Resource Operators Conference

Faculty of Engineering and Information Sciences

2024

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INVESTIGATING THE AXIAL AND SHEAR PERFORMANCE OF FIBERGLASS ROCK BOLTS

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Abstract: This paper primarily evaluates the axial and shear performance of fully grouted fibreglass-reinforced polymer (FRP) rock bolting systems. For this purpose, a FRP rock bolt with a diameter of 20 mm was selected for examination. To evaluate the axial performance, several samples with a double-embedment length of 150 mm and an exposed length of 200 mm were cast using an 80 MPa cementitious grout and cured for 28 days. Pull-out tests were then conducted at a controlled rate of 1 mm/min with a 1000 KN MTS apparatus to determine the pull-out performance of the FRP bolts. Furthermore, a comparative analysis involved testing a 20 mm fully grouted steel rock bolt with a 150 mm encapsulation length, was conducted. The results indicated that the axial bearing capacity of the FRP bolts varied between 84 KN and 110 KN, while the steel bar exhibited a capacity of 144.5 KN. The load-displacement curves analysis showed that steel rebar rock bolts absorb more energy during the debonding process compared to the FRP bolts. Along with pull-out tests, the shear behaviour of the FRP bolts was also determined by conducting single and double-shearing tests. With this aim, after casting the concrete blocks in a double-shearing box, three different pretension values were applied to the samples. The results showed that pretension values had a direct impact on the displacement values, while they did not have a direct impact on the peak shear force values. Additionally, the tensile properties of the FRP and the steel bolts showed a different behaviour in the uniaxial tensile test.

BACKGROUND

Supporting and stabilising surface slopes and underground spaces have always been a priority for people's safety and financial losses in mining, civil and geotechnical engineering (Jodeiri Shokri et al., 2023; Nourizadeh et al., 2023). Using tendons such as rock bolts, cable bolts and ground anchors as either primary or secondary support in the rock mass is one of the efficient and highly recommended methods of ground-controlling techniques in such projects (Rastegarmanesh et al., 2022). A rock bolt is commonly used to reinforce the rock mass (Nourizadeh et al., 2021). The traditional rock bolting system typically consists of steel bars to enhance the load-bearing capacity of the excavated rock mass. This rebar is installed in a hole drilled into the rock mass, and then grout is injected as an internal fixture to fill the gap. Although steel bolts have been used extensively as underground support for many years, fibre-reinforced polymer composites (FRP) have been considered in the last three decades to improve some of the weaknesses of steel rock bolts. FRP bolts comprise strands of high-strength fibres such as carbon, glass or polymeric materials covered with high-performance resin as an alternative to the steel rebars. Due to some advantages of FRP rock bolts over steel bolts, the FRP bolts have played a great role in the mining industry in recent years. Steel bolts are vulnerable to corrosion when exposed to chemicals, moisture, or an acidic environment so FRP bolts may result in reducing maintenance or replacement of the bolts. FRP bolts are easily cut without sparks resulting in a mire safe environment specifically in the underground coal mines. Compared to rock bolts, their high tensile strength, easy installation, and cuttability are some of the other advantages of FRP bolts. It should be noted that applying FRP bolts reduces carbon emissions compared to steel reinforcement rebars by about 40% (Sbahieh et al., 2022).

For several decades, mechanical behaviour of rock bolting system, including axial and shearing properties has been studied by applying pull-out tests, single, and double shearing tests in the laboratory or in the situ (Anzapour et al., 2022; Aziz et al., 2016; Aziz et al., 2014; Entezam et al., 2023; Gilbert et al., 2015; Gregor, 2023a, 2023b; He et al., 2021; Jodeiri Shokri et al., 2023; Mirza,

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2016; Mirzaghorbanali, 2019; Motallebiyan et al., 2023; Nourizadeh et al., 2023a; Nourizadeh et al., 2023; Rastegarmanesh et al., 2023). Due to the novelty of the application of fibreglass rock bolts, limited studies have been conducted on their axial load transfer mechanism. Gilbert et al. (2015) studied the strength properties of fibreglass rock bolts (FRP) by conducting a series of comprehensive tensile, single, and double guillotine shear and double shearing tests. For this purpose, they conducted several tests on isotropic and anisotropic rock bolts and found out that the FRPs achieve 85% of the ultimate tensile strength (UTS) of rebar bolts when axially loaded while the FRPs showed the average failure of 25% of the steel rock bolts subjecting shearing loads. Despite their low performance against shear loading, FRP bolts still offer significant advantages over metal ones. After modifying double shearing apparatus, Gregor et al. (2023a) and (2023b) investigated the shear behaviour of fibreglass rock bolting systems for both infilled and clean joints in various pretension loads after determining an appropriate experimental design and modified testing scheme. The results of the double shear tests revealed that increasing in the pretension load causes an increase in the induced confining pressures at the shear interfaces for clean joints. Also, as pretension load in the case of infilled joints increased, the angle experienced at the hinge points also increased incrementally. He et al. (2021) studied the anchorage behaviour of steel and FRP bars in two different host rocks including expansive soil, and soft rock through in-situ tests. They suggested that under the ultimate load, the failure mode of the steel bar is pulling-out failure, while the failure mode of the FRP bar is fracture failure.

Exploring FRP's behaviour under axial and shear loads provides the opportunity to better understand its mechanical characteristics, failure modes and performance under different types and strengths of loading. Therefore, this research will focus on comparing the axial and shear performance of FRP which has achieved as the results of a series of comprehensive pull-out and shear tests.

MATERIALS AND METHODS

Material properties

To investigate the axial and shear behaviour of fully grouted FRP rock bolts, several samples were prepared utilising FRP rock bolts and subjected to pull-out test, single shear test and double shear test. For comparison with conventional steel rock bolts, additional samples were prepared using steel bolts, which underwent pull-out testing as well. The specifications of the FRP and steel bolts are provided in **Table 1**. The mechanical properties of the grout used for encapsulation of the bolts are shown in **Table 2**.

Table 1: The FRP bolts mechanical and geometrical specification used in this study

Bolt Type	Tensile Strength (kN)	Nominal Bolt Diameter (mm)	Nominal Cross Section Area of Bolt (mm^2)	Major Bar Dimension (mm)
FRP	200	20	310	25
Steel	220	22	370	24

Table 2: Mechanical properties of grout

E (GPa)	UCS (MPa)	γ
21.1	**96**	**0.24**

The tensile tests also were conducted to determine the tensile properties of the steel and the FRP bolts. The stress-strain curves exhibited distinct characteristics across two different types of rock bolts, as depicted in **Figure 1**. Notably, for FG bolts, the initial stress-strain relationship closely resembled a linear trend, followed by a gradual decrease in stiffness as elongation increased until final failure. Throughout this process, the tensile modulus was constant until failure occurred. Conversely, steel rock bolts showcased two distinct stages during tensioning: an initial elastic stage succeeded by a subsequent plastic stage. Typically, the failure strain of the FRP bolt fell within the range of 4-6%, while for the steel bolt it was recorded in the range of 17-19%.

Single shear test was done to determine the ultimate shear strength of the FRP rock bolts. For this purpose, two FRP bolt with the length of 150 mm with partial threads were tested using a Guillotine Box (**Figure 2**). The single shear average peak load was recorded 43 kN.

