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Insertion and pull-out response of snakeskin-inspired 3D printed friction rock bolts

Réponse d'insertion et de retrait des boulons à friction imprimés en 3d inspiré de la peau de serpent

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ABSTRACT: Split Sets, which are popular friction rock bolts, integrate into the rock mass through interface friction. Patterned Split Sets with direction-dependent (insertion and pull-out) frictional resistance may have several advantages. The present study explores the effect of snakeskin-inspired patterns that exhibit frictional anisotropy on the behaviour of Split Sets. The pattern of ventral scales of a snake is selected, and different models of patterns are developed by varying the scale angle. A pattern of a commercially available rock bolt (HA25) is also selected for a comparative study. All the patterns are incorporated into Split Set models and 3D printed using Polylactic Acid (PLA) material. The 3D printed Split Sets are tested for insertion and pull-out loads in cylindrical blocks made of Plaster of Paris, using a modified Universal Testing Machine. The results of the tests show that insertion and pull-out loads exhibit bilinear relationships with scale angles (10°, 13°, 16°, and 19°), and all the snakeskin-inspired patterns show significant frictional anisotropy. To gain further insights into the peculiar behaviour shown by the Split Sets, a numerical analysis of the same was carried out using ANSYS Workbench. The contact pressure, frictional stress contours and from the numerical analysis exhibit a similar bilinear relationship with scale angle for insertion, while the pull-out results are ambiguous. The study opens up possibilities of snakeskin-inspired frictional anisotropic patterns for efficient and economic rock bolts.

RÉSUMÉ : Les Split Sets, qui sont des boulons d'ancrage à friction populaires, s'intègrent dans la masse rocheuse par friction d'interface. Les Split Sets à motifs avec une résistance au frottement dépendante de la direction (insertion et extraction) peuvent présenter plusieurs avantages. La présente étude explore l'effet des motifs inspirés de la peau de serpent qui présentent une anisotropie de frottement, sur le comportement des Split Sets. Le motif des échelles ventrales d'un serpent est sélectionné et différents modèles de motifs sont développés en faisant varier l'angle d'échelle. Un modèle d'un boulon d'ancrage disponible dans le commerce (HA25) est également sélectionné pour une étude comparative. Tous les motifs sont incorporés dans des modèles de jeux séparés et imprimés en 3D à l'aide d'un matériau d'acide polylactique (PLA). Les Split Sets imprimés en 3D sont testés pour les charges d'insertion et de retrait dans des blocs cylindriques en plâtre de Paris, à l'aide d'une machine d'essai universelle modifiée. Les résultats des tests montrent que les charges d'insertion et d'extraction présentent des relations bilinéaires avec les angles d'échelle (10 °, 13 °, 16 ° et 19 °) et tous les motifs inspirés de la peau de serpent montrent une anisotropie de frottement significative. Pour mieux comprendre le comportement particulier des Split Sets, une analy se numérique de ceux-ci a été effectuée à l'aide d'ANSYS Workbench. La pression de contact et les contours de contrainte fricitonale de l'analyse numérique présentent une relation bilinéaire similaire avec l'angle d'échelle pour l'insertion, tandis que les résultats d'extraction sont ambigus.L'étude ouvre des possibilités de modèles anisotropes à friction inspirés de la peau de serpent pour des boulons de roche efficaces et économiques.

KEYWORDS: Split Sets, Bolt-Rock Interface, Snakeskin-Inspired Patterns, Frictional Anisotropy, Numerical Analysis of Split Sets.

1 INTRODUCTION.

A friction bolt is a type of rock bolt that can supply support pressure with the help of the friction that develops between the bolt shanks and the rock surfaces of drilled holes and the lateral pressure exerted by the bolt on the rock surface. The first friction rock bolts are Split Sets which are tubes with a C-shaped cross-section (Davis, 1979; Komurlu and Demir, 2019; Li, 2017; Scott, 1977, 1973). Split Sets are installed by pushing it into a drilled hole of a slightly lower diameter than that of the rock bolt, which generates a radial spring force due to the compression of the tube, providing the frictional anchorage.

While the ease of practical application and the ability to directly take the load without waiting for the grout materials to cure make the Split Sets hugely popular, they are limited by the lower load-bearing capacity and lesser pull-out strength due to the plain bolt shank. The contact of the surfaces of the bolts to the surrounding rock surface is conventionally enhanced by introducing surface corrugations (Komurlu et al., 2017; Li et al., 2014; Thenevin et al., 2017). However, the unilateral increase in the frictional resistance due to the introduction of surface corrugations may become ineffective and energy-consuming to the project owing to the significant increase in the insertion load. There are numerous patterns in nature that show an optimised frictional behaviour, like the ventral scales of snakes that exhibit frictional anisotropy(Greiner and Schäfer, 2015; Liu et al., 2015; Malshe et al., 2013). Introducing corrugations on the bolt shank inspired by such bio-inspired patterns can provide sustainable and economical solutions to rock bolt applications (DeJong et al., 2017; DeJong and Kavazanjian, 2019; Malshe et al., 2013; Martinez et al., 2021).

This paper is a systematic study on the effect of snakeskin-inspired patterns on the behaviour of Split-sets. The pattern of ventral snake-scale is selected for this purpose, and the results are compared with a commercially available pattern. The study also takes advantage of the advancements in 3D printing technology to replicate the sophisticated patterns onto a Split Set model, using Polylactic Acid (PLA), a bio-degradable, thermoplastic polymer. The results of the experimental study are further validated by a numerical analysis using ANSYS Workbench. The study has promising results for snakeskin-inspired frictional anisotropic patterns for efficient rock bolts and opens up possibilities for further research.

2 MATERIALS.

2.1 *Plaster of Paris*

Cylindrical blocks made from Plaster of Paris (POP) are prepared by taking a water content of 60 % of the total weight of the mix constituent, as suggested by Sharma et al. (2018), to simulate a weak rock mass. The POP block with a diameter of 100 mm and a height of 240 mm, has a pre-cast hole of diameter 32 mm and a depth of 200 mm from the top, into which the Split Set models are inserted. The mechanical properties of the mix are given in Table 1, and Figure 1 shows the casted POP blocks.

Figure 1. POP blocks prepared for the experimental program

Table 1. Mechanical Properties of the POP mix

Density (kg/m³)	Elastic Modulus (GPa)	Poisson's ratio	UCS (MPa)	Friction angle (degree)	Cohesion (MPa)
1170	4.48	0.22	6.78	51	0.78

2.2 *Polylactic Acid (PLA)*

The 3D printed Split Set models used in the study are made of Polylactic Acid (PLA) and is printed using an FDM 3D printer. PLA is a biodegradable thermoplastic and is widely used as a material for 3D printing due to its ease of usage and low printing temperature. Some of its physical properties obtained from the manufacturer and the engineering properties found as per ASTM standards (Materials, 2015; Specimens, 2015) in the laboratory are given in Table 2.

Table 2. Physical and Mechanical Properties of PLA

Property	Value
Physical Properties	
Density (kg/m^3)	1200
Crystallisation Temperature (°C)	114
Softening Temperature (°C)	129-132
Melting Temperature (°C)	150
Mechanical Properties	
Elastic Modulus (Compression) (MPa)	2.77
Elastic Modulus (Tension) (MPa)	2.63
UCS (MPa)	45
UTS (MPa)	53
Poisson's Ratio	0.22

3 DESIGNING OF SURFACE PATTERNS

The pattern of ventral scales of a viper snake is selected, and different models of patterns are developed by varying the scale angle in Autocad Inventor. A pattern of a commercially available rock bolt (HA25) is also selected for a comparative study. Figure 2 shows the 3D printed Split Sets with the different bolt shank surfaces.

