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Assessing the tensile strength of rocks and geological discontinuities via pull-off tests

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1. Introduction

The pull-off test (POT) is a practical method for testing material strength; it is widely used for in situ tests of concrete and bound interfaces between different materials, but not in rock. For these purposes, the POT is classified as a partially destructive technique that is used to assess the surface zone strength of structures.[1] The test consists of pulling off a metal disc attached directly to the surface of a partially drilled core (Fig. 1a). Epoxy resins are used to attach the metal disc to the surface to ensure that the material fails. Although the POT is an established method for the in situ testing of concrete materials, there are no scientific reports discussing its particularities and practical advantages for rock engineering. This technical note presents the equipment, methodology, results and correlations to determine the in situ tensile strength of rocks and geological discontinuities using the POT.

The POT is closely related to the direct tension test (DTT) once the partial core in Fig. 1a is submitted to only a vertical tension force until failure. However, the boundary conditions create heterogeneous stress distributions along the partial core. Bungey and Madandoust[1] and Austin et al.[2] used finite element analyses to evaluate the stress distribution in POTs, considering the concrete as a linear elastic, homogeneous and isotropic material. From these analyses, the following conclusions are highlighted:

1. The maximum tensile stresses are concentrated at the base peripheries of the partial core due to the test boundaries.
2. The disc material (aluminium or steel) does not affect the maximum tensile stress (at the core base periphery) for discs having a thickness of 20 mm (or higher) and a diameter of 50 mm.
3. The maximum tensile stress at the core base peripheries decreases with the core depth but remains constant for core depths higher than 1.5–2.0 cm.
4. At about 10–15 mm above the core base, the stress concentration at the partial core peripheries is significantly reduced, indicating more homogeneous stress distributions from the centre line to the peripheries of the partial core.

Considering that the POT is applied orthogonally to the concrete structure surfaces, it becomes attractive for assessing the bond strength of interfaces between overlapping materials, such as concrete repairs, porcelain tiles, and mortar layers. Austin et al.[2] evaluated the POT for the bound strength assessment of overlay interfaces considering different geometries (interface depth), material mismatching, and surface conditions. This subject has garnered the interest of many concrete and building material researchers.[3–5] As described by ASTM,[6] the POT (applied to concrete with repairs) can provide three valid failure modes: substrate material failure, bond failure (concrete/overlay interface) and overlay material failure. Bond failure at the epoxy and overlay interface is not suitable for characterizing the material strength.

Similar failure modes are expected in other materials, such as rocks; thus, the POT can be useful for assessing the tensile strength. However, to our knowledge, no previous studies have used the POT for rocks or compared it with other tensile strength testing methods often used in rock mechanics. Similar to concrete, the failure of homogeneous and isotropic rocks is likely to occur at the base of the core (mode 1L in Fig. 1b) due to the stress concentrations associated with the test boundary. Failure can also occur along the core, although this situation is less likely (mode 1U in Fig. 1a). In heterogeneous and anisotropic

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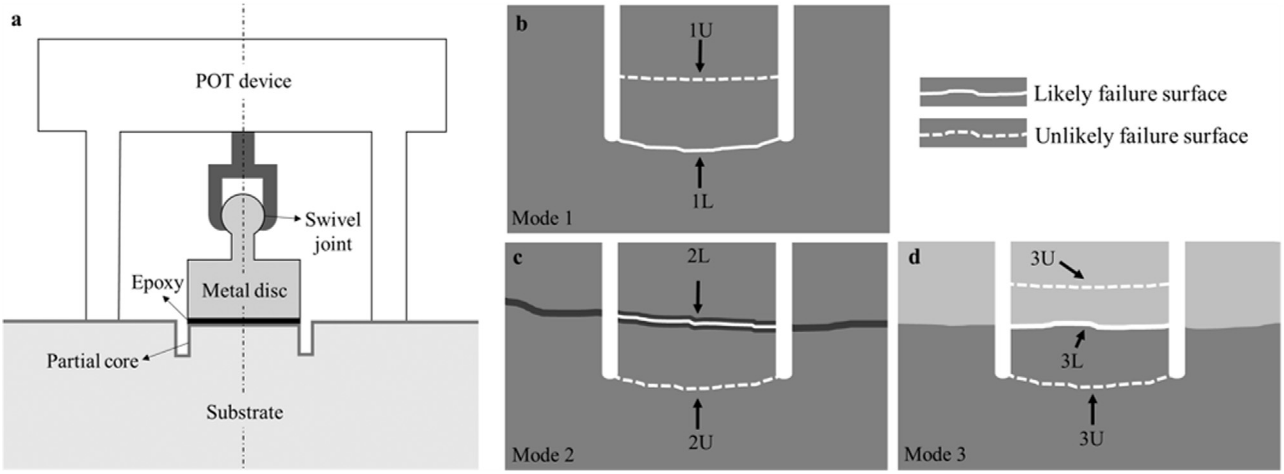

Fig. 1. Idealized POT failure modes in rocks and geological discontinuities indicating the likely (L) and unlikely (U) failure surfaces: a. Pull-off test setup; b. Mode 1; c. Mode 2; d. Mode 3.

rocks, failure is likely to occur through the weaker region or geological discontinuity along the core (2L in Fig. 1c). In the case of a rock core crossing two or more overlayered rock types (or petrological unities), such as in heterogeneous gneiss with mafic and felsic banding, failure mode 3L (Fig. 1d) is likely to occur through contact. Other failure modes are less likely (dashed white lines in Fig. 1b, c and d) but not impossible; for example, such modes may occur in the case of cores crossing high-tensile-strength geological discontinuities[7] or cores with micro-fissures along the intact rock materials.

At present, the tests most frequently used to assess the tensile strength of rocks are the indirect Brazilian disc test (BDT) and the DTT. Perras and Diederichs[8] reviewed important aspects of these tests and presented correlations between them using a wide literature database. The correlations indicated that the tensile strength obtained by the BDT (σ_{BDT}) was approximately 5–30% higher than the tensile strength obtained by the DTT (σ_{DTT}) depending on the rock type and specimen geometry. Aside from this difference, the BDT is generally preferable for laboratory investigations because the test procedure and specimen preparation are simpler, faster and less susceptible to bias. For these reasons, the BDT has been used in many rock mechanics studies, resulting in extensive literature on experimental data, numerical modelling and analytical solutions.[9]

Considering the practical advantages of the POT for concrete materials and interface tensile strength assessment, this technical note introduces this method for rock engineering applications, particularly in situ. A laboratory campaign was conducted to show the use of the POT to be a practical alternative for tensile strength assessment of rocks and geological discontinuities. Four visually homogeneous and isotropic rock types were tested by the POT, BDT, and DTT for comparison and test validation and used to evaluate the influence of the core depth on the POT tensile strength (σ_{POT}). Moreover, POTs were performed on anisotropic and heterogeneous gneiss to evaluate the σ_{POT} of geological discontinuities and characterize the different failure modes associated with the rock fabric. The practical advantages of the POT over other standard tensile strength tests for rock materials are discussed, and recommendations are given for the application of the POT in the laboratory and in situ (with a practical example) using rock blocks or outcrops.

2. Materials and methods

Six rock types were used in this work: marble (basic mineralogical composition: calcite and dolomite); red granite (basic mineralogical composition: feldspar, quartz, and biotite); white granite (basic mineralogical composition: feldspar, quartz, garnet, and biotite); andesite (basic mineralogical composition: plagioclase, pyroxene, chlorite and quartz) and para-gneiss (basic mineralogical composition: quartz, feldspar, biotite and cordierite). The marble, granites, and andesite are visually homogeneous with expected isotropic behaviour; thus, they were used to compare the POT, BDT, and DTT and evaluate the variation in σ_{POT} with the partial core depth. All specimens used in each test (POT, BDT and, DTT) were removed from the same rock block to avoid major differences between specimen groups. The gneiss was used to assess the tensile strength of geological discontinuities and lithological unity (mafic and felsic banding) contacts. Additionally, a biotite ortho-gneiss (basic mineralogical composition: quartz, feldspars, and biotite) block was used to exemplify the POT applied in situ.

2.1. Pull-off test

The POT was performed with an automated pull-off tester (Fig. 2a) commercially known as DY-216™, manufactured by Proceq SA (Schwerzenbach, Zürich Switzerland). The DY-216™ is a portable, lightweight and practical operation instrument, with a tensile load ranging from 1.6 to 16 kN (0.81–8.1 MPa for 50 mm-diameter cores). The main advantage of this equipment is the built-in feedback controlled motor, which provides a fully automated test with a constant load rate, avoiding the operator influence of manual devices. The load range of the DY-216™ was not suitable for the andesite because of the high tensile strength of this rock type ($>$ 10 MPa). In this case, a metal bar was adapted to a DL-10000™ universal machine (maximum load of 100 kN), manufactured by Emic SA (São José dos Pinhais, Paraná Brazil), to hold the specimen during the test (Fig. 2b). Torsion and bending effects were minimized on the POT using swivel joints connecting the load equipment to the metal discs (Fig. 2a and b).

For POT, the rock blocks were drilled using the DD-160 drilling machine manufactured by Hilti SA (Schaan, Liechtenstein), with a 50 mm-diameter (internal) diamond core bit, resulting in 49.4–49.6 mm core diameters. The rock block surfaces were kept horizontal and perpendicular to the drilling machine to avoid inclined cores. Stainless steel discs with diameters of 50 mm and thicknesses of 25 mm were fixed to the core surfaces using an epoxy adhesive commercially known as Araldite AV138™ (with the HV998™ hardener resin), manufactured by Huntsman SA (The Woodlands, Texas USA). All tests were conducted with a constant load rate of 0.04 MPa/s until failure.[6]

POTs and DTTs with epoxy/rock interface failure are invalid; thus, they must be discarded and repeