FAILURE CHARACTERIZATION OF ROCK ANCHOR BOLTS BY THERMAL CHANGE DETECTION UNDER TENSILE STRENGTH TESTING

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Abstract: *Rock bolts are widely used in tunnels, underground openings, and also rock slopes to provide support and attach blocks to the rock mass in various engineering fields. They have a significant role for the stability of underground structures and natural rock slopes both in the mining and civil engineering industry. The understanding of the rock bolt behavior under stress conditions plays a key role in the long term stability and sustainability of rock slopes, nearby structures, and underground openings. The detection of the failure type and the investigation of failure behavior can be supported by thermal imaging of certain regions on the anchor bolt during tensile testing. In this context, anchor bolt behavior under tensile testing with a force controlled testing environment was analyzed with a LWIR (Longwave Infrared) thermal camera. The heat dissipation during experiments was recorded by a thermal camera together with the force reading from the hydraulic press data logger. As a result of the experiments, it was seen that there is a relation between the temperature change and bolt failure behavior. Therefore, it is expected that this study will provide an opportunity to detect the failure characteristics of the anchor bolts under tensile strength test by the help of infrared thermal camera.*

Keywords: ROCK BOLT, ANCHOR BOLT, TENSILE STRENGTH TEST, PULL-OUT TEST, INFRARED THERMAL CAMERA, FAILURE CHARACTERISTICS OF BOLT

1. Introduction

The main purpose of mining activities is extracting the resources for energy generation and raw material requirement. Because of the decreasing availability of the shallow resources, importance of operating underground operations has increased and will become more crucial in the near future. For this reason, new resources are explored consistently. The exploration of new resources aims underground mining operations that could be operated safely and more efficiently. Rock mechanics is a field of research that focuses on the analysis of rock behavior under stress and tension conditions. It has a crucial role for underground activities. Therefore, integrating new technologies such as thermal cameras, acoustic emissions, high speed cameras, etc. to mining industry, especially rock mechanics, plays a key role for safer and more efficient mining.

Rock bolts are defined as long anchor bolts and are used for stabilizing rock excavations for engineering purposes. The main aim of using of rock bolts is to transfer the load from the unstable object to a stable object. The correct design of the rock bolts is very substantial for safety and sustainability of mining operations (Hoek, Kaiser & Bawden, 2000; Peng & Tang, 1984). To ensure the continuity, capacity of bolts, and possible failure types should be known properly (Ballarini, Shah & Keer, 1986). This knowledge can be achieved by performing experiments in laboratory environment and on field.

To determine the strength of the rock bolts, some experiments can be carried out. In laboratory testing, tensile strength tests can be performed to determine the yielding force and the maximum tensile force that the material can withstand. As a result of such experiments, the structures can be designed in the light of information regarding the strength of the required support. On site, pull-out tests are carried out to determine the maximum tensile force to pull the bolt from the rock surface regarding the testing equipment used. This study involves the tensile testing and pull-out tests of rock bolts for a specific site. As a result of the experiments, the capacities of bolts and failure types were compared.

Laboratory tests were monitored by a longwave infrared thermal camera to detect the failure region of the bolts during loading stages. The reason of utilizing the thermal camera instead of a video camera is to track the change in the temperature along the failure region of bolt and try to related it with the failure region.

Researchers in this field commonly worked on finding out the failure modes of rock bolts by experimental testing. These failure types are investigated for bolts under tensile loading, bolt- grout interface failures where the bolts are pulled out of grout, slipping of the bolt with grout from the rock, and failure of the rock (Brown,2015; Yang, Thota & Zhao, 2015). There are suggested design methods for each type of these failure modes. To prevent the failure, possible failure region of the bolt should also be well defined. By considering the failure region, more reliable and critical bolt selection and design can be performed. Figure 1 shows the failure modes of rock bolts.