Four different models of snakeskin-inspired patterns are developed by changing the longitudinal scale angle (□), as shown in Figure 3. The thickness of the inner core of the Split Set model and the highest thickness of the corrugation is 3 mm each. The scale angles considered are 10°, 13°, 16° and 19°. Thus, the Split Sets are named HA25 for the conventional rock bolt pattern and "SSI_□" for the snakeskin-inspired pattern.

Figure 2. 3D printed Split Set models with snakeskin-inspired surface pattern and HA25 pattern

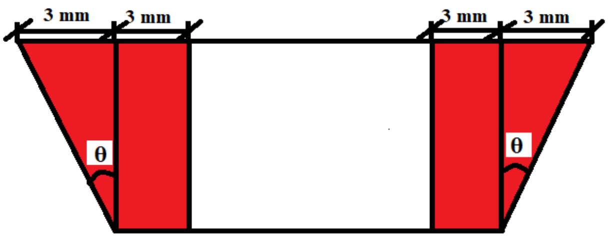

Figure 3. Cross-section of a single corrugation of snakeskin-inspired pattern

4 METHODOLOGY

4.1 *Experimental Setup and Procedure*

The experimental program consists of the insertion and pull-out tests of the Split Set models using POP blocks. A computer-controlled Universal Testing Machine (UTM) with a load cell of 50 kN capacity is modified for this purpose by fabricating customised upper plates for the triaxial cell. The Split Set model is clamped to the load cell by a specially designed clamping system. The triaxial cell is clamped to the UTM at the bottom using a threading mechanism. The LVDT sensors attached to the UTM continuously record the displacement of the Split Set model. The complete experimental setup is shown in figure 4.

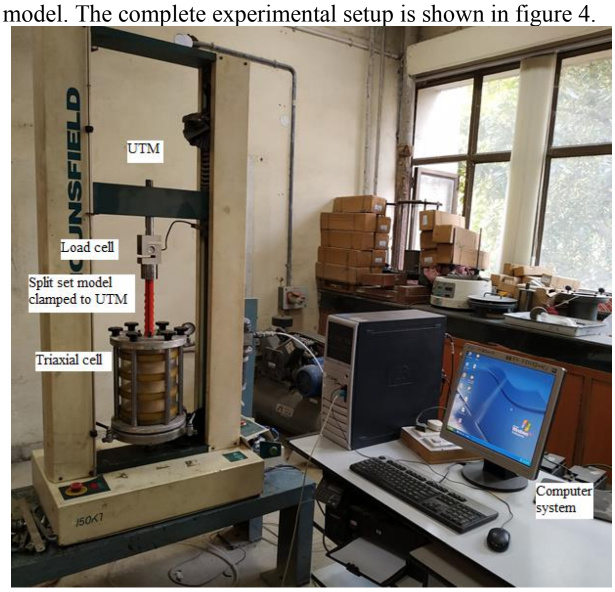

Figure 4. Experimental setup

All the tests are carried out in the unconfined condition at a 100 mm/min deformation rate for insertion and 20 mm/min for pull-out, with a maximum displacement of 160 mm for the Split Set models. The insertion tests are done first on a Split Set model, followed by the pull-out tests.

4.2 *Numerical Procedure*

The numerical simulations of insertion and pull-out tests are carried out using ANSYS Workbench to validate the experimental tests and obtain the frictional stress contours and contact pressure contours of the Split Set models. The geometry models are imported as STL files, and the material properties of POP and PLA, as given in Table 1 and Table 2, are assigned to the relevant geometries. The process of meshing is then carried out. Meshing is an integral part of the simulation process where complex geometries are divided into simple elements to be used as discrete local approximations of the larger domain. Hex Dominant meshes are preferred for cylindrical geometries, which comprise prisms with quadrilateral base hexahedron or hex (Benzley et al., 1995). Therefore, a Hex Dominant mesh of size 10 mm is used in the study, as shown in Figure 5.

