahaaddini et al. 2012, 2016a; Moosavi et al. 2014; Wasantha and Ranjith 2014) successfully. This technique has been designed based on orthogonal array (OA) and analysis of variance (ANOVA) to optimize the required number of experiments leading to improvement in the quality of the output. With the aid of OA, it is feasible to estimate the variation in the input parameters from the experimental data which then will be used as an input for ANOVA. From this method, the complex impact of those parameters which are least significant can be eliminated leading to the reasonable and statistically sound outcomes in the investigation.
3.1 Taguchi Method

Taguchi (Taguchi and Konishi 1987) introduced three main phases for optimization of the required number of experiments including: design of system, design of parameters and design of tolerance. In the first phase, the inputs or parameters with substantial effect on the output or response are determined (e.g., $L$, $\gamma$, JRC and $\sigma_a$ in this study). Then, in the second phase the nominal levels for the design of parameters are selected in a form of OA where each parameter is assigned to one column and each row attains a set of values corresponding to the levels of parameters. Some columns may remain unfilled for inclusion of error or the interaction of the parameters. Examples of predefined OA include L4, L9 and L16 where the number of each term refers to the required number of tests that needs to be conducted. After completion of the second phase, the design of the tolerance is conducted to minimize the alteration of statistically important parameters.

Finally, the weighting contribution of each input (e.g., $L$, $\gamma$, JRC and $\sigma_a$ in this study) to output (e.g., $t_e$ of non-persistent jointed rocks) is estimated using ANOVA. For detailed information on the mathematical aspects of ANOVA, the readers are referred to Bahaaddini et al. (2016a) and Wasantha and Ranjith (2014) studies. ANOVA is available as a predefined function in some software including Microsoft Excel, MATLAB and R. In this study, R was used for conduction of ANOVA.

4 Experimental Results

The selection of four inputs or parameters including $L$, $\gamma$, JRC and $\sigma_a$ with four levels for each parameter resulted in L16 ($4^4$) OA according to Taguchi DoE approach. The level selection for each parameter was performed by considering the maximum and minimum effective range of each parameter in addition to two levels in between. For example, for JRC, the minimum level (1) was assigned to JRC profile of 4–6 where the sensible joint surface roughness starts from this profile. The highest level (4) was assigned to the maximum JRC profile (18–20), and the other two levels were assigned to two JRC profiles in between. Similar logic was followed for assigning the values to different levels of $L$, $\gamma$ and $\sigma_a$ as shown in Table 1 which summarizes all the parameters and levels. As a result, sixteen direct shear tests were performed on specimens with non-persistent joints exhibiting rough surfaces (see Table 2).

| Table 1 Defined levels for each parameter in the experimental design |
|-----------------|---|---|---|---|
| Parameters | Code | Levels |
| Joint roughness coefficient | JRC | 4–6 | 10–12 | 14–16 | 18–20 |
| Bridge angle (degree) | $\gamma$ | 90 | 120 | 150 | 180 |
| Bridge length (mm) | $L$ | 10 | 27 | 44 | 60 |
| Normal pressure (MPa) | $\sigma_a$ | 0.50 | 1.33 | 2.17 | 3.00 |

| Table 2 Shear strength results obtained from the experiments |
|-----------------|---|---|---|---|---|
| Test no. | Parameters | Response |
| JRC | $\gamma$ (degree) | $L$ (mm) | $\sigma_a$ (MPa) | $t_e$ (MPa) |
| 1 | 10–12 | 180 | 44 | 0.50 | 3.02 |
| 2 | 18–20 | 180 | 10 | 3.00 | 8.61 |
| 3 | 18–20 | 120 | 44 | 2.17 | 8.34 |
| 4 | 10–12 | 150 | 60 | 3.00 | 6.00 |
| 5 | 10–12 | 120 | 10 | 1.33 | 5.34 |
| 6 | 04–06 | 090 | 10 | 0.50 | 2.07 |
| 7 | 18–20 | 150 | 27 | 0.50 | 3.03 |
| 8 | 04–06 | 150 | 44 | 1.33 | 3.21 |
| 9 | 14–16 | 120 | 60 | 0.50 | 2.67 |
| 10 | 18–20 | 090 | 60 | 1.33 | 4.20 |
| 11 | 14–16 | 150 | 10 | 2.17 | 7.34 |
| 12 | 14–16 | 090 | 44 | 3.00 | 6.88 |
| 13 | 04–06 | 120 | 27 | 3.00 | 6.27 |
| 14 | 14–16 | 180 | 27 | 1.33 | 5.00 |
| 15 | 10–12 | 090 | 27 | 2.17 | 7.00 |
| 16 | 04–06 | 180 | 60 | 2.17 | 6.00 |

4.1 Cracking Process of Specimens with Non-persistent Joints

The cracking process of the specimens was investigated based on Wong and Einstein (2009) study who proposed a classification for cracking patterns including tensile cracking, shear cracking and combination or mixed mode of tensile and shear cracking.

In this study, the schematic drawing of the cracks is provided based on the following:

1. The cracking process of specimens detected using digital camcorder.
2. Opening of the resulting cracks at the tips of the joints was classified as tensile cracking.
3. At the end of the experiment, the newly created cracks which their surfaces were covered by crushed material were classified as shear cracking process.
4. Cracks with square fractures (Broek 2012) were classified as tensile cracking.
4.1.1 Tensile Cracking

The failure pattern of specimens 3 and 5 was classified as tensile cracking. In these two specimens, the tensile crack initiated at the tip of one joint and then propagated toward the surface of the next joint along the bridge zone (see Fig. 8). The resulting cracks were opened and thus were classified as tensile cracking.

From a simple quantitative analysis, it was noted that the JRC and $\gamma$ were mainly responsible for tensile cracking process. In both specimens, $\gamma$ was 120° and their JRC profiles were relatively high at 18–20 and 10–12 for S3 and S5, respectively.

### Fig. 8  Tensile cracking appeared at the bridge zones of specimens 3 and 5

4.1.2 Shear Cracking

Specimens 1, 2, 11, 14 and 16 were grouped in shear cracking category. Figure 9 shows the shear cracking process of these specimens resulted from shear tests. In all the specimens, the crack initiation and propagation occurred in the bridge area. It was observed that the shear cracks initiated from the tip of one joint and then propagated toward the tip of the other one while due to shearing process some crushed materials were visible inside the cracks at the end of the experiment (see Fig. 10). In this category, the role of $\gamma$ was important. For almost all specimens (except S11), $\gamma$ was 180° which was the maximum assigned value to this parameter according to DoE. Interestingly, the other parameters were variables for these five specimens. It is noteworthy that the specimens with coplanar joints exhibited shear cracking process. In S11, $\gamma$ was 150° which was the second highest angle and its $L$ was the minimum value at 10 mm.

4.1.3 Combination or Mixed Mode of Tensile and Shear Cracking

This category can be divided into two subcategories based on the resulting cracking process. The first includes only the combination of shear and tension or mixed mode of tensile–shear while in the second subcategory apart from a mixed mode of tensile–shear an additional individual tensile and/or shear can happen.

### Fig. 9  Shear cracks at the bridge zones of specimens 1, 2, 11, 14 and 16

### Table

<table>
<thead>
<tr>
<th>Specimen Code</th>
<th>S1</th>
<th>S2</th>
<th>S11</th>
<th>S14</th>
<th>S16</th>
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<td>Failure Pattern (Pure shear)</td>
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joint and then interestingly linked to the surface of the other joint far from the bridge zone. This unique behavior can be related to its $L$ which was the maximum (60 mm).

Specimens 6 and 8 with a simple mixed mode tensile–shear crack had relatively low JRC profile (4–6) which could be a contributing factor to their simple mixed mode failure. In almost both of these two specimens, the cracking process started from the tip of one joint and then propagated toward the tip of another one near the bridge zone. It was found that the specimens in this subcategory had $\gamma$ of 90° and 150° and both specimens were tested under normal stresses less than 1.33 MPa.

4.1.3.2 Mixed Mode of Tensile–Shear Plus Individual Tensile and/or Shear Cracking Specimens 9, 12, 13 and 15 were included in this subcategory where their cracking process was mainly combination of shear and tension plus a single random tensile and/or shear crack (see Fig. 12). It is believed that due to the interlocking of asperities and high $\sigma_n$, tensile cracks were initiated from the asperities and then propagated toward the boundary of the specimen. Asperity interlocking due to high $\sigma_n$ potentially triggered tensile cracking process during the shearing stage. Such cracks are called “interlocking cracks” which typically occur due to relatively high JRC profile and $\sigma_n$ (e.g., see Table 2 for S9 and S12).

