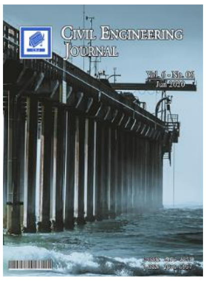
Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 6, No. 6, June, 2020



Numerical Analysis of the Influence of Bolt Set on the Shear Resistance of Jointed Rock Masses

Yan-Ping Wang [a], Liang-Xiao Xiong [b*]

[a] *Shandong University of Technology, Zibo, Shandong Province, 255000, China.*

[b] *East China Jiaotong University, Nanchang, Jiangxi Province, 330000, China.*

Received 05 February 2020; Accepted 20 May 2020

Abstract

Bolt reinforcement is a standard reinforcement method for jointed rock masses. However, regarding rock anchoring, the mechanical characteristics of the joint surface, as well as the angle between the bolt and the joint sliding surface, are important factors that affect rock support. Therefore, to understand the influence of a set angle, length, normal load, and other conditions that affect the shear strength of bolt joints, this study uses numerical software to establish the shear sliding model of bolt rock masses and analyzes the influence of the setting conditions of the bolt on the shear strength of a bolt rock mass, which can be done by changing the setting method of the bolt and normal mechanical conditions of the sliding surface. The results show that the shear strength of the anchor joint is not affected after the anchor reaches a certain length. The angle of the anchor strongly influences the shear strength of the anchor joint, and the shear strength curve is V-shaped, where the anchor angle is less than 90°. Moreover, the shear strength curve indicates a downward trend when the anchor angle is greater than 90°, and the shear strength of the anchorage joint increases with the increase of the normal load. Under the same anchor length (4 cm) in the anchor angle and shear strength coordinate system, the shear strength curve of the single anchor is above the shear strength curve of the double anchor, which is exclusively in the local anchor angle section under the condition of a large normal load and a large anchor angle. The shear strength curve of the double anchor is above the shear strength curve of the single anchor.

Keywords: Jointed Rock Mass; Rock Bolts; Numerical Simulation; Shear Strength.

1. Introduction

Jointed rock masses are standard in slopes, water conservancy, hydropower, mining, as well as highway construction, among other projects. Because of disturbances caused by excavations or weathering, the rock mass is often destroyed along the joint surface, resulting in natural disasters, such as landslides or collapses [1]. Therefore, rock bolts are widely used for rock mass reinforcement [2]. The shear resistance of an anchored rock mass can be affected by many factors, and much research has been done on the topic. Liu et al. (2020) [3] proposed an improved method to predict the contribution of the passive full grouting anchor to the shear resistance of jointed rock. Moreover, Wu et al. (2019) [4] found that the influence of a cyclic load on the shear capacity of the bolt is far greater than that of the shear capacity of the bolt itself. Lia et al. (2019) [5] determined that the shear behavior of the bolt on the joint surface of the reinforced rock included the axial shear behavior along with the bolt interface and the local transverse shear behavior of the bolt deflection section. Through numerical simulation analysis, two boundary anchorage lengths were found in the bolt shear test. Chen et al. (2018) [6] conducted direct shear tests on the pre-set joint examples of

* Corresponding author: xionglx1982@126.com

http://dx.doi.org/10.28991/cej-2020-03091527

bolt support, which were unsupported by different normal stress actions. The results showed that the deformation of the bolt decreased with the increase of normal stress and increased with the increase of roughness. Liu et al. (2018) [7] noticed that bolt anchoring could increase the equivalent cohesion and internal friction angle of the joint rock surface and that the compressive strength of the rock material has a significant impact on the mechanical properties of the bolt joint surface. The softer the lithology is, the closer the mechanical properties of the bolt and similar rock materials are. Moreover, the harder the lithology is, the greater the increase of the shear strength of the bolt-on joint rock surface and the more significant the reinforcement effect of the bolt is. Chen (2020) [8] showed that the strength of layered rock increases with the anchoring effect. In the case of no bolt, the failure mode of rock changes from a shear failure to a split failure. When bolt reinforcement was used, the failure plane was parallel to the axis of the bolt, and the shearing began at the interface between hard rock and soft rock. Furthermore, Li et al. (2019) [9] indicated that the bolting angle and grout strength play significant roles in influencing the bolt contribution. With increases of the bolting angle, the bolt contribution initially rises and then reduces; they obey a parabola relationship. Notably, the contribution of the bolt is less than its ultimate tensile load by a large margin when the bolt steeply intersects the rock joint. Moreover, Yao et al. (2019) [10] observed that water had a significant effect on the shear bond strength of the rock resin interface, and the failure was concentrated at the interface of the rock resin after immersion. Building upon this, Ma et al. (2019) [11] proposed an analytical model that could predict the shear characteristics of anchored rock and verify the model. The study by Wang et al. (2019) [12] demonstrated that the loading rates at a low strain rate may influence the mechanical properties and fracture characteristics of the anchored and unanchored sandstone samples. The elastic modulus of the anchored sandstone samples was slightly improved with the increase of loading rates at a low strain rate. Through a cyclic shear test, Wu et al. (2019) [13] found that the influence of the cyclic load on the shear strength of a rock bolt is far greater than that of the rock joint itself. The numerical results of Li et al. (2019) [14] indicated that two demarcation anchorage lengths existed in the cable shear tests. In the case of a plain super strand cable bolt subjected to lateral shear loading at a 90° angle, the two demarcation anchorage lengths were approximately 2.09 and 0.61 m.

The above research results are all experimental studies that assume the condition that the bolt and the shear plane intersect at an angle of 90°. However, in practical engineering cases, such as slopes and tunnels, as a result of the change of joint occurrence and the different positions of the bolt in the tunnel, the angle between the anchor and joint surface is not fixed. Thus, the question arises: do different setting methods of the anchor rod affect the shear strength of the anchored rock mass? Lin et al. (2014) [15] used FLAC (Fast Lagrangian Analysis of Continua) to analyze peak shear strength under low stress (0.1, 0.3, 0.5, and 0.7 MPa) and different anchoring angles (15°, 30°, 45°, 60°, 75°, and 90°). The results showed that the change of an anchor angle and the normal stress of a joint had a significant influence on the peak shear strength of the anchor rock. The curve slope of the angle shear strength curve reached the maximum value within 15°–30° of the bolt inclination. Subsequently, with the increase of the anchor angle, the shear strength decreased gradually, and the final curve tended to be stable. Chen et al. (2015) [16] found that five displacement angles between 0° (pure tension) and 90° (pure shear) were used in the anchoring rock test. The test results indicated that when the displacement angle was more than 40°, the test block may be crushed under the bolt, which reduced the stiffness of the anchor. Moreover, the tests of Li et al. (2019) [17] demonstrated the shear strength of an anchored cement block with anchor angles at 45°, 60°, 75°, and 90°. The test results showed that the shear strength of the anchored cement block decreased with the increase of the anchor angle. Under the condition of small normal stress and an angle less than 90°, the influence of high normal stress and the anchor angle of the anchor on shear strength were not considered. Moreover, the conclusions of the above research were inconsistent. Riyad et al. (2020) [18] and Ceroni et al. (2020) [19] looked at the influence of the anchor bolt length on shear strength as a size effect. The tensile strength of the anchor bolt is affected by its anchor length, but after exceeding a certain anchor length, the tensile strength will not increase. Whether the length of the bolt affects the shear strength of the joint surface is not given in this paper.

Because of the above issues, this study intends to use discrete element software to analyze and calculate the influence of the joint surface on the shear strength of the anchorage under the conditions of various anchor angles, normal loads, anchor lengths, and a number of anchor bolts. The setting conditions of each anchor are calculated per the cross-setting method. The research flow chart is shown in Figure 1.

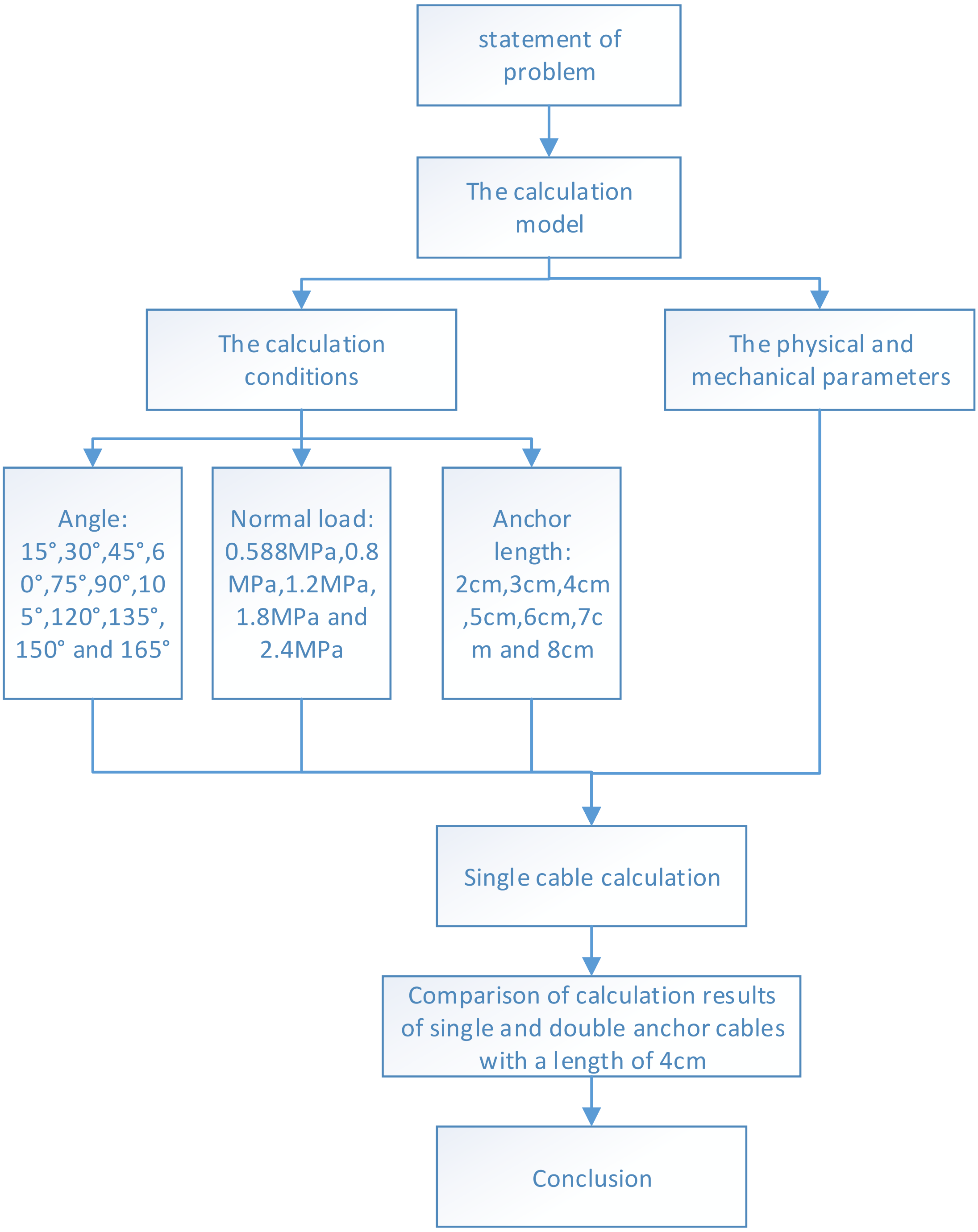


Figure 1. Research methodology flow chart

2. Experimental Model Design

In support engineering, rock mass shearing along a joint surface is a result of excavation and unloading. Nevertheless, the angle between the bolt and joint surface is not fixed, as a result of a change in the joint occurrence and bolt position. The angle between the support bolt and the horizontal plane is often set in a small range of 10°–20°. However, the occurrence of rock joints varies significantly in different regions of a rock slope (0°–360°). Therefore, the angle between the bolt and rock joints is different in the different areas of rock bolt support projects. Therefore, the supporting effect of the rock anchor must be changed. Second, rock joints in a specific tunnel project are typically pre-determined. Still, in the anchoring support of a tunnel, as a result of the various anchoring positions, the angle between the anchor bolt and joint surface also varies. In tunnel engineering, even for the same tunnel section, rock anchors may have different reinforcement effects caused by different bolt positions.

Per the above analysis, the reinforcement effect of the anchor bolt in the anchorage system may vary. Therefore, according to the above characteristics of the angle difference between the bolt and joint surface, the experimental model is realized (Figure 2).

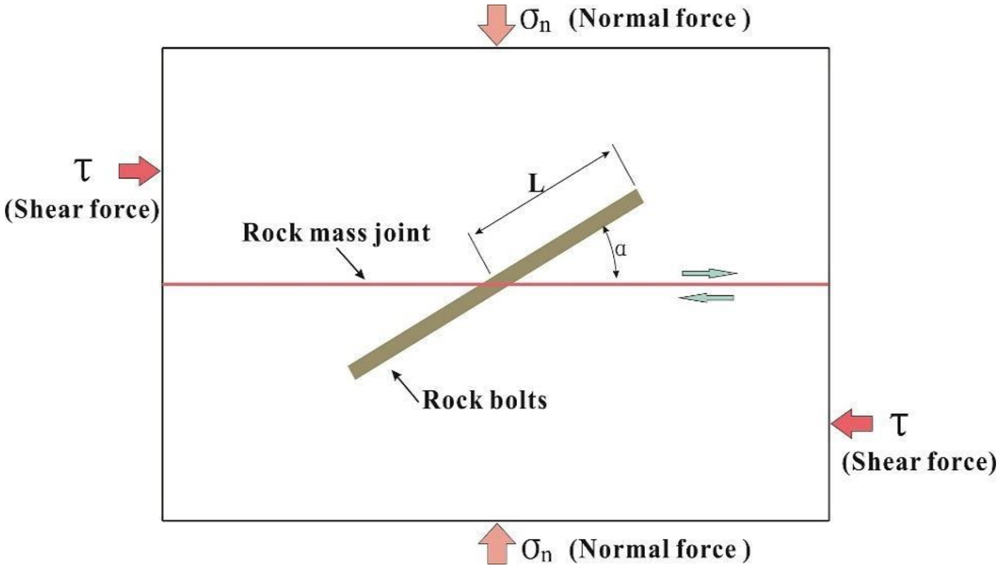


Figure 2. Shear abstract model of the joint in the anchored rock mass

2.1. Numerical Model

UDEC software was used for the numerical simulations. The abstract model can be seen in Fig. 2 and indicates the issue of reducing the shear plane after shear deformation. Therefore, the abstract model in Fig. 2 has been improved, the length of the lower block of the abstract model has been increased, and the lower block has been fixed. Then, the improved numerical model is shown in Figure 3.

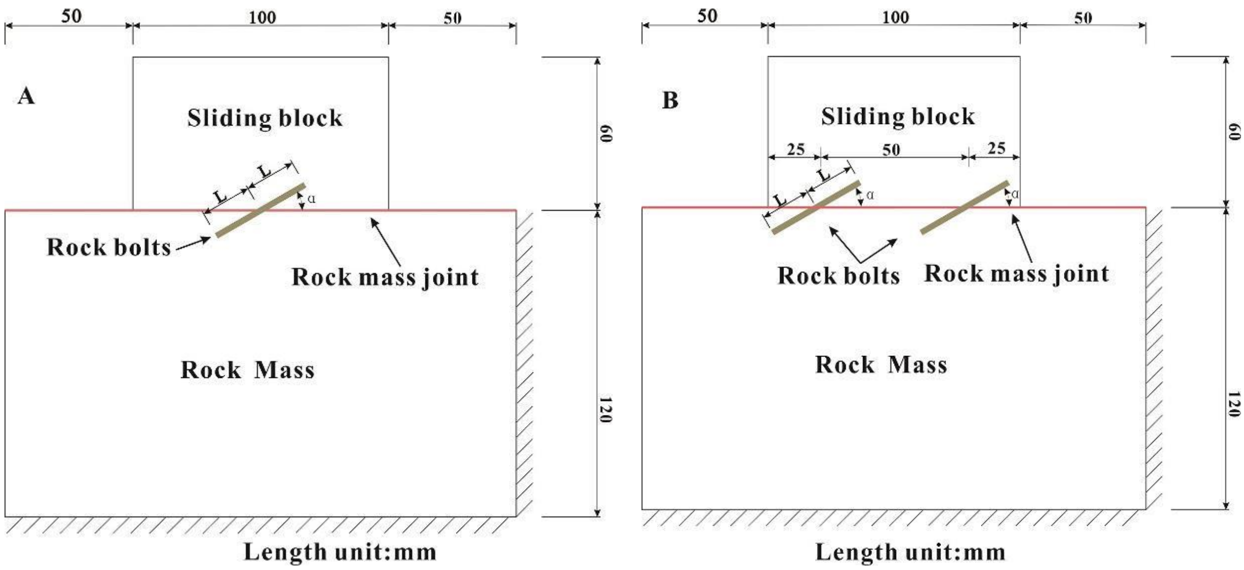


Figure 3. Numerical model; A: Single bolt numerical model. B: Double bolt numerical model

The calculation of a single bolt and double bolt was then performed. According to the principle of the rock shear test, the boundary conditions of the upper and lower blocks were set. A uniformly distributed normal load was applied to the top of the upper slider, the fixed shear rate of horizontal right was applied on the left side of the upper slider, and the bottom and right sides of the lower slider were fixed. The physical and mechanical parameters of the upper and lower blocks and joint surfaces of the model, as well as the calculation parameters of anchor bolts (Tables 1, 2, and 3), were calculated by the parameters used by Luo (1991) [20]. The length of the bolt in the upper and lower blocks remained the same.

Table 1. Rock mass material parameters

	Density (kg/m³)	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Friction angle (°)	Tensile strength (MPa)	Dilation angle (°)
Rock mass	1400	2.98	2.05	0.9	42	0.163	0
Joint	-	0.9	0.18	0	32	0	0

Table 2. Bolt grouting material parameters

Density (kg/m³)	Compressive force (kN)	Young's modulus (GPa)	Tensile strength (kN)	Cross section area (mm^2)	Extensional failure strain	Grout shear stiffness (MPa)	Grout shear strength (MPa)
2700	4	700	4	7.07	0.01	160	0.16

Table 3. Material parameters of bolt steel

	Axial stiffness (MN/m)	Shear stiffness (MN/m)	Ultimate axial capacity (kN)	Ultimate shear capacity (kN)
Reinforce	968	105	4	4

2.2. Numerical Calculation Group

According to angle α between the bolt and the joint surface (per the counterclockwise rotation angle), the normal load σ_n on the joint surface and the length L of the bolt groups were made. The shear failure calculation of the double anchor model with the anchor length of 4 cm was then conducted.

Table 4. Numerical calculation group with different values of L, α, and σ_n

Bolt length L (cm)	Normal load σ_n (MPa)	Bolt angle α (°)
2	0.558, 0.8, 1.2, 1.8, and 2.4	15, 30, 45, 60, 75, 90, 105, 120, 135, 150, and 165
3	0.558, 0.8, 1.2, 1.8, and 2.4	15, 30, 45, 60, 75, 90, 105, 120, 135, 150, and 165
4	0.558, 0.8, 1.2, 1.8, and 2.4	15, 30, 45, 60, 75, 90, 105, 120, 135, 150, and 165
5	0.558, 0.8, 1.2, 1.8, and 2.4	15, 30, 45, 60, 75, 90, 105, 120, 135, 150, and 165
6	0.558, 0.8, 1.2, 1.8, and 2.4	15, 30, 45, 60, 75, 90, 105, 120, 135, 150, and 165
7	0.558, 0.8, 1.2, 1.8, and 2.4	15, 30, 45, 60, 75, 90, 105, 120, 135, 150, and 165
8	0.558, 0.8, 1.2, 1.8, and 2.4	15, 30, 45, 60, 75, 90, 105, 120, 135, 150, and 165

3. Analysis of Calculation Results

A uniform horizontal displacement was applied to the left side of the upper sliding block of the calculation model, which resulted in the model sliding block shear being at a uniform speed until the upper sliding block reached yield failure.

3.1. Shear Strength Curves of Different Bolt Lengths

The test bolt lengths were 2, 3, 4, 5, 6, 7, and 8 cm. Five different normal loads were applied to the test model. The anchor angle was set according to Table 4. Moreover, the calculated shear strength curves are shown in Figures 4 to 10.