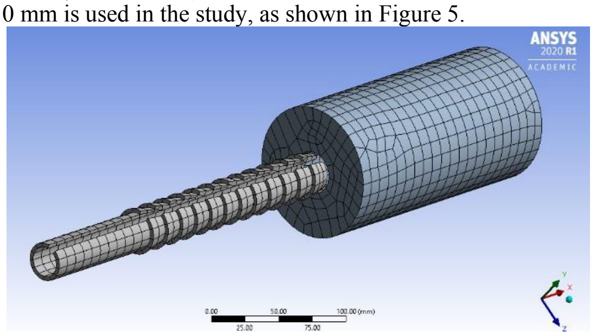

Figure 5. Meshing of geometry

The contact between the Split Set model and the POP block is considered frictional, and a frictional coefficient of 0.2 is assumed for the simulations. The contact formulation uses a simple equation:

$$F_{normal} = k_{normal} * x_{penetration} \quad (1)$$

where, F_{normal} is the force reaction on the walls of the Split Set, k_{normal} is the normal stiffness at the contact and $x_{penetration}$ is the distance of penetration of the Split Set into the hole in the POP block.

The top and bottom faces of the block are taken as fixed supports. Then, the displacement of the Split Set model is applied in multiple sub-steps for a total displacement of 160 mm o replicate the displacement-loading conditions in the numerical study, and a non-linear analysis is carried out using the Full Newton-Raphson method.

5 RESULTS AND DISCUSSIONS

5.1 *Experimental Analysis*

Initially, a few trials of the tests are repeated to ensure the repeatability of the test results. All the snakeskin-inspired patterns exhibit similar load-displacement relationships, albeit with significantly different peak loads, in both insertion and pull-out. Figure 6 presents the typical load-displacement responses of the Split Set models. Figure 6 also includes the load-displacement response of an additional trial of SSI_19 to show the repeatability of the tests for both insertion and pull-out tests. The close match between the plots of different trials confirms the repeatability of the test conditions.

It is observed that 19o shows the highest loads in both insertion and pull-out among the four scale-angles, while 16° shows the least load values. This indicates a bilinear relationship between the insertion and pull-out loads, and the scale angles, as shown in Figure 7. It is also observed that for the HA25 surface pattern, the insertion load decreases with insertion length. This decrease can be attributed to the surface profile of the HA25 pattern. With an increase in insertion length, the interaction of the HA25 pattern reduces, leading to a decrease in the insertion load.