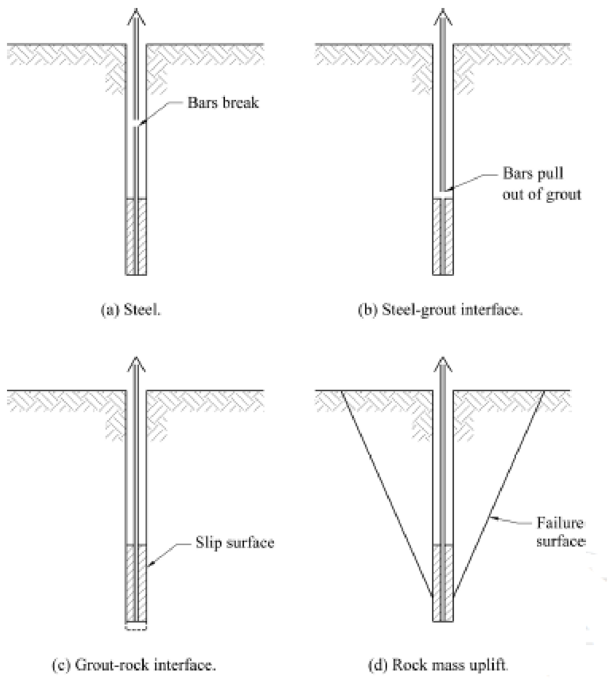

Figure 1: *Failure modes of rock bolts under tension (Pease & Kulhawy, 1984)*

Based on these reasons, this article aims to provide an application of thermal imaging to detect failure type and failure behavior of rock bolts under tension. The results are based on laboratory testing and also pull-out tests conducted on site. This provided an insight to the field conditions of the rock mass that is planned to be supported by rock bolts. The isolated environment of the rock mechanics laboratory might cause deficiencies in representing the surface conditions of the rock mass and also the impact of weathering and other environmental conditions.

2. Objectives and Methodology

The samples used in the experiments were steel rods of two different types, which are non-ribbed and ribbed type. Non-ribbed steels have rather a flat surface whereas rods with protruding surface are named as ribbed steel. Ribbed steels have greater tensile strength compared to non-ribbed steels. They provide better interlocking properties when used together with rock minerals. By these ribs, the displacement of the steel material within the rock mass becomes more difficult. Ribbed steel types of rods were used for the experiments within the scope of this study. According to the technical specifications about the steel, their minimum yielding strength is 420 MPa and the minimum tensile strength is about 500 MPa with a minimum final elongation is 10%. These values were compared with the experimental results.

The reason of using thermal imaging technology in rock mechanics experiments is that an essential engineering field should always be improved by integrating new technologies to achieve more reliable data at critical time intervals. The current devices used for rock mechanics testing can be misleading because of the weak remote sensing capability of the equipment. Hence, some inferences must be made for interpreting the results of experiments. By integrating new technologies to this research field, these inferences can be minimized to a certain extent and can be based on more information.

The objectives of this study can be summarized as to achieve more detailed and visual data about the failure moment of rock bolts and to compare field and laboratory test results. It was planned to investigate the concept whether stress concentration points are related with temperature increase on the tested sample or not. Regarding this problem, some laboratory experiments on the bolt samples were performed at the rock mechanics laboratory with a load controlled equipment. One of the tests was monitored by a longwave infrared thermal camera to collect thermo-images. The load controlled testing machine was used for tensile stress determination. In addition, some field experiments were performed to compare the laboratory and field test results. Figure 2 and Figure 3 represent the experimental setup and the infrared thermal camera that was used, respectively.

Figure 2: *Experimental Setup, Force controlled test machine*

Figure 3: *Uncooled longwave infrared thermal camera*

Methodology of this study covers the field tests and laboratory tests of rock bolts. On site, ten pull out tests were conducted and the results were recorded. Different types of grout and epoxy were used to test the adherence of the contact surface between the rock mass and the rock bolt. In laboratory testing, tensile strength tests of rock bolts were performed. One of the tests was monitored by an infrared thermal camera. The infrared thermal camera was placed in front of the sample at about 1 meter distance for safety precautions. The temperature changes recorded on the rock bolt could be followed by the software of the thermal camera. In this software, an average temperature curve on selected lines and a histogram plot can be visualized in real-time and also as a recording. The maximum and minimum temperature values on selected lines can also be recorded as separate profiles. These values were monitored during the laboratory experiments. As a result of this thermal camera recording, the difference between the maximum and the minimum temperature provided the temperature increase on certain regions of the sample. Hence, certain relations could be examined between stress concentration points and temperature increase. The graphical user interface of the infrared thermal camera software can be seen in Figure 4.

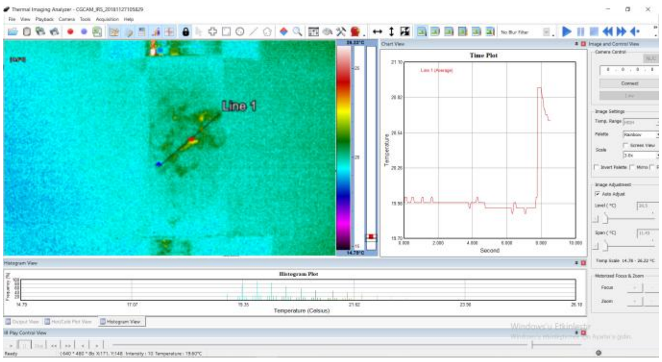

Figure 4: *Interface of the infrared thermal camera software*

There are research questions related to the utilization of thermal cameras, such as the aim of using this equipment or the available technology. According to Fematek (2018), the reason of utilizing this equipment is that thermal energy is observed at the range of infrared, which cannot be seen with naked eye by human beings. Thermal cameras convert the readings about heat to images and figures that can be interpreted easily. The long wavelength infrared thermal cameras work in 8-14 micron band, mid wavelength infrared thermal cameras work in 3-5 micron band, and short wavelength infrared thermal cameras work efficiently in ranges up to 1.5 micron. At room temperature, the wavelength emitted from an object is at most about 10 microns. At 300º C temperature, the wavelength emitted by an object is approximately 5 microns. The sun wavelength emits around 0.5 microns. Therefore, the most ideal thermal camera setup for laboratory testing of samples is commonly suggested as a long wavelength infrared thermal camera as it was chosen for this study. The reason of utilizing an uncooled thermal camera system is that the cooled systems are much more expensive and require maintenance frequently because of the separate cooling apparatus. Cooled systems are preferred mostly for long distances whereas uncooled systems do not operate together with cooling systems of the detectors. These detectors are named as micro bolometers and the temperature change in the object is converted to electrical signals. Uncooled systems have to work with longwave infrared thermal cameras whereas cooled systems can be operated with middle wave and longwave infrared thermal cameras. Resolution of the thermal camera used in this study is 640 x 480 pixels which provides a comparably better detail in images than cameras with 160 x 120 and 320 x 240 resolution. The first stage of the determination of tensile strength of rock bolts was based on the pull out tests on site.

3. Experimental Results

The experimental studies were divided into two stages, pull-out tests and laboratory tests of the rock bolts.

- ***Pull-out tests***

Pull out tests were performed on site. Five samples with 90 cm length and five samples with 120 cm length were tested by using different chemicals as bonding material between the inner surface of the drilled hole in the rock mass and the rock bolt. The results are summarized in Table 1.

Table 1*: Pull-Out Test Results*

Sample Nr.	*Anchor Length (cm)*	*Chemical*	*Test Result (kN)*
K1	90	Epoxy	285.09
K2	90	Grout	380.12
K3	90	Epoxy	380.12
K4	90	Epoxy	380.12
K5	90	Grout	380.12
U1	120	Grout	380.12
U2	120	Epoxy	142.55
U3	120	Epoxy	380.12
U4	120	Grout	380.12
U5	120	Epoxy	380.12

The results in Table 1 show that the maximum force that can be withstand by the rock bolt was approximately 380 kN. However, this should not be misinterpreted as the samples did not fail at this load. The samples can withstand more, but due to safety precautions of the testing team on site and the capacity of the testing equipment the experiments were finalized before the material yielded completely. By considering the technical considerations of the project where the bolts were planned to be used, 250 kN was determined as a minimum threshold value defined for bolt capacity. Hence, only 1 sample result did not satisfy the required capacity stated in the technical specifications. When the different chemical types were analyzed, it was seen that bolts used together with grout achieved a stronger adhesion than samples which were used together with epoxy. Although the pull-test results were successful in representing the site conditions in a more realistic manner, the technical capacity of the testing equipment limited the tests. Therefore, a set of experiments were also performed in the rock mechanics laboratory.

- ***Tensile Strength tests***

Tensile strength tests were performed at the rock mechanics laboratory where four samples with dimensions as seen in Figure 5 were tested.

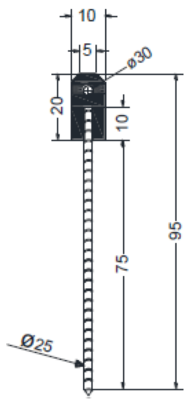

Figure 5: *Dimensions of the anchor bolt*

The samples were attached to the testing machine which has 500 kN capacity. The test results can be seen in Table 2.

Table 2: *Tensile Strength Test Results*

Sample Nr.	*Anchor Length (cm)*	*Yielding Force (kN)*	*Max. Tensile Force (kN)*
S1	95	248.40	308.19
S2	95	226.75	295.30
S3	95	234.47	293.60
S4	95	226.80	291.60

When the test results are evaluated, all samples have more bearing capacity than the required technical specifications. Although they have enough capacity, test results do not give exact information about failure type and failure region. At this point, requirement of new technologies arises. In this context, one of the experiments was monitored by an infrared thermal camera. By recording this test, possible failure regions and failure type of the rock bolt were investigated.

4. Thermal Response

When the test result was monitored by the thermal camera, it was seen that temperature increase on the failure region is related with failure type and failure region of the sample. Figure 6 shows the relation between the temperature increase at certain regions and the force that is applied on the bolt.

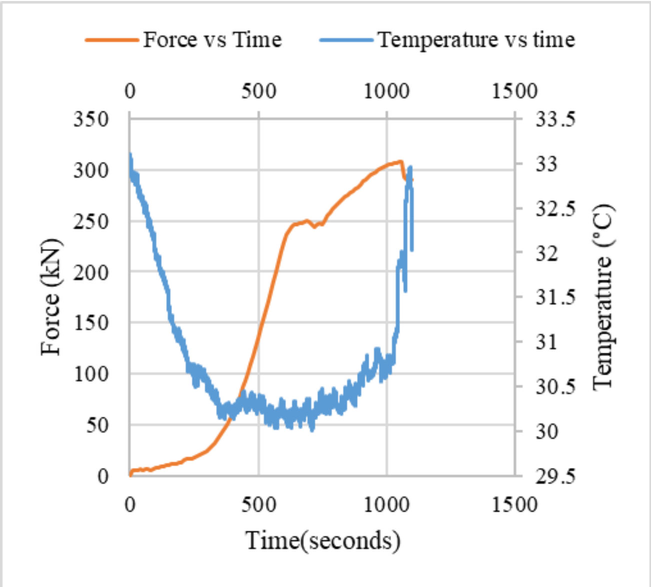

Figure 6: *Relation between force and temperature increase on the failure region*

It can be seen that the temperature decreased to 30.5ºC until yielding point. After that, it remained constant at approximately 30.5ºC. When the force started to increase again until failure, where the maximum tensile force was recorded, the temperature started to increase again within this region. Finally, temperature achieved the peak value which was recorded as 33ºC.

As a result of the laboratory experiments, it can be said that the temperature increase in certain regions of the rock bolt is directly related with the possible failure region. Thermal images also give a clue about the failure type. Figure 7 and Figure 8 show the thermal image of the bolt at yielding point and failure point, respectively. The temperature range is represented by a color range defined in the thermal camera software.