Specimens 13 and 15 specifically revealed two types of cracking process in the bridge zone including a single shear crack as well as a single tensile crack. The tensile crack initiated from the tip of one joint and then propagated toward the tip of another one while the shear crack commenced from

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**Fig. 10** Shear cracking process in the bridge area with some crushed materials inside the crack (specimen 11)

**Fig. 11** Mixed mode (tensile–shear) failure in the bridge area of specimens tested under direct shearing
4.2 Effect of Different Parameters on Shear Strength

The ANOVA results for $r_n$ are listed in Table 3. It is evident that $\sigma_n$ is the most influential parameter on $r_n$ while $\gamma$ has the least effect. Noise percentages in Table 3 indicate the possibility of occurrence of a weighting contribution due to noise. The resulting low noise data validate the weighting contributions of all parameters. The second effective parameter is the physical model followed by $L$ and JRC, respectively. The graphical representation of the effect of each parameter on $r_n$ is shown in Fig. 13.

It is noteworthy that all the experimental results presented here are quite novel and no similar data have been reported previously in the literature. Therefore, any corresponding explanation given for the effect of each parameter on the shear behavior of tested specimens is at very early stage which requires further investigation from both experimental and numerical viewpoints.

4.2.1 Effect of Normal Stress

The effect of $\sigma_n$ on $r_n$ is shown in Fig. 13a. Overall, the increase in $\sigma_n$ leads to substantial increase in $r_n$, and above 2.17 MPa normal stress, $r_n$ remained approximately constant with a slight decrease. To explain this behavior, it is believed that due to “interlocking cracks” at the joint asperities with high JRC profile, asperity interlocking triggered the tensile cracking process. At the same time, due to high normal stress (3.00 MPa) which was close to the tensile strength of the tested specimen the tensile cracking process was activated in the intact area of the specimen leading to potential failure of specimen at slightly less $r_n$ compared to the cases where normal stresses were less than 3.00 MPa. In other words, the formation of these tensile cracks (orienting normal or angular to the surface asperities of joint) due to high JRC and $\sigma_n$ weakened the intact part of the specimen leading to slight decrease in $r_n$ up to about 2.87% where $\sigma_n$ increased from 2.17 to 3.00 MPa. Figure 14 illustrates the cracking process in specimen 2 showing two tensile cracks normal to the joint surface formed during the normal loading.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sum of squares</th>
<th>Degree of freedom</th>
<th>Mean square</th>
<th>Weighting contribution (%)</th>
<th>Noise (%)</th>
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<td>Model</td>
<td>64.38</td>
<td>12</td>
<td>5.37</td>
<td>20</td>
<td>0.03</td>
</tr>
<tr>
<td>Joint roughness coefficient (JRC)</td>
<td>5.53</td>
<td>3</td>
<td>0.84</td>
<td>3.15</td>
<td>0.57</td>
</tr>
<tr>
<td>Bridge angle ($\gamma$)</td>
<td>1.88</td>
<td>3</td>
<td>0.63</td>
<td>2.33</td>
<td>0.88</td>
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<tr>
<td>Bridge length ($L$)</td>
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<td>3</td>
<td>1.84</td>
<td>6.87</td>
<td>0.18</td>
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<tr>
<td>Normal stress ($\sigma_n$)</td>
<td>54.44</td>
<td>3</td>
<td>18.15</td>
<td>67.65</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Residual</td>
<td>0.06</td>
<td>3</td>
<td>0.02</td>
<td></td>
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</tr>
</tbody>
</table>
Figure 13 illustrates the growth of tensile cracks in specimen 12 that initiated from joint asperity angular to the joint surfaces. The growing process of these tensile cracks is shown step by step in Fig. 15 to highlight their roles during the shear test.

The final cracking process of tested specimens under various normal stresses is compared and shown in Fig. 16. It is evident that increase in normal stress leads to increase in the number of tensile cracks formed angular to joint surfaces. The JRC profile of all these specimens was 14–16.

4.2.2 Effect of Bridge Length

The influence of $L$ on $r_n$ is shown in Fig. 13b. In general, an increase in $L$ from 10 to 60 mm led to decreases in $r_n$. To explain this trend, particular focus was given to the path of the cracking process where with increase in $L$, the way
that cracks formed between the joints was variable. At low $L$, the crack propagated from tip of one joint to the tip of another one (e.g., specimen 13 in Fig. 17). By contrast, with an increase in $L$ the link between the joints by the resulting crack changed in a way that from a tip of one joint the crack linked to the center point of another joint (e.g., specimen 10 in Fig. 17). As a result, it is believed that due to the linking between the two joints at the points other than the tips during the formation of a new crack, the effect of joint on shear strength reduced leading to decrease in $\tau_n$. Such a phenomenon is evident in specimen 10 with 60 mm bridge length where the “S”-shaped crack started from the tip of one joint and then propagated toward the surface of the other joint adjacent to its other end far from the bridge area. This can lead to less contribution of the second joint in the shearing process leading to potential decrease in $\tau_n$.

4.2.3 Effect of JRC

The trend of $\tau_n$ due to JRC is shown in Fig. 13c where increase in JRC leads to increase in $\tau_n$. This outcome agrees well with the findings of the earlier researchers (Barton 1973; Barton and Choubey 1977; Saeb and Amadei 1992;...
Sanei et al. (2015; Serrano et al. 2014) who reported increase in joint roughness leads to increase in $\tau_n$.

4.2.4 Effect of Bridge Angle

Figure 13d reveals the fluctuation of $\tau_n$ due to change in $\gamma$. It is hypothesized that such a trend is associated with the effect of stress concentration at the joints tips during the experiment. This result is very similar to that reported by Gehle and Kutter (2003) who investigated the effect of joint inclination on $\tau_n$. In Gehle and Kutter (2003), study $\gamma$ was variable from 0 to 180°, and interestingly, the change in $\tau_n$ within the range of 0° to 90° was consistent to that reported between 90 and 180°. In other words, the trend of change in $\tau_n$ was consistent every 90°. This is similar to what has been observed here where the variation of $\tau_n$ to high extent is consistent every 60°. It is noteworthy that $\gamma$ has the least effect on $\tau_n$ based on ANOVA. Thus, the unusual fluctuation of $\tau_n$ due to $\gamma$ is not as important as the effect of other parameters.

5 Conclusions

For the first time, an extensive experimental study was conducted on the shear strength and cracking process of non-persistent jointed artificial rock specimens with rough joint surfaces. In total, 16 specimens were tested and the effect of bridge length ($L$), bridge angle ($\gamma$), joint roughness
coefficient (JRC) and normal stress ($\sigma_n$) on shear strength ($\tau_s$) was investigated simultaneously based on the Taguchi approach and the validity of the results was assessed by analysis of variance (ANOVA).

The cracking process of the tested specimens was classified into three different categories including: tensile cracking, shear cracking and combination of tension and shear or mixed mode of tensile–shear. Specimens 3 and 5 with bridge angle of 120° and JRC profile of 10–12 or more exhibited tensile cracking. Specimens 1, 2, 11, 14 and 16 revealed shear cracking where their bridge angle was equal or more than 150°. It was concluded that the bridge angle was the responsible parameter for shear cracking. The rest of the specimens with bridge angle of 90° or 120° which were tested under high normal stress mostly showed mixed mode of tensile–shear cracking process.

From ANOVA, $\sigma_n$ was found to be the most influential parameter on $\tau_s$ while $\gamma$ had the least effect on $\tau_s$. L and JRC lied in the second and third positions, respectively. Increase in $\sigma_n$ from 0.5 to 3 MPa led to substantial increase in $\tau_s$ compared to other parameters. L had reverse correlation with $\tau_s$ where an increase in L led to decrease in $\tau_s$ by 20%. On the other hand, there was a direct correlation between JRC and $\tau_s$ where an increase in JRC resulted in increase in $\tau_s$.

The effect of $\gamma$ on $\tau_s$ was negligible leading to the fluctuation of $\tau_s$.

References

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