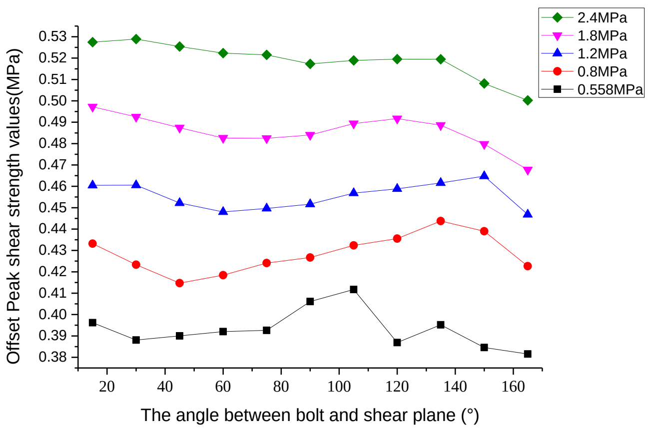


Figure 4. Relationship between the anchor angle and shear strength with an anchor length of 2 cm

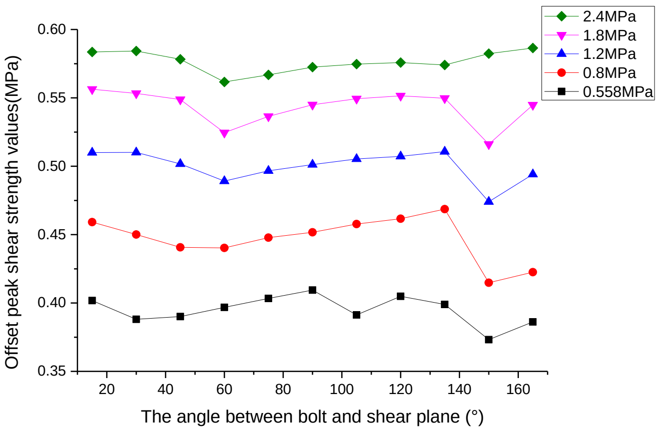


Figure 5. Relationship between the anchor angle and shear strength with an anchor length of 3 cm

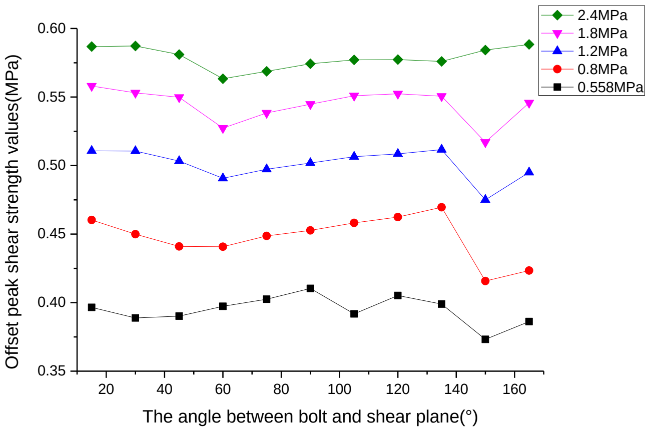


Figure 6. Relationship between the anchor angle and shear strength with an anchor length of 4 cm

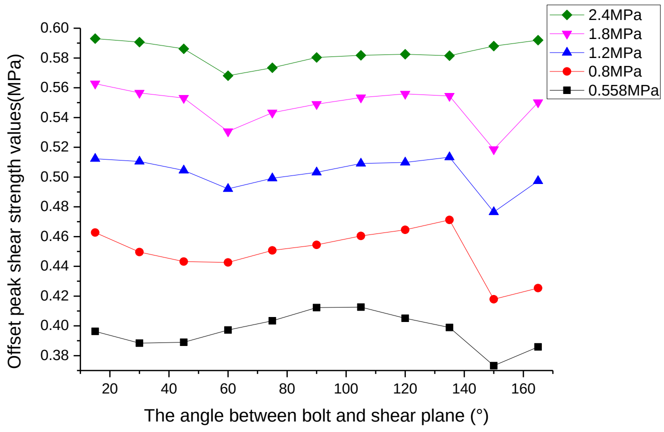


Figure 7. Relationship between the anchor angle and shear strength with an anchor length of 5 cm

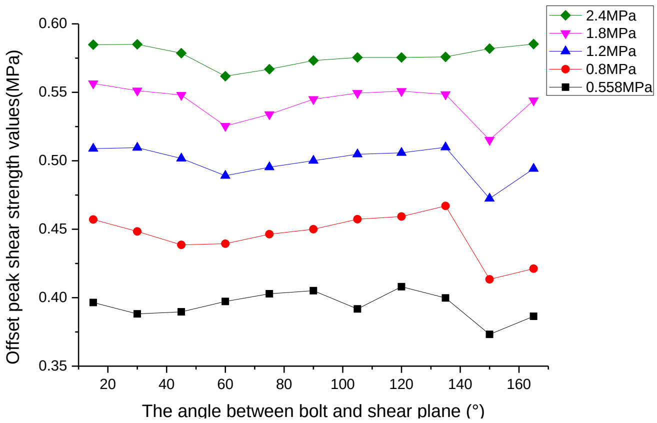


Figure 8. Relationship between the anchor angle and shear strength with an anchor length of 6 cm

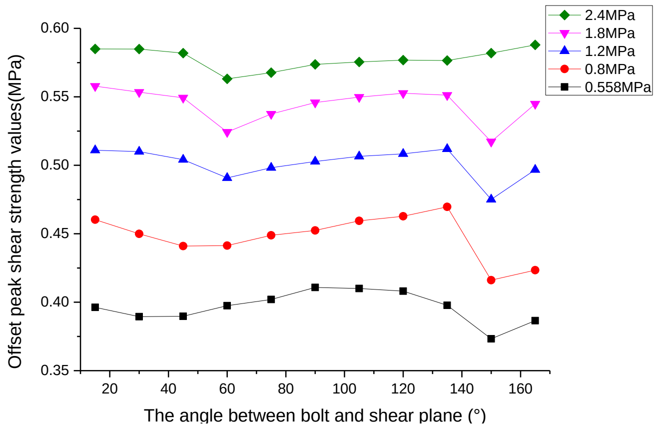


Figure 9. Relationship between the anchor angle and shear strength with an anchor length of 7 cm

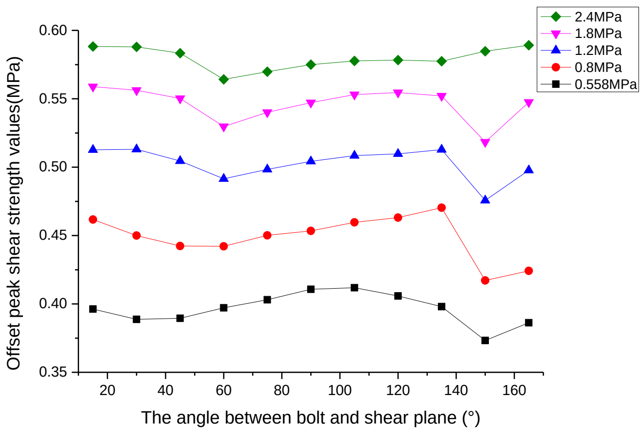


Figure 10. Relationship between the anchor angle and shear strength with an anchor length of 8 cm

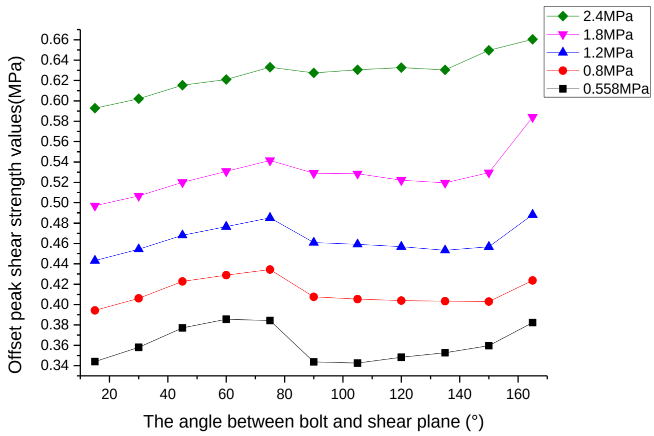


Figure 11. Relationship between the anchor angle and shear strength with a double anchor length 4 cm

Based on the analysis of the above shear strength curves, the shear strength of seven different lengths of single bolt and one double bolt increased with the increase of a normal load. The normal load strongly influenced the angle shear strength curve of a single bolt. When the normal load was 0.8, 1.2, or 1.8 MPa, the angle shear strength curves of the bolts were similar. The normal loads of 0.558 and 2.4 MPa have different angle shear strength curves. For the double anchor model, the normal loads of 0.558, 0.8, 1.2, and 1.8 MPa have a similar angle shear strength curve. However, the angle shear strength curve with a normal load of 2.4 MPa is slightly different from that of the other normal loads.

3.2. Shear Strength Curve under the Same Normal Load

According to the calculation results of the model, the change characteristics of shear strength under different anchor lengths and anchor angles were analyzed when the normal load of the model was the same.

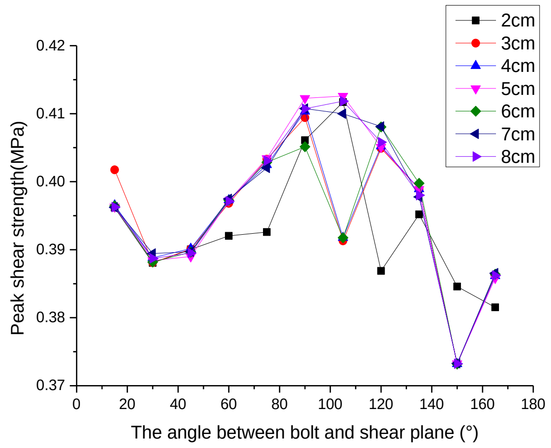


Figure 12. Relationship between the angle of the anchor bolt and shear strength under a normal load of 0.558 MPa

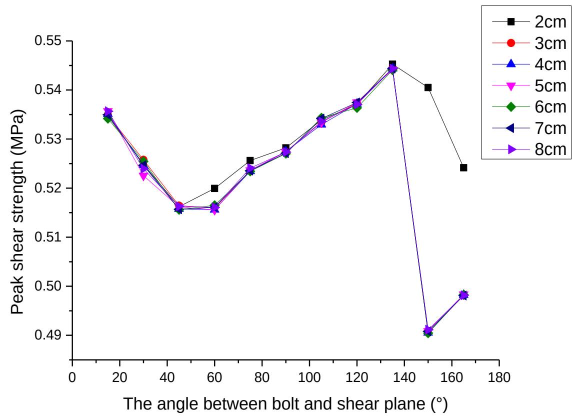


Figure 13. Relationship between the angle of the anchor bolt and shear strength under a normal load of 0.8 MPa

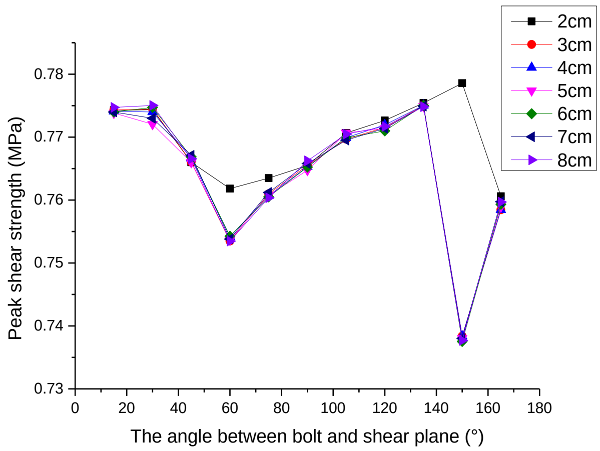


Figure 14. Relationship between the angle of the anchor bolt and shear strength under a normal load of 1.2 MPa

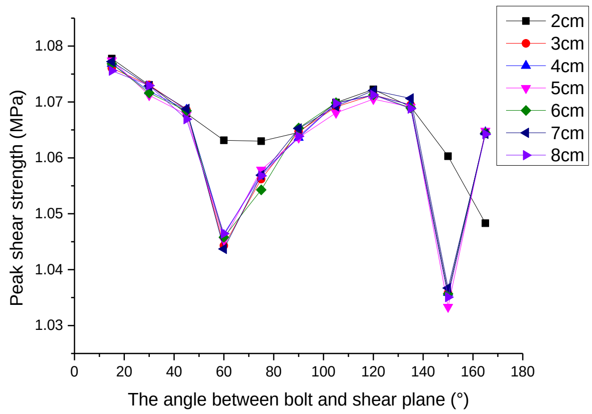


Figure 15. Relationship between the angle of the anchor bolt and shear strength under a normal load of 1.8 MPa

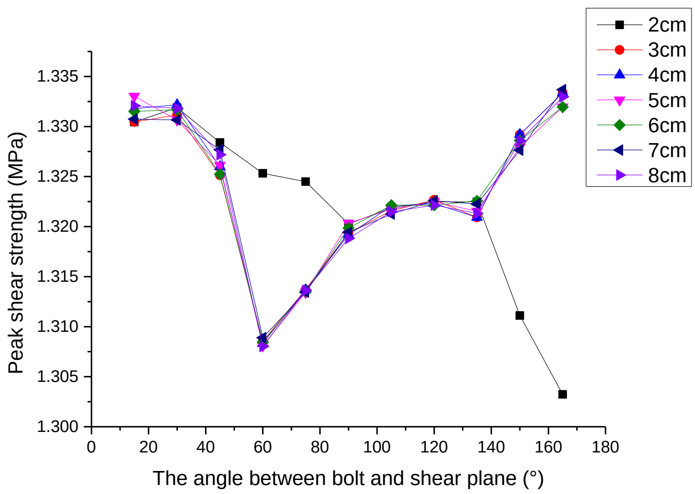


Figure 16. Relationship between the angle of the anchor bolt and shear strength under a normal load of 2.4 MPa

Figures 12 to 16 were analyzed to observe the influence of the bolt angle change on shear strength under the same normal stress condition. In Figure 12, the normal load is 0.558 MPa, and the length of the anchor rod strongly influences shear strength. The maximum shear strength of anchor bolts with lengths of 3, 4, 6, and 7 cm was located at 90° of the anchor bolt angle, and the maximum shear strength of anchor bolts with lengths of 2, 5, and 8 cm was located at 105° of the anchor bolt angle. When the angle of the anchor was less than 90°, the influence of the anchor length on the changing trend of shear strength was small, and the shape of the shear strength curve remained the same. Both decreased initially and then increased. In the range of 90°–120° of the anchor angle, the influence of the anchor length on shear strength was great, and the changing trend of the shear strength of each length of an anchor in this area was varied. The shear strength curves of the bolts with lengths of 3, 4, and 6 cm were V-shaped. The shear strength curves of bolts with lengths of 5, 7, and 8 cm decreased in a straight line. After the angle of the anchor bolt reached 120°, the shear strength curves of anchor bolts with lengths of 3, 4, 5, 6, 7, and 8 cm initially decreased and then increased.

In Figures 13 to 16, the normal stress is 0.8, 1.2, 1.8 and 2.4 MPa, respectively, and the anchor angle strongly influences the peak strength. The shear strength curves in Figure 13 to 15 show two parallel V-shapes with low peaks at 60° and 150°. When the normal load was 2.4 MPa (Figure 16), the peak strength curve was in an approximate V-shape, and the low peak was located at the anchor angle of 60°. In these figures, the shear strength curve (the approximate S-shape of dumping) of the 2 cm bolt was different from that of other bolt lengths.

The above analysis indicates that the normal load influences the shear strength, and the length and angle of the anchor influence the shear strength when the normal load is small. When the normal load is large, the bolt length has little influence on the shear strength of the bolt. However, the angle of the bolt has a great influence on the shear strength of the bolt.

3.3. Shear Strength Curve under the Same Anchor Angle

According to the calculation results, the characteristics of change of the shear strength of the model under the conditions of various bolt lengths and normal stress under the same bolt angle were analyzed.

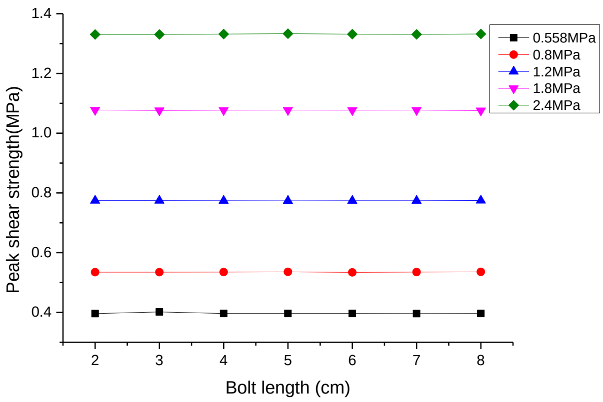


Figure 17. The length of the shear strength curve at an anchor angle of 15°

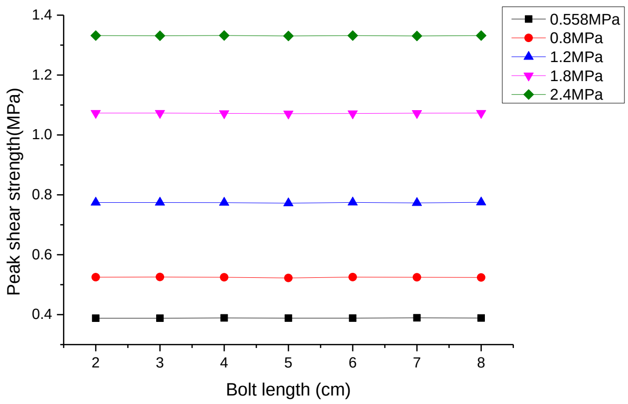


Figure 18. The length of the shear strength curve at an anchor angle of 30°

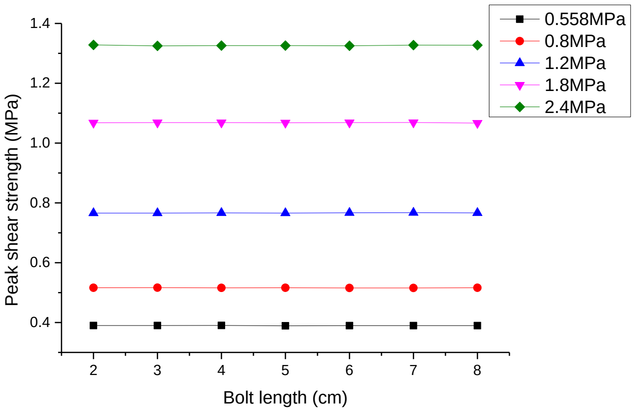


Figure 19. The length of the shear strength curve at an anchor angle of 45°

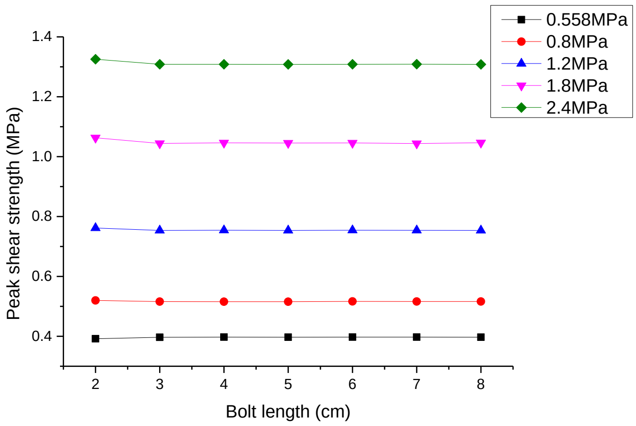


Figure 20. The length of the shear strength curve at an anchor angle of 60°

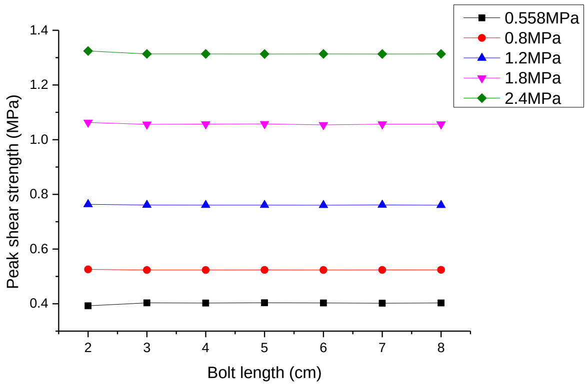


Figure 21. The length of the shear strength curve at an anchor angle of 75°

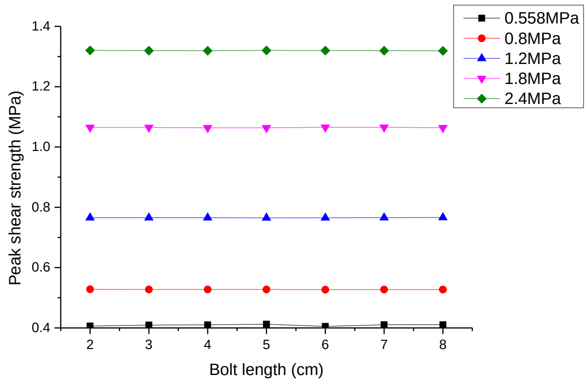


Figure 22. The length of the shear strength curve at an anchor angle of 90°

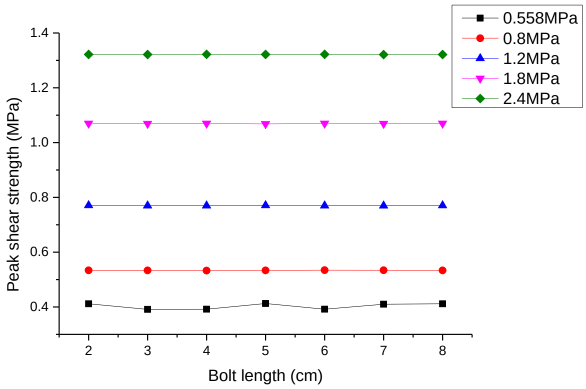


Figure 23. The length of the shear strength curve at an anchor angle of 105°

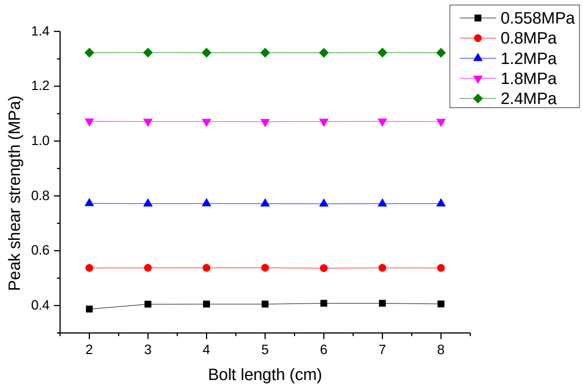


Figure 24. The length of the shear strength curve at an anchor angle of 120°

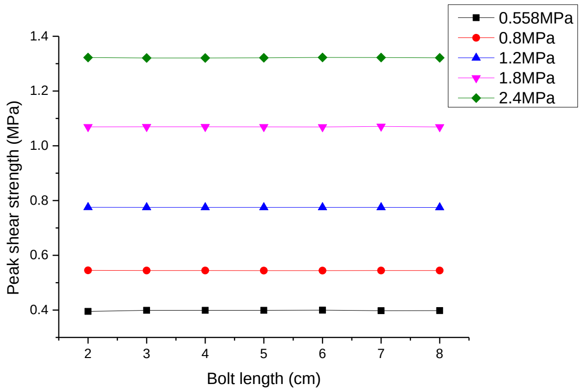


Figure 25. The length of the shear strength curve at an anchor angle of 135°

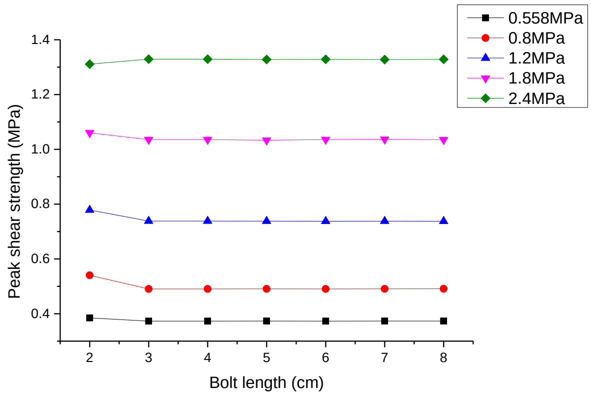


Figure 26. The length of the shear strength curve at an anchor angle of 150°

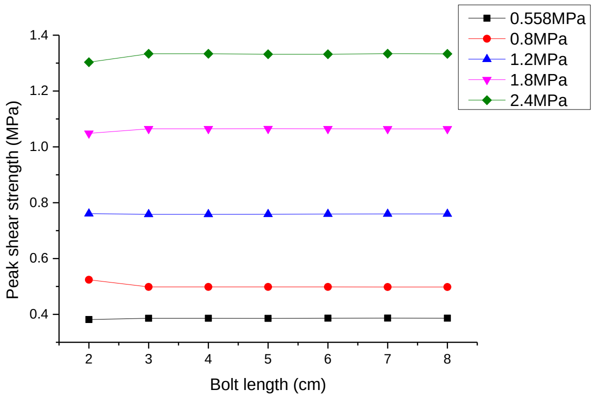


Figure 27. The length of the shear strength curve at an anchor angle of 165°

Analysis of Figures 17 to 27 shows that the curves in the figures are relatively straight, indicating that the bolt length has little influence on shear strength under the same bolt angle. At anchor angles of 15°, 30°, and 45°, the shear strength curve of each normal load was nearly horizontal, which showed that the length of the anchor does not affect shear strength. At anchor angles of 60°, 75°, 150°, and 165°, the shear strength of the anchor with a length of 2 cm slightly fluctuated. At anchor angles of 60°, 75°, 150°, and 165°, the shear strength of the anchor with a length of 2 cm slightly fluctuated, although the strength curve of the other length of the anchor was nearly horizontal, which indicated that when the anchor length was long, the influence of the anchor length on the shear strength was small, although the influence of the anchor length on the shear strength was relatively large when the anchor length was small. Nevertheless, when the bolt length was smaller, the bolt length had a relatively large impact on the shear strength.

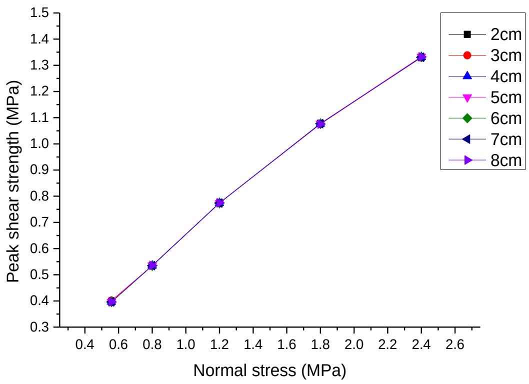


Figure 28.The normal stress–shear strength curve at an anchor angle of 15°

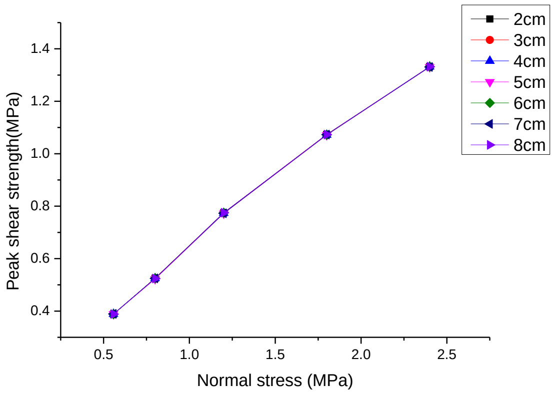


Figure 29. The normal stress–shear strength curve at an anchor angle of 30°

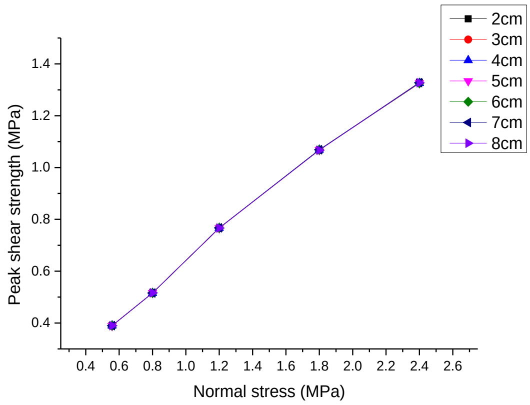


Figure 30. The normal stress–shear strength curve at an anchor angle of 45°

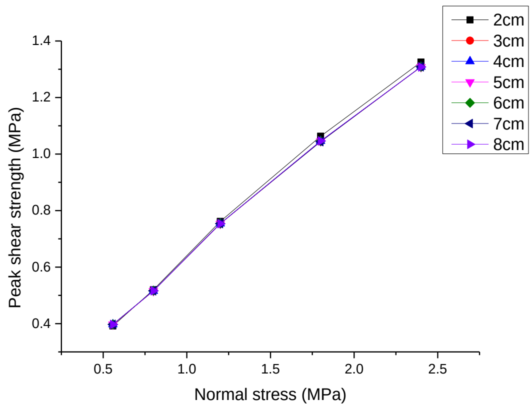


Figure 31. The normal stress–shear strength curve at an anchor angle of 60°

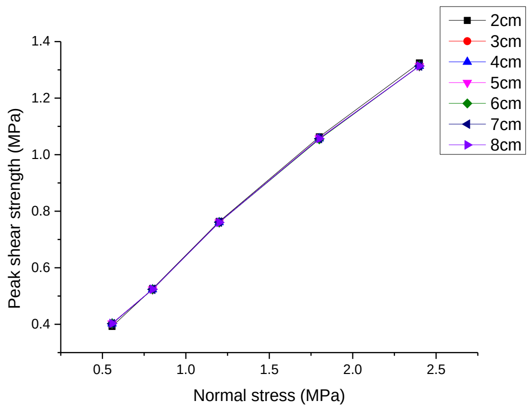


Figure 32. The normal stress–shear strength curve at an anchor angle of 75°

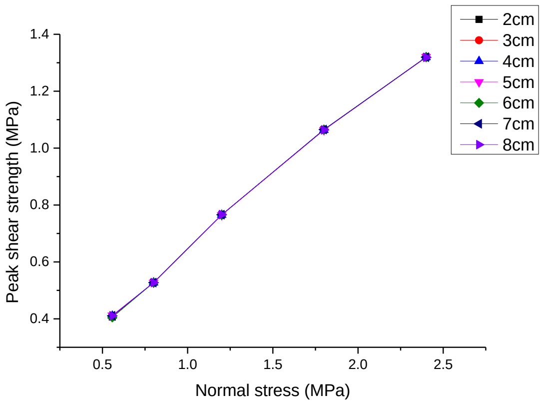


Figure 33. The normal stress–shear strength curve at an anchor angle of 90°

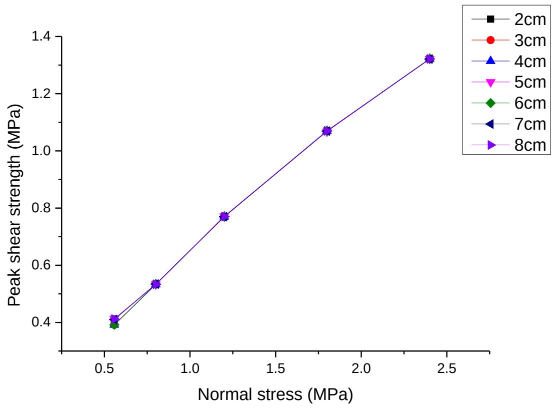


Figure 34. The normal stress–shear strength curve at an anchor angle of 105°

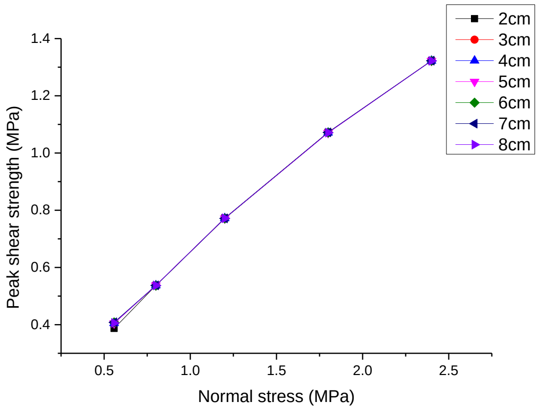


Figure 35. The normal stress–shear strength curve at an anchor angle of 120°

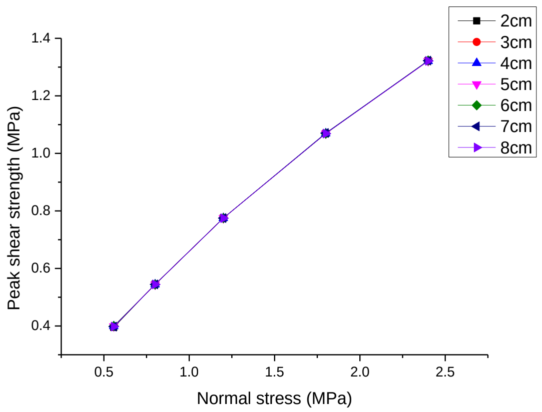


Figure 36. The normal stress–shear strength curve at an anchor angle of 135°

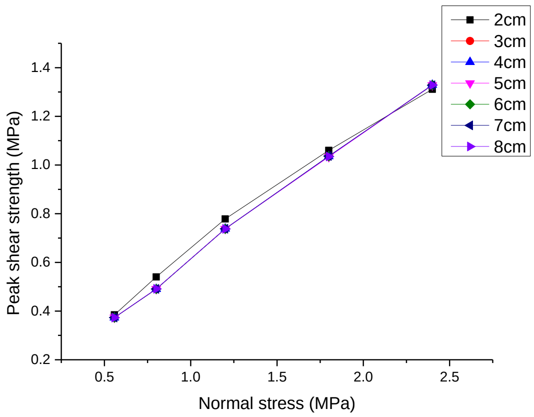


Figure 37. The normal stress–shear strength curve at an anchor angle of 150°

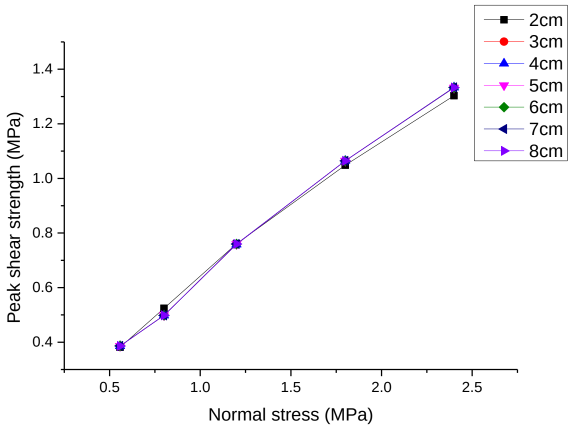


Figure 38. The normal stress–shear strength curve at an anchor angle of 165°

According to the analysis of Figures 28 to 38, normal stress does not affect the length of the bolt when the angle of the bolt is 15°, 30°, 45°, 75°, or 135°. According to the analysis of Figures 29 to 39, the normal stress–shear strength curves of each length of anchor bolt coincide at anchor angles of 15°, 30°, 45°, 75°, and 135°, indicating that the influence of anchor length on shear strength under each stress condition was small. At anchor angles of 60°, 90°, and 120°, the anchor length was 2 cm, which was significantly affected by normal stress. However, when the angle of the anchor was 60°, and the normal stress was 2.4 MPa, the shear strength curve of the anchor with a length of 2 cm was separated from the shear strength curve of other lengths, indicating that, in the high-stress area, and considering the length of the anchor being short, the length of the anchor had an impact on shear strength.

3.4. Shear Strength Analysis of Single Bolts and Double Bolts

A model shear calculation of single bolts and double bolts with a length of 4 cm was performed. The model calculation parameters were set according to Tables 1 to 3. The calculation model of single and double anchor bolts was set according to Figure 3.

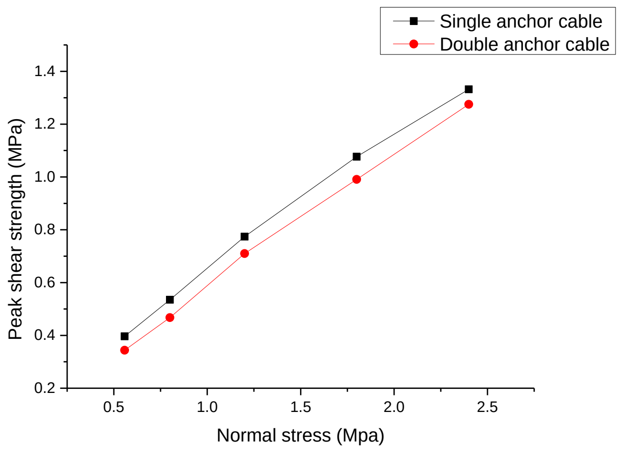


Figure 39. The shear strength curve of the single and double bolts under different normal stress when the angle of the bolt is 15°.

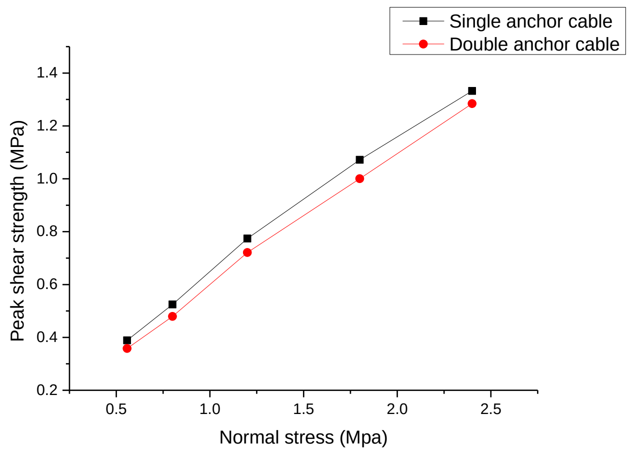


Figure 40. The shear strength curve of the single and double bolts under different normal stress when the angle of the bolt is 30°.

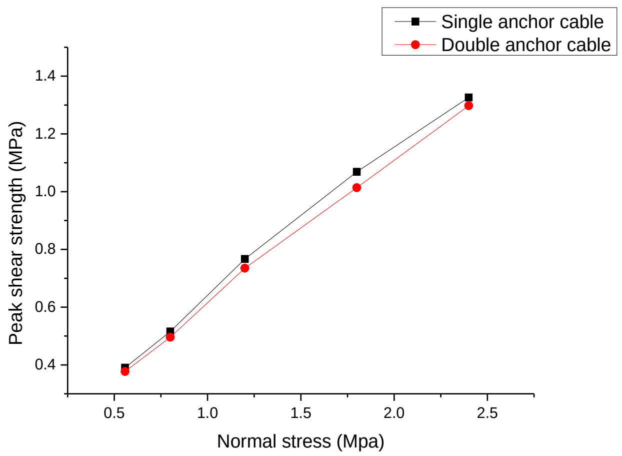


Figure 41. The shear strength curve of the single and double bolts under different normal stress when the angle of the bolt is 45°.

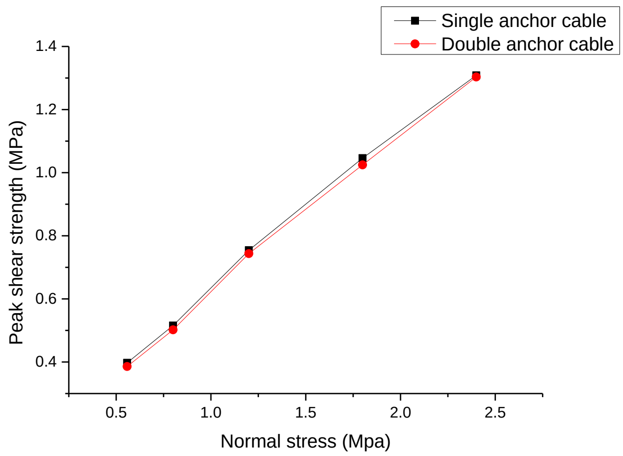


Figure 42. The shear strength curve of the single and double bolts under different normal stress when the angle of the bolt is 60°.

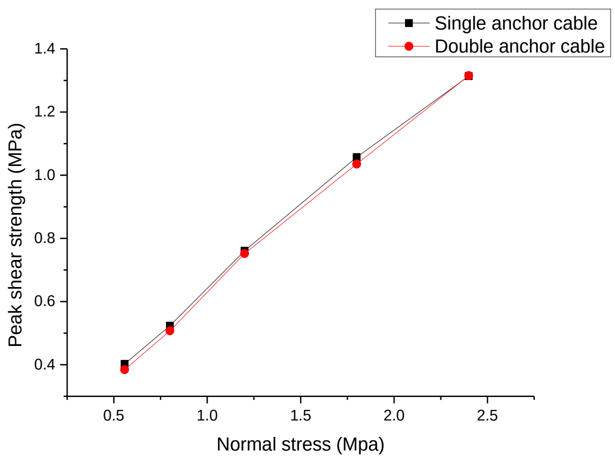


Figure 43. The shear strength curve of the single and double bolts under different normal stress when the angle of the bolt is 75°.

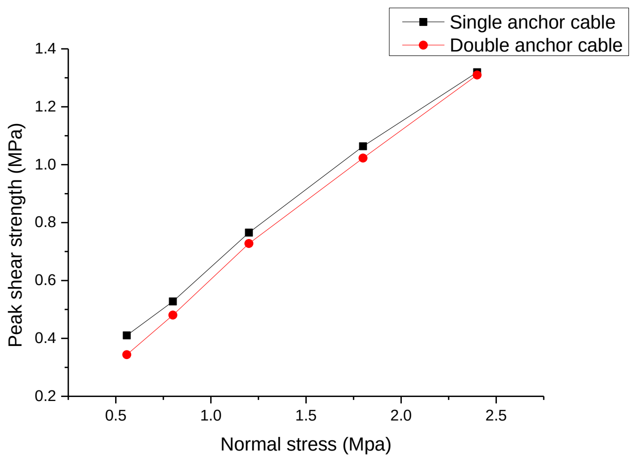


Figure 44. The shear strength curve of the single and double bolts under different normal stress when the angle of the bolt is 90°.

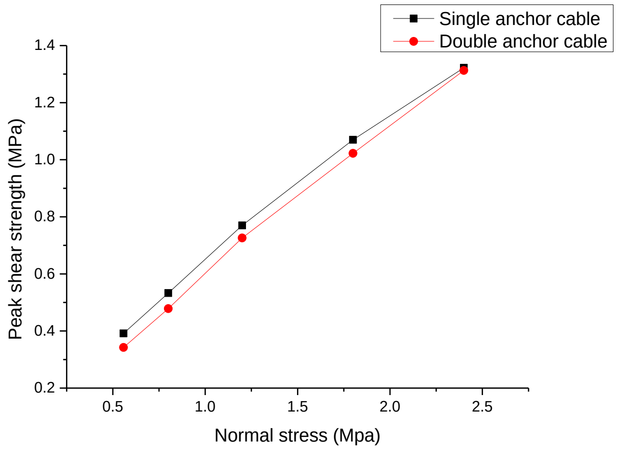


Figure 45. The shear strength curve of the single and double bolts under different normal stress when the angle of the bolt is 105°.

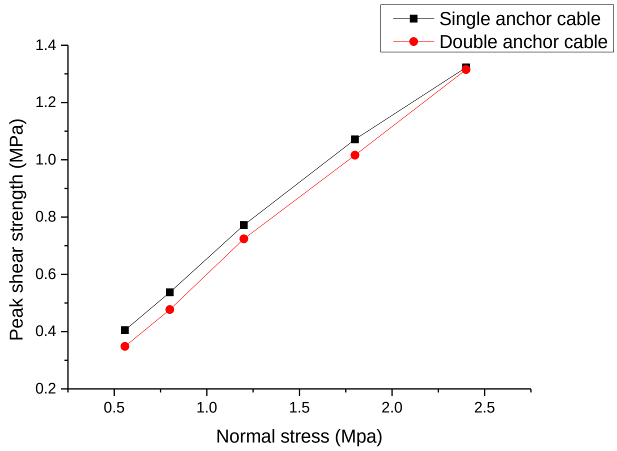


Figure 46. The shear strength curve of the single and double bolts under different normal stress when the angle of the bolt is 120°.

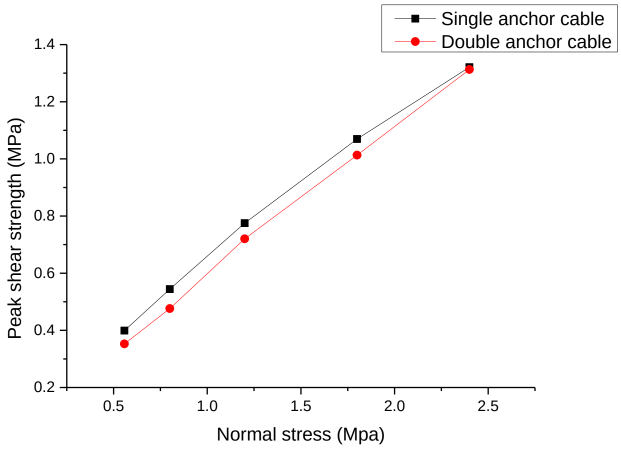


Figure 47. The shear strength curve of the single and double bolts under different normal stress when the angle of the bolt is 135°.

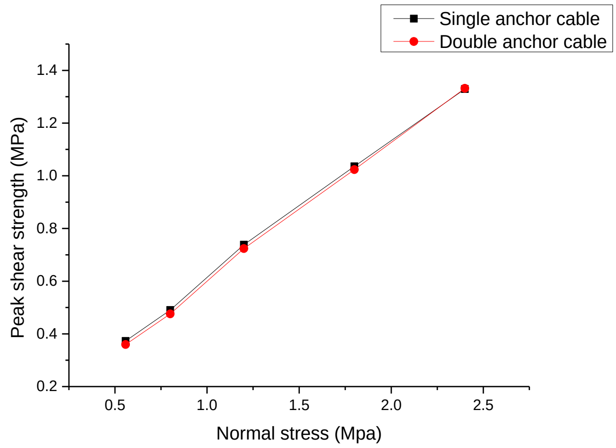


Figure 48. The shear strength curve of single and double bolts under different normal stress when the angle of the bolt is 150°.

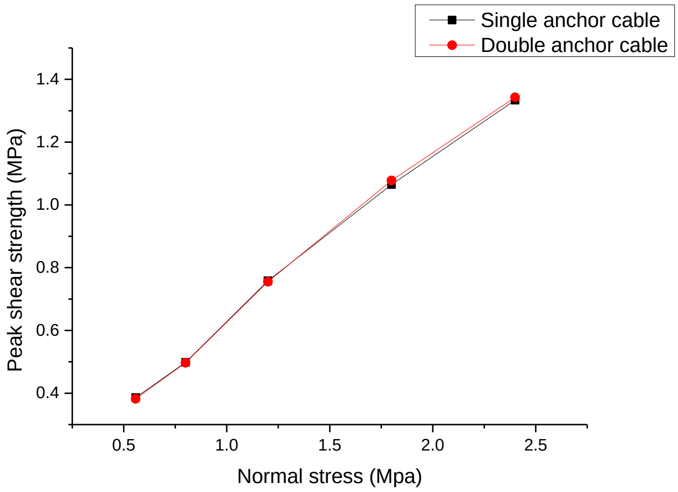


Figure 49. The shear strength curve of the single and double bolts under different normal stress when the angle of the bolt is 165°.

The results in Fig. 39–49 were analyzed. In Fig. 49, the angle of the anchor bolt is 165°, and the shear strength of the double anchor bolt with a normal stress of 1.8 and 2.4 MPa is greater than that of the single anchor bolt. Under the condition of other anchor angles and normal stress, the shear strength of a single anchor is greater than or equal to that of the double anchor. When the anchor angle is 60°, 75°, 150°, or 165°, the shear strength curves of the single anchor and double anchor almost coincide. Nevertheless, for other anchor angles, the shear strength curve of the single anchor is located in the upper region of the shear strength curve of the double anchor.

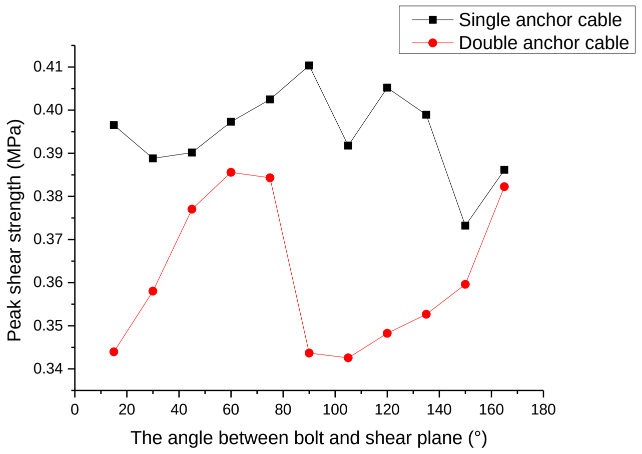


Figure 50. The shear strength curve of the single and double anchor under the normal stress of 0.558 MPa

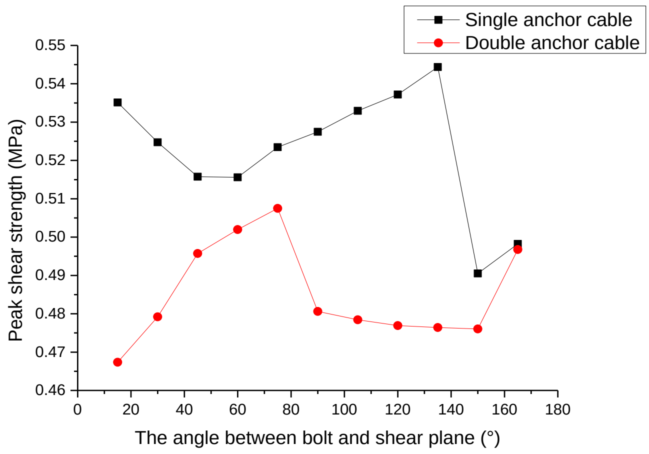


Figure 51. The shear strength curve of the single and double anchor under the normal stress of 0.8 MPa

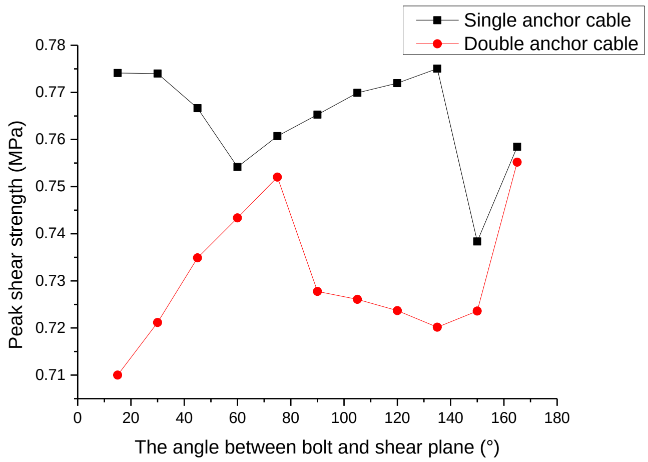


Figure 52. The shear strength curve of a single and double anchor under the normal stress of 1.2 MPa

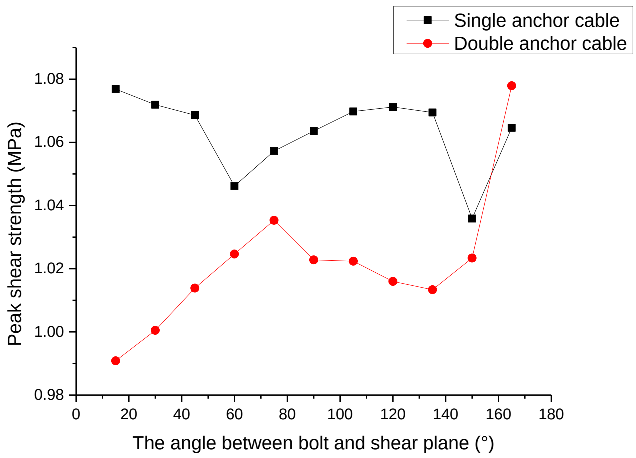


Figure 53. The shear strength curve of a single and double anchor under the normal stress of 1.8 MPa

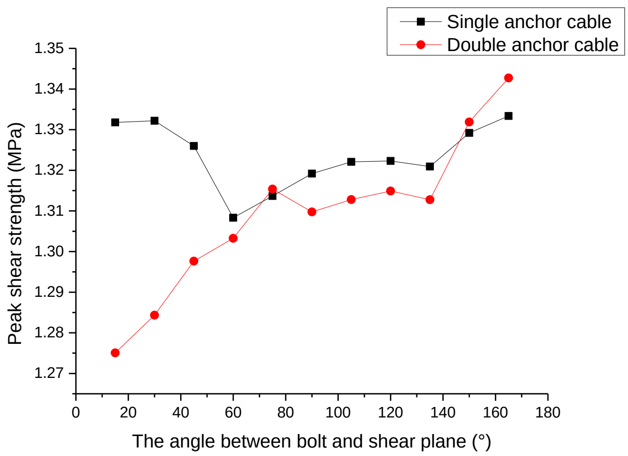


Figure 54. The shear strength curve of a single and double anchor under the normal stress of 2.4 MPa

The results in Figures 50 to 54 were analyzed. The shape of the shear strength curve of the single bolt was different from that of the double bolt. In Fig. 50, 51, and 52, the normal load is 0.558, 0.8, and 1.2 MPa, respectively, and the shear strength curve of the single bolt is above that of the double bolt. In Fig. 53, the normal stress is 1.8 MPa, the angle of the anchor is 165°, the shear strength of the double anchor is greater than that of the single anchor, and the shear strength of the double anchor is less than that of the single anchor. In Fig. 54, the normal stress is 2.4 MPa, and the angles of the anchor bolt are 75°, 150°, and 165°. The shear strength of the double anchor bolt was greater than that of the single anchor bolt, and the shear strength of a single anchor bolt of the other anchor bolt angles was greater than that of the double anchor bolt.

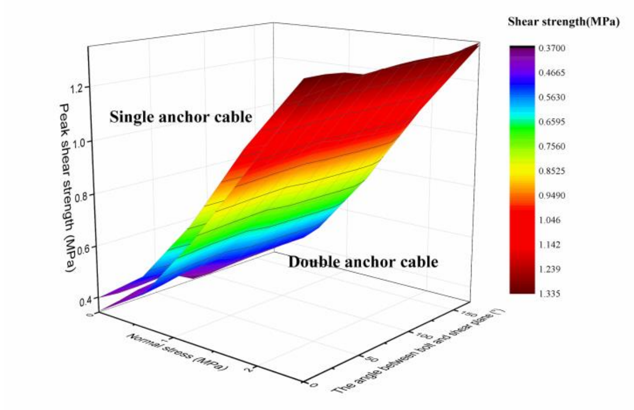


Figure 55. Cloud chart of the shear strength of the single and double anchor bolts

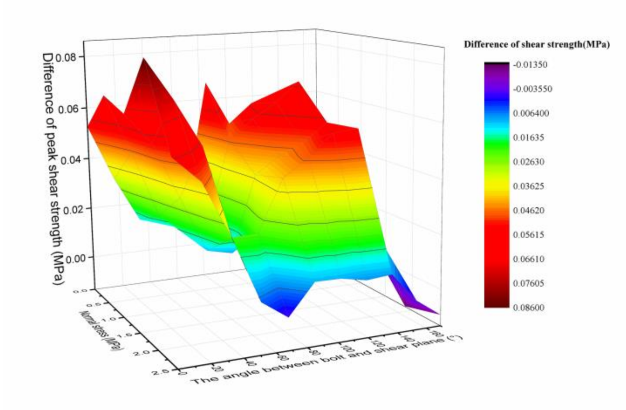


Figure 56. Cloud chart of the shear strength difference of the single and double anchor bolts

Figures 55 and 56 were analyzed. The nephogram of shear strength of a single bolt is located in the upper region of the nephogram of the shear strength of the double bolt, although there is a local intersection under the condition of a high-stress area and large angle. In Figure 56, the cloud chart of shear strength indicates a difference between the single bolt and double bolt under the conditions of a large bolt angle, large normal stress, and a 75° bolt angle, and the shear strength of the double bolt is greater than that of a single bolt.

4. Conclusions

Through the above numerical calculation and analyses, we can arrive at the following conclusions:

- Under the same anchor angle, the shear strength increases with the increase of normal load. The influence of the bolt length on the shear strength of the anchorage joint surface was small, and the shear strength curve was near the horizontal line in the coordinate system with the length of the horizontal axis. However, under the condition of 0.588 MPa of a low normal load, the shear strength curves with 90° and 105° angles fluctuated significantly in the coordinate system with the horizontal axis. When the anchor angle was 150° or 165°, with shear strengths of 2 and 3 cm, respectively, anchor lengths fluctuated under different normal load conditions.
- Under the same bolt length, the shear strength increased with the increase of the normal load. However, in the section with an anchor angle less than 90°, the low peak shear strength occurred at 30°, 45°, and 60° anchor angles when the normal load was 0.588, 1.8 and 1.2 MPa, respectively, excluding a 2 cm anchor length. When the normal load was 1.2, 1.8, and 2.4 MPa, the low peak shear strength appeared at a 60° angle to the bolt, and the shear strength curve was V-shaped.
- Under the same bolt length, when the bolt angle was greater than 90°, and the normal load was 0.588 MPa, the shear strength curve decreased with the increase of the bolt angle, and a low peak wave appeared near the bolt angle of 105°. When the normal load was 0.8, 1.2, 1.8, or 2.4 MPa, the shear strength curve increased with the increase of the anchor angle. The peak value of the normal load was 0.588, 0.8, 1.2, and 1.8 MPa at a low anchor angle of 150°. However, the shear strength curve of the normal load of 2.4 MPa did not indicate such characteristics of change.
- When the normal load was 0.588 MPa, the shear strength curve of each length of the anchor was quite different. Nevertheless, when the anchor angle was less than 90°, the shear strength curve of each length of the anchor initially decreased and then increased with the increase of the anchor angle and a low peak value between 30° and 45°. When the anchor angle was greater than 90°, the shear strength curve of each length of the anchor indicated a downward trend. However, the shear strength curve of different lengths of the anchor between 90° and 120° demonstrated more difference. When the normal load was 2.4 MPa, excluding when the length of the bolt was 2 cm, the shear strength curve of all other lengths was V-shaped, although the shear strength curve was nearly horizontal in the 90°–135° bolt angle range. The shear strength curve of a 2 cm length bolt was different from that of other bolt lengths under a normal load.
- Under the same 4 cm bolt length, the shear strength curve of the single bolt was located in the upper region of the shear strength curve of the double bolt, and only in the partial angle section, the shear strength curve of the double bolt was located in the upper region of the shear strength curve of a single bolt. When the normal load was 1.8 MPa and the anchor angle was 165°, the shear strength of the double anchor was greater than that of the single anchor. When the normal load was 2.4 MPa and the anchor angle was 75°, 150°, or 165°, the shear strength of the double anchor was greater than that of the single anchor.

5. Funding

This work was supported by the Natural Science Foundation of Shandong Province of China (Grant No. ZR2019PEE016), and the National Natural Science Foundation of China (Grant No. 51808327).

6. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Runqiu, Huang. "Some Catastrophic Landslides Since the Twentieth Century in the Southwest of China." Landslides 6, no. 1 (February 24, 2009): 69–81. doi:10.1007/s10346-009-0142-y.

[2] Wu, Xuezhen, Yujing Jiang, and Bo Li. "Influence of Joint Roughness on the Shear Behaviour of Fully Encapsulated Rock Bolt." Rock Mechanics and Rock Engineering 51, no. 3 (December 5, 2017): 953–959. doi:10.1007/s00603-017-1365-1.

[3] Liu, Caihua, and Yuzong Li. "Predicting the Shear Resistance Contribution of Passive Fully Grouted Bolts to Jointed Rock." International Journal of Geomechanics 20, no. 2 (February 2020): 04019174. doi:10.1061/(asce)gm.1943-5622.0001581.

[4] Wu, Xuezhen, Yujing Jiang, Bin Gong, Zhenchang Guan, and Tao Deng. "Shear Performance of Rock Joint Reinforced by Fully Encapsulated Rock Bolt Under Cyclic Loading Condition." Rock Mechanics and Rock Engineering 52, no. 8 (January 2, 2019): 2681–2690. doi:10.1007/s00603-018-1698-4.

[5] Li, Xuwei, Guanyu Yang, Jan Nemcik, Ali Mirzaghorbanali, and Naj Aziz. "Numerical Investigation of the Shear Behaviour of a Cable Bolt in Single Shear Test." Tunnelling and Underground Space Technology 84 (February 2019): 227–236. doi:10.1016/j.tust.2018.11.016.

[6] Chen, Na, Xiaobo Zhang, Qinghui Jiang, Xixia Feng, Wei Wei, and Bing Yi. "Shear Behavior of Rough Rock Joints Reinforced by Bolts." International Journal of Geomechanics 18, no. 1 (January 2018): 04017130. doi:10.1061/(asce)gm.1943-5622.0001048.

[7] Liu Quansheng, Lei Guangfeng, Peng Xingxin, Wei Lai, and Luo Ciyou. "Study on Mechanical Shear Properties of Sandstone, Marble, and Granite after Anchoring." Chinese Journal of Rock Mechanics and Engineering 37, no. 2 (2018): 4007-4015. doi:10.13722/j.cnki.jrme.2017.0646.

[8] Chen, Yulong, Junyang Teng, Rana Ammad Bin Sadiq, and Ke Zhang. "Experimental Study of Bolt-Anchoring Mechanism for Bedded Rock Mass." International Journal of Geomechanics 20, no. 4 (April 2020): 04020019. doi:10.1061/(asce)gm.1943-5622.0001561.

[9] Li, Yuzong, and Caihua Liu. "Experimental Study on the Shear Behavior of Fully Grouted Bolts." Construction and Building Materials 223 (October 2019): 1123–1134. doi:10.1016/j.conbuildmat.2019.06.207.

[10] Yao, Qiangling, Chuanjin Tang, Liu Zhu, Zhenyu Li, Zhijun Niu, and Xuehua Li. "Study on the Weakening Mechanism of Anchorage Interface Under the Action of Water." Engineering Failure Analysis 104 (October 2019): 727–739. doi:10.1016/j.engfailanal.2019.06.066.

[11] Ma, Shuqi, Zhiye Zhao, and Junlong Shang. "An Analytical Model for Shear Behaviour of Bolted Rock Joints." International Journal of Rock Mechanics and Mining Sciences 121 (September 2019): 104019. doi:10.1016/j.ijrmms.2019.04.005.

[12] Wang Bin, Ning Yong, Feng Tao, and Guo Zeyang. "Experimental study on anchoring effect of brittle rock mass influenced by loading rates at low strain rate." Meitan Xuebao/Journal of the China Coal Society 44, no. 9 (September 2019): 2691-2699. doi:10.13225/j.cnki.jccs.2018.1249.

[13] Wu, Xuezhen, Yujing Jiang, Bin Gong, Zhenchang Guan, and Tao Deng. "Shear Performance of Rock Joint Reinforced by Fully Encapsulated Rock Bolt Under Cyclic Loading Condition." Rock Mechanics and Rock Engineering 52, no. 8 (January 2, 2019): 2681–2690. doi:10.1007/s00603-018-1698-4..

[14] Li, Xuwei, Guanyu Yang, Jan Nemcik, Ali Mirzaghorbanali, and Naj Aziz. "Numerical Investigation of the Shear Behaviour of a Cable Bolt in Single Shear Test." Tunnelling and Underground Space Technology 84 (February 2019): 227–236. doi:10.1016/j.tust.2018.11.016.

[15] Lin, Hang, Zheyi Xiong, Taoying Liu, Rihong Cao, and Ping Cao. "Numerical Simulations of the Effect of Bolt Inclination on the Shear Strength of Rock Joints." International Journal of Rock Mechanics and Mining Sciences 66 (February 2014): 49–56. doi:10.1016/j.ijrmms.2013.12.010.

[16] Chen, Yu, and Charlie Chunlin Li. "Performance of Fully Encapsulated Rebar Bolts and D-Bolts Under Combined Pull-and-Shear Loading." Tunnelling and Underground Space Technology 45 (January 2015): 99–106. doi:10.1016/j.tust.2014.09.008.

[17] Li, Yuzong, and Caihua Liu. "Experimental Study on the Shear Behavior of Fully Grouted Bolts." Construction and Building Materials 223 (October 2019): 1123–1134. doi:10.1016/j.conbuildmat.2019.06.207.

[18] Riyad, A.S.M., Md. Rokonuzzaman, and Toshinori Sakai. "Progressive Failure and Scale Effect of Anchor Foundations in Sand." Ocean Engineering 195 (January 2020): 106496. doi:10.1016/j.oceaneng.2019.106496.

[19] Ceroni, Francesca, Hossein Darban, and Raimondo Luciano. "Analysis of Bond Behavior of Injected Anchors in Masonry Elements by Means of Finite Element Modeling." Composite Structures 241 (June 2020): 112099. doi:10.1016/j.compstruct.2020.112099.

[20] Sheng-fang Luo. "Study on Numerical Simulation of Direct Shear Test of Bolted Joints." Master's Thesis, National Taiwan University of Science and Technology (1991).