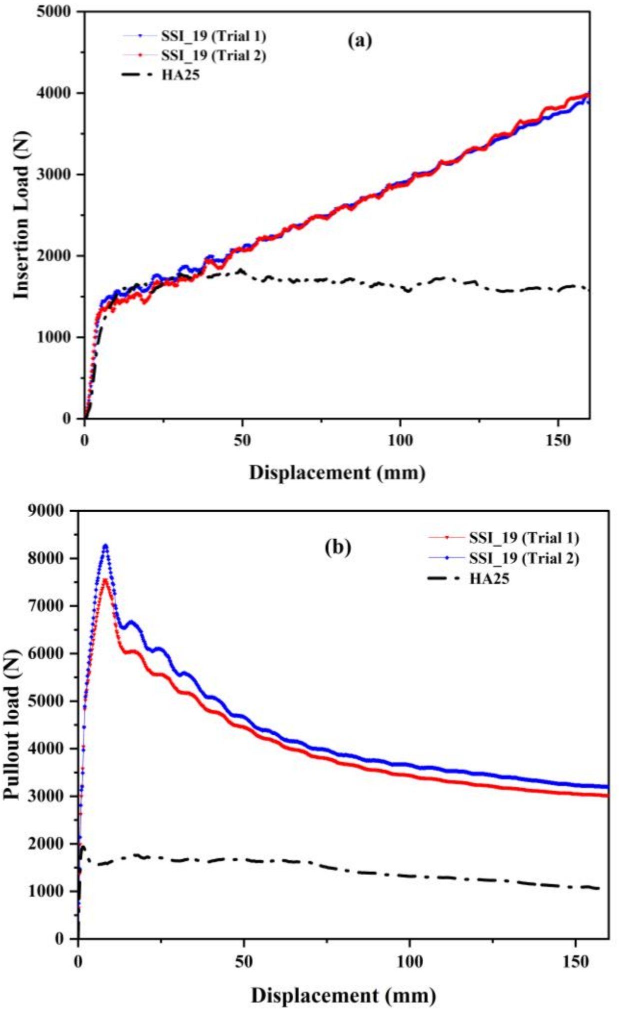

Figure 6. Load-displacement response of (a) insertion tests and (b) pull-out tests of split-set models

To understand the reason behind the bilinear relationship between the insertion and pull-out loads and the scale angles, the interaction of the Split Sets with the POP blocks is studied. For this purpose, the weight of the POP blocks is taken before and after the tests. The difference in the weights indicates the interaction between the Split Set and the POP block. Figure 7 shows the interaction of the different snakeskin-inspired patterns. It is observed that the interaction of the different snakeskin-inspired patterns also shows a bilinear relationship with the scale-angle, with 16° having the least interaction and 19° showing the highest. Thus, it is inferred that the snakeskin-inspired patterns with higher interaction exhibit higher insertion and pull-out loads and vice-versa.

5.1.1 *Frictional Anisotropy*

The significantly higher values of the pull-out loads in the snakeskin-inspired patterns than insertion loads clearly indicate frictional anisotropy. Frictionally anisotropy, as exhibited by the scales of a snake, is defined as the difference in the resistance between two directions of frictional interaction (Hazel et al., 1999; Jagota and Hui, 2011; Martinez and Palumbo, 2018). In this study, frictional anisotropy is computed as the difference between pull-out and insertion loads. From Figure 8, it is clear that out of different snakeskin-inspired patterns, SSI_19 exhibits the highest and SSI_16 exhibits the lowest frictional anisotropy. It is also clear that the HA25 pattern exhibits negligible frictional anisotropy when compared to snakeskin-inspired patterns.

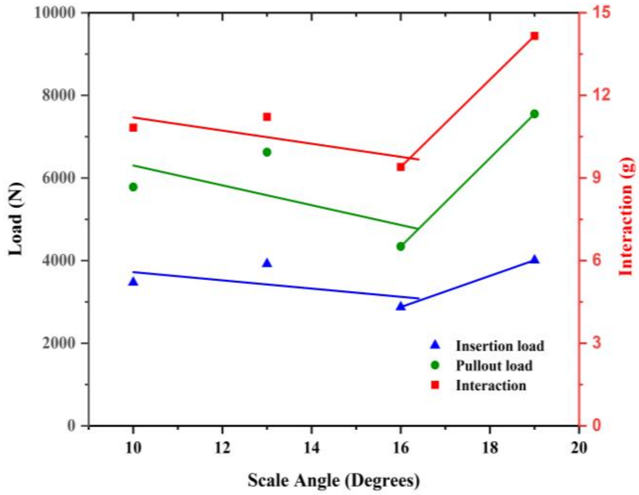

Figure 7. Bilinear relationship of insertion and pull-out loads, and interaction with scale angles

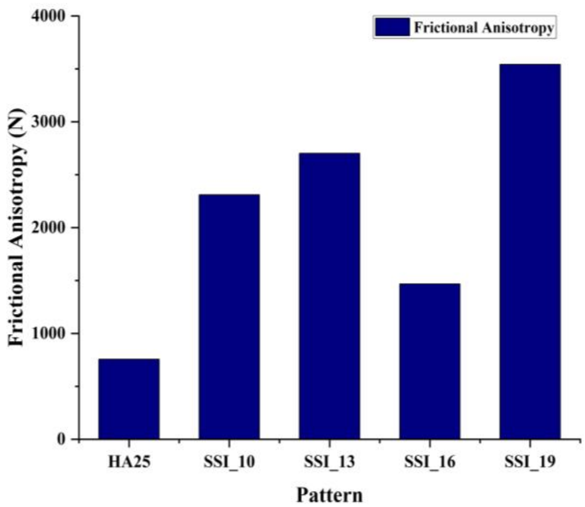

Figure 8. Frictional anisotropy for different surface patterns

5.2 *Numerical Analysis*

A numerical study is undertaken to gain further insights into the peculiar behaviour of snakeskin-inspired Split Sets using ANSYS Workbench. The results of numerical analysis are shown in the form of stress contours.

5.2.1 *Numerical analysis of insertion*

Contact stress and frictional stress contours of the insertion tests are presented here to understand the behaviour of the oversized Split Set when it is inserted into an undersized hole. The contact stress and frictional stress contours are shown in Figure 9 and Figure 10, respectively and a summary of the numerical modelling results is presented in Table 3.

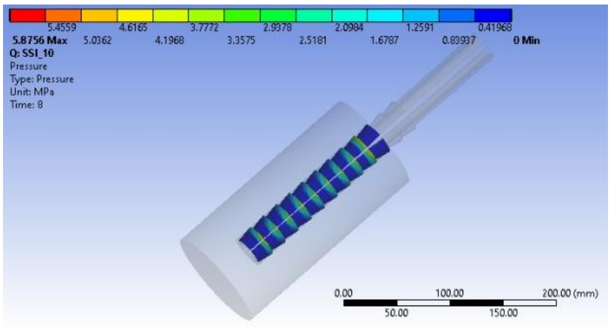

Figure 9. Contact stress contours during insertion

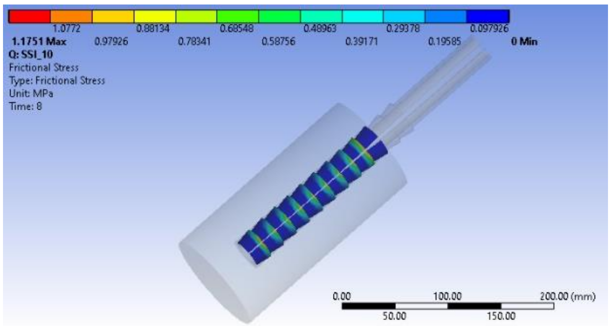

Figure 10. Friction stress contours during insertion

From Table 3, it can be seen that the force reaction values obtained from the numerical modelling are similar to the values obtained from the experimental program. Furthermore, a similar bilinear relationship with the scale-angles is observed from numerical modelling for the insertion tests, as shown in Figure 11. Thus, the numerical modelling in ANSYS using Full Newton Raphson Method is appropriate for the insertion tests and give accurate results for the existing test conditions.

Table 3. Summary of results of numerical modelling

Scale angle (°)	Contact pressure (MPa)	Frictional stress (MPa)	Force reaction (N) (ANSYS)	Insertion load (N) (Experiment)
10	5.87	1.17	3300.8	3316
13	6.42	1.28	3635.1	3600
16	5.09	1.01	3250.7	3308
19	7.37	1.47	4108.1	3965

5.2.2 *Numerical analysis of pull-out*

Numerical analysis of pull-out is conducted in a manner similar to insertion tests by assuming a friction coefficient of 0.2. Figure 12 shows the pull-out loads with scale angles from experimental and numerical tests.