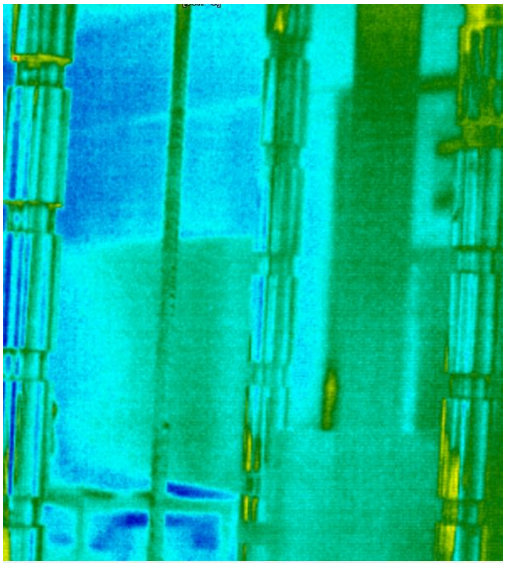

Figure 7: *Thermal image of the anchor at yielding point*

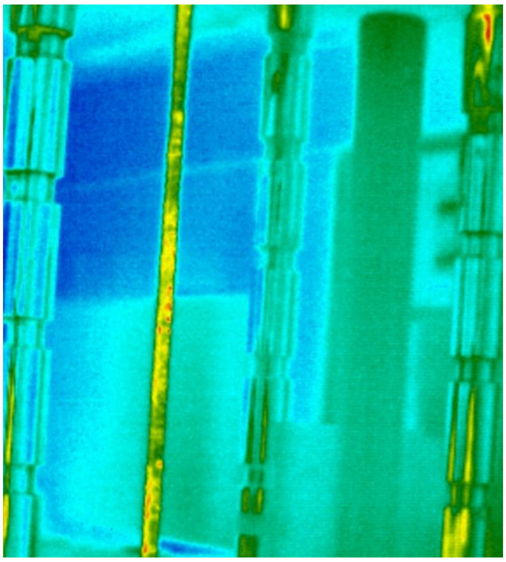

Figure 8: Thermal image of the anchor at failure point

As it can be seen, the thermal response of the rock bolt is directly related with failure region of the sample. Regions that are highlighted by the green color turn to yellow and red color at yielding period. The red color represents the maximum temperature reading in the thermal image whereas the lowest temperature can be seen in blue color. In addition to the failure region, failure type can also be estimated from the views. For example, possible failure type for this sample was estimated to be the breaking of the anchor from the middle since temperature increase was observed in the middle. This shows also stress concentration points on the sample.

5. Results and Discussion

Ten anchor bolts were tested on site by pull-out tests with different chemical types. The results showed that bolts have enough capacity by considering the technical specifications and the capacity also depends on the used chemical. Rock bolts with grout could withstand more force than bolts applied with epoxy. Therefore, selection of the chemical is a very important criterion for field tests. Since the bolt is placed inside the rock mass by means of a drilled hole, the pull-out tests could not be monitored by a thermal camera.

Four anchor bolts were tested at the rock mechanics laboratory by tensile strength tests. As a result of the experiments, all bolts have enough capacity by considering technical specification. As for the thermal behavior, there is an expected increase of temperature at the failure region of the sample. Tests recorded with the thermal camera showed that there is 2.5ºC temperature increase at failure region.

Hence, there is a relation between the failure characterization and temperature response, the integration of new technologies will provide more information about failure behavior of the samples in the near future.

6. Conclusion

Rock mechanics plays a significant role for the stabilization of structures and is therefore essential for mining and civil engineering industry. The detection of the possible failures of engineering material must be performed in detail. In this context, new technologies such thermal cameras, high-speed cameras, acoustic emission systems can be integrated to field. This will help to detection of the failure behavior of samples easily. These devices provide more reliable and detailed data about failure behavior of the samples. This study provided a preliminary implementation of a thermal camera setup for tensile strength testing in the laboratory where a temperature increase of 2.5ºC was recorded at the failure moment. Although the capacity of the load controlled testing equipment was also not sufficient, similar to the pull-out test equipment, it was possible to record the thermal behavior during testing.

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