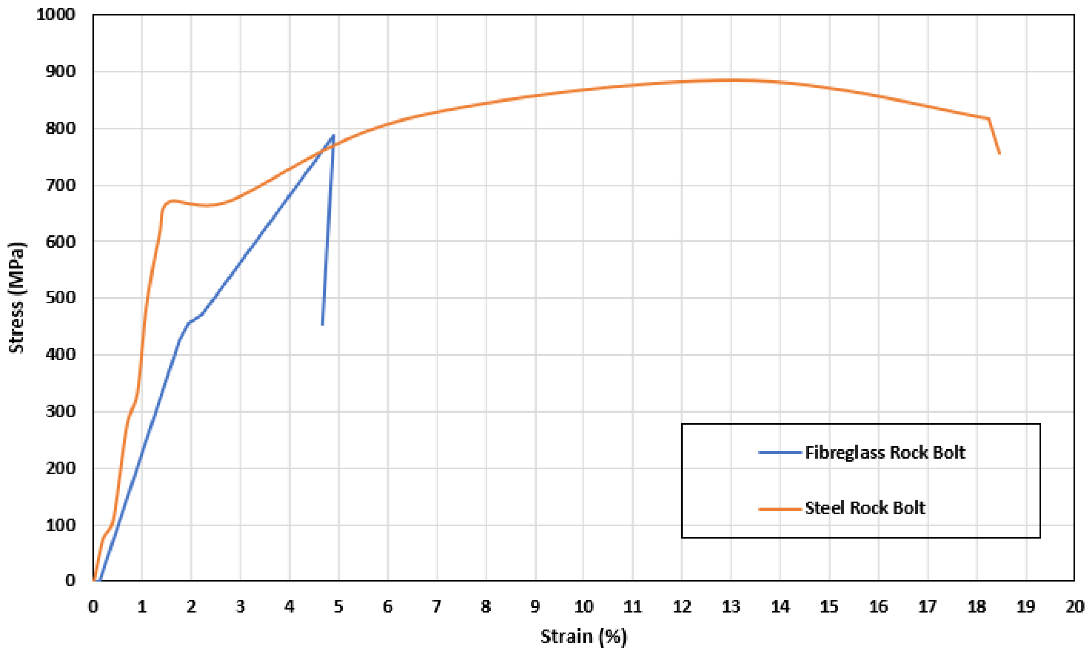


Figure 1: Stress-strain curves of steel and fibreglass rock bolts

Figure 2: Single shear fibreglass samples

Preparation of pull-out test samples

The FRP samples were designed with a double-sided embedment, each side having a length of 150 mm, and an exposed bolt area of 200 mm (**Figure 2**). As depicted in **Figure 2**, the FRP bolts were anchored on each end using threaded steel sleeves with a diameter of 45 mm and a thickness of 5 mm. To optimise the grouting process, a slight rotation was applied during insertion, and plastic wedges were then used to ensure that the FRP bolts were cantered and levelled. All confinements were rifled internally at a specific angle of 5 degrees to mimic in-situ conditions and provide sufficient interlocking bond between the grout and the confinement. To achieve the appropriate strength of grout, the samples were placed in the curing room and cured for 28 days. A similar procedure was followed to prepare the steel rock bolt samples, as shown in **Figure 3**. However, it should be noted that the steel bolt samples had a one-sided embedment.

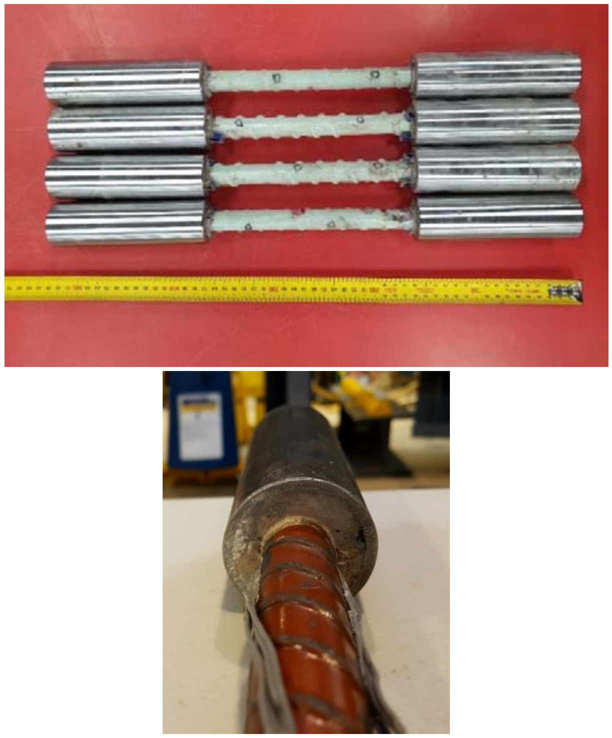
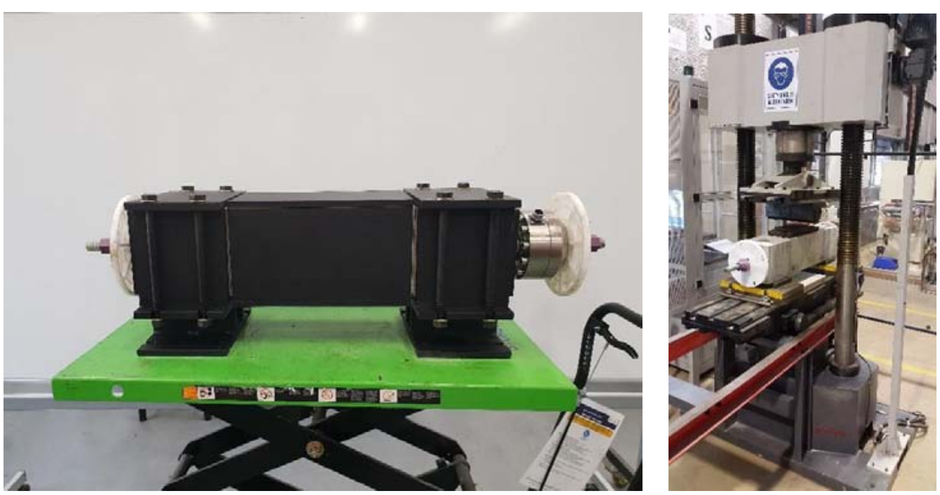