From Figure 12, it is clear that the numerical analysis of pull-out tests in ANSYS using the Full Newton Raphson method is not appropriate. The prominent bilinear relationship of the pull-out loads with scale-angles, as observed from the experimental program, is not captured by the numerical analysis. Furthermore, the load values obtained from the numerical analysis is significantly lower than the values reported from the experiments. This anomaly is probably due to the complex interaction of the snakeskin-inspired patterns with the POP block, in addition to the radial spring force arising out of the compression of the Split Set in the under-sized hole, that is unable to be captured by the simple algorithm used in the Full Newton Raphson Method. Hence, numerical analysis using an advanced algorithm is required to correctly simulate and validate the pull-out behaviour of the snakeskin-inspired Split Sets observed in the experiments.

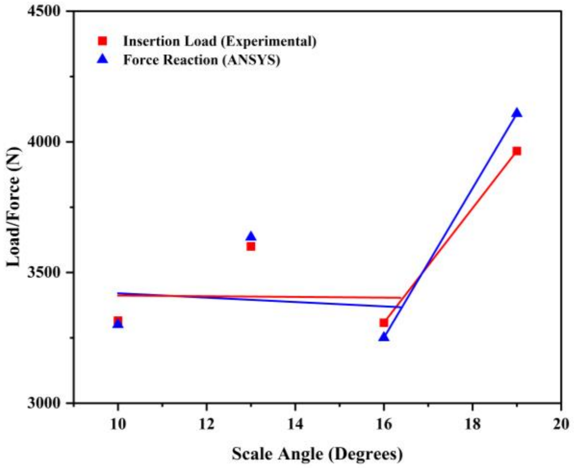

Figure 11. Bilinear relationship of insertion loads with scale angles, from experimental and numerical tests

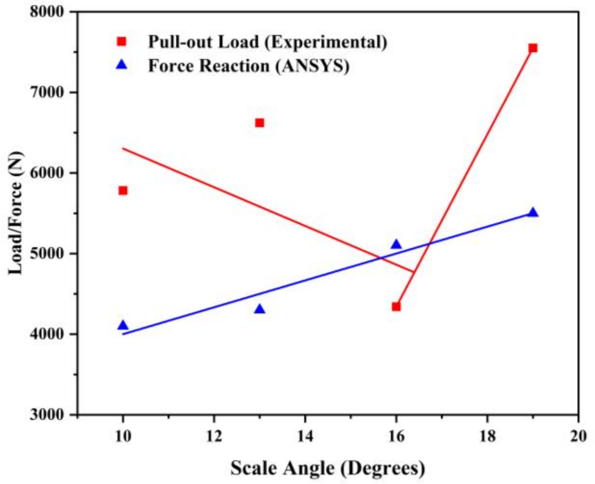

Figure 12. Relationship of pull-out loads with scale angles, from experimental and numerical tests

6 CONCLUSIONS

The study investigates the effect of snakeskin-inspired patterns on the behaviour of Split Sets. The frictionally anisotropic patterns are a novel approach for efficient friction rock bolts.

- The four different snakeskin-inspired patterns exhibit a similar trend in insertion and pull-out behaviour in the experimental program. A bilinear relationship between the insertion and pull-out loads and the longitudinal scale angles exists.
- The four different models of snakeskin-inspired patterns exhibit higher frictional anisotropy when compared to conventional rock bolt patterns. The SSI_19 shows the highest frictional anisotropy among the snakeskin-inspired patterns, whereas HA patterns exhibit minimal frictional anisotropy.
- The numerical analysis of the insertion and pull-out behaviour of the snakeskin-inspired Split Sets can correctly capture the insertion behaviour. Moreover, the force reaction values obtained in the numerical analysis of insertion tests exhibit a bilinear relationship similar to the experimental program.
- The numerical analysis of the pull-out tests gave ambiguous and lower results when compared to the experimental results. Hence, advanced algorithms are required to correctly capture the pull-out behaviour and the complex interaction of the snakeskin-inspired Split Sets with the surrounding rock mass.

The study has encouraging results for the adoption of snakeskin-inspired patterns for energy-saving and efficient friction rock bolts. Advanced research, including numerical modelling, can provide deeper insights into the mechanisms of the snakeskin-inspired rock bolts.

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