Figure 3: Pull-out samples; FRP bolt samples (left) and steel bolt samples (right)

Preparation of double shearing test samples

The Double Shearing Test involved embedding FRP bolts in concrete blocks. For this purpose, concrete blocks with an overall length of 800 mm were cast using rectangular moulds. To facilitate the shear test, a 10 mm clearance was created on both sides of the shearing box as the shearing planes. The concrete blocks, with a UCS of 40 MPa, were prepared based on the study conducted by Gilbert et al. (2015). After casting the required samples, they were placed in the curing room for 28 days. Following the curing period, the FRP bolt was positioned in its pre-designed place. Subsequently, an axial load cell and washer plates were assembled for the samples (**Figure 4a**). Three designated pretension values, namely 10 kN, 15 kN, and 20 kN, were applied to the samples. In the final stage of sample preparation, the reinforced concrete blocks were grouted through the pre-designated holes on top of the sample. Once the samples were prepared, they were positioned in the compression-testing machine, and shear loads were applied to the centre of the samples with a shearing rate of 1 mm/min. A view of the double shearing test is shown in **Figure 4b**.

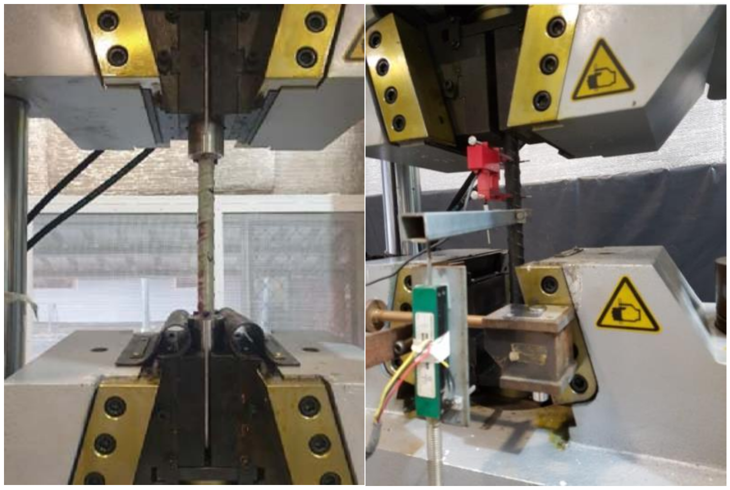


(a) (b)

Figure 4: (a) Double shearing box (b) A view of the double shearing

RESULTS AND DISCUSSION

After preparing the required samples, the pull-out tests were conducted using a Universal Testing Machine (UTM) with a load capacity of 1000 KN at the structural laboratory at the University of Southern Queensland (UniSQ). The samples were pulled out at the rate of 1 (mm/min). **Figure 5** shows the fully grouted FRP bolts and the steel rebar sample in the UTM.



(a) (b)

Figure 5: View of (a)the FRP bolt and (b) steel rebar in the UTM apparatus

The load-displacement curves obtained from the pull-out tests of the fully FRP bolts are shown in **Figure 6**. The ultimate axial bearing capacity of the four samples were found to be 84.2 KN, 84.1 KN, 94 KN, and 110 KN as shown in **Figure 7**. Investigating the samples after pull-out testing revealed that that the failure of FRP samples mainly occurs at the bolt surface which was due to shearing off the bolt surface ribs as shown in **Figure 8**.

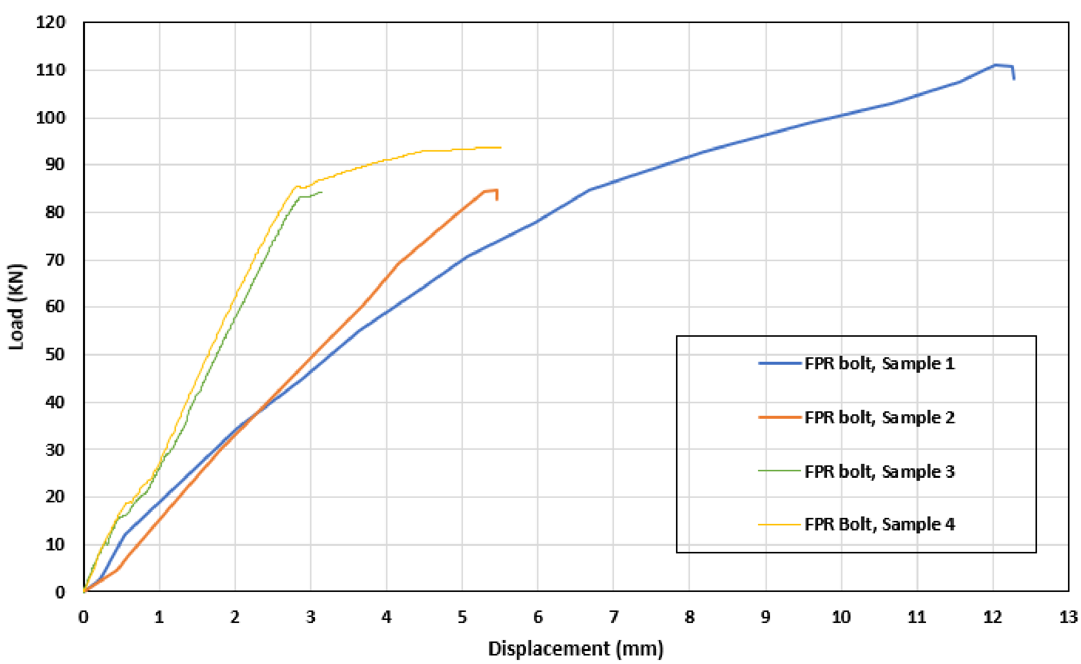


Figure 6: Load-displacement curves of pull-out tests conducted on the fully grouted FRP bolts

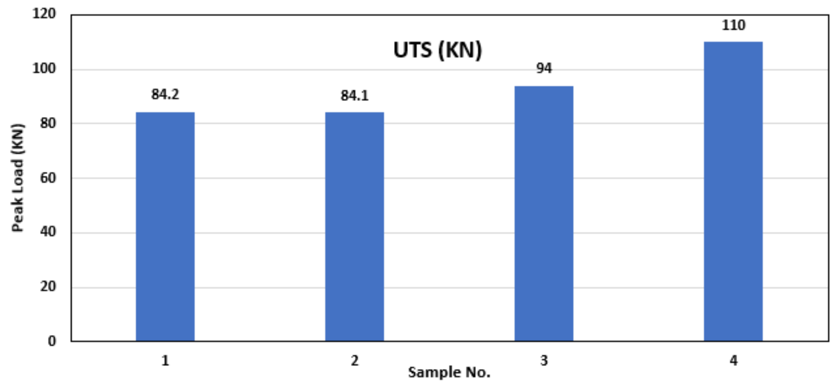


Figure 7: Ultimate bearing capacity of the FRP bolts

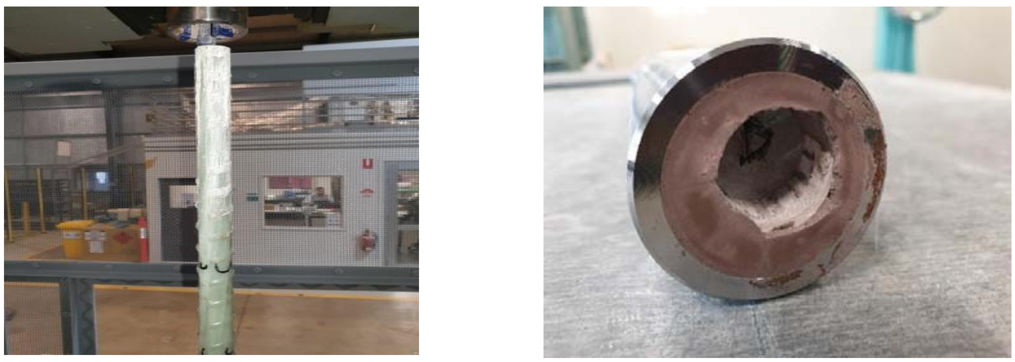


Figure 8: Failure mode of the FRP samples

The load-displacement curve obtained from the pull-out test of the specimen encapsulated using a steel bar is presented in **Figure 9**. It reveals a peak load of 144.5 kN. Examination of the specimens post-tests indicated that system debonding occurred at the rebar/grout interface at the measured peak load. This failure primarily resulted in shearing of the grout, accompanied by the formation of radial cracks in the grout, as illustrated in **Figure 10(a)**. In contrast, failure at the FRP bolts was due to sheared-off bolt ribs and minimal damage to the grout. **Figure 10(b)** shows that in the steel bolt samples, the grout suffered substantial damage. Analysing the load-displacement curve depicted in **Figure 9**, the bolt undergoes three stages: elastic deformation, plastic deformation leading to bolt failure, and finally, the post-failure stage where frictional resistance between the grout and bolt generates some resistant forces.

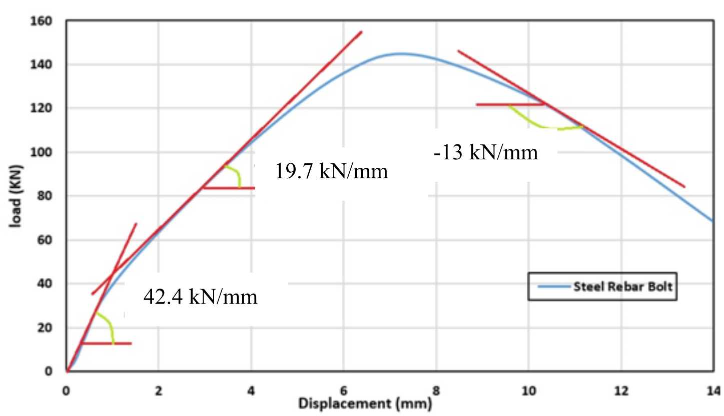
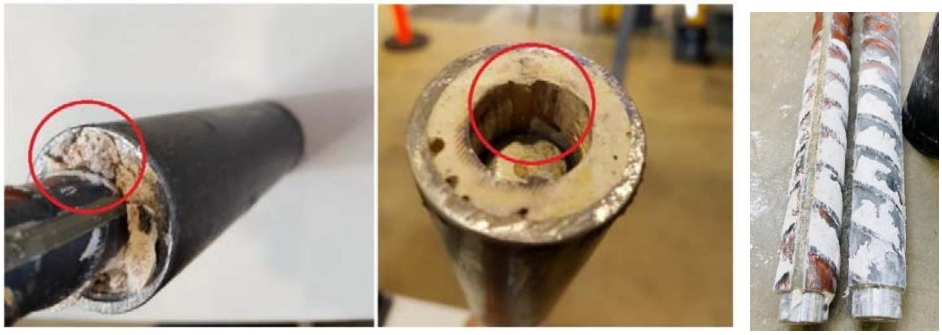


Figure 9: Load displacement curve for the pull-out test of the fully grouted steel bolt



(a) (b) (c)

Figure 10: (a) Radial cracking in the grout medium (b) and (c) sheared off the grout

The comparison of results from steel and FRP pull-out tests indicates that the FRP bolts reached 58% to 75% of the maximum capacity of the steel bolts. Additionally, examining the curves shown in **Figures 5** and **8** leads to the conclusion that FRP bolts could absorb more energy than their steel counterparts. Furthermore, the analysis of the results reveals that the stiffness of the FRP specimens ranged from 13 to 31 kN/mm. In contrast, the steel rock bolts exhibited a stiffness of 42 kN/mm during the elastic stage.

The Results of double-shearing tests of the FRP bolt

The samples under double shear testing showed the same shearing load profiles, including three stages of elastic, strain-softening and failure regions. The results of the double shearing test by applying a pretension value of 15 kN is given in **Figure 11**. As seen after reaching the elastic yield, a plastic deformation occurred. The gradient angle of the strain-softening region, 84.8° was lower than the angle of the elastic zone, 87.7°. The test continued until the failure of the sample with the ultimate peak shear of 136.3 kN.

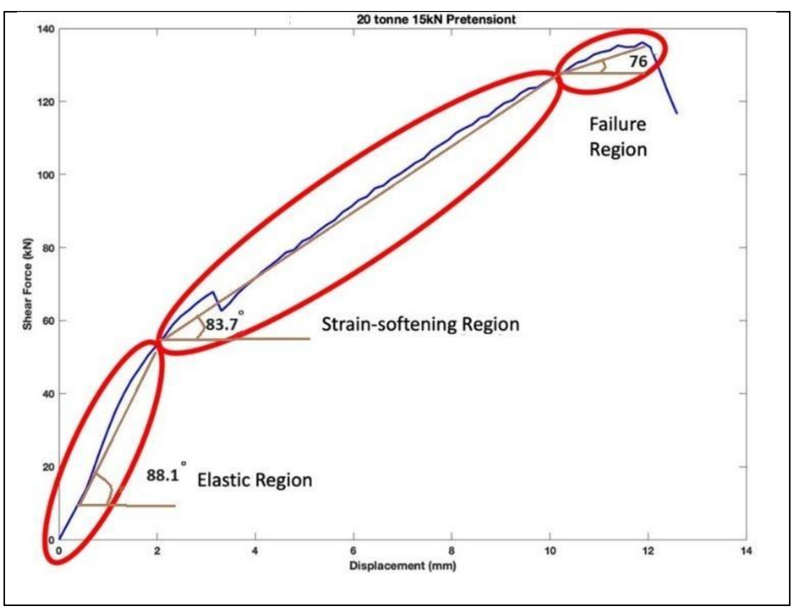


Figure 11: The result of the double shearing test by applying a pretension value of 15 kN

The gradient angle of the failure zone was 76.0°. The results of the double shearing test are given in **Table 3**. Comparing the results from the 10kN and 20kN pretension samples, it is obvious that the increase in pretension values had a direct impact on the failure displacement, resulting in up to a 4mm decrease in its failure displacement. However, it seems that the pretention valued did not have an impact on the peak shear force.

Table 3: The results of the double shearing test by applying different pretension values

Pretension Value	Peak Shear Force (kN)	Displacement at Peak Shear (mm)	Peak Shear Stress (GPa)	Elastic Gradient (°)	Strain-Softening Gradient (°)	Failure Gradient (°)
10kN	133.3	12.1	0.42	87.7	84.8	78.7
15kN	136.3	11.9	0.43	88.1	83.7	76.0
20kN	133.4	8.4	0.42	88.1	85.9	76.0

CONCLUSIONS

This paper compared the pull-out capacity of the fully grouted FRP bolt and the steel rebar bolt. For this purpose, five fully grouted specimens were cast using FRP and steel bolts and Stratabinder-HS grout produced by Minova grout with a UCS of 80 MPa. After a proper curing process, pull-out tests were carried out to determine the axial bearing capacity. The results revealed that the FRP bolts provide 58% to 75 % of the peak load value of the that of steel rebar bolt. Along with the pull-out tests, single and double shearing tests were done to determine the shear behaviour of the FRP bolt. The double shear samples were pretensioned in three different values including 10 kN, 15 kN and 20 kN. The results showed that the pretension did not have direct impact on the peak shear force, but sheared displacement values were decreased by increasing the pretension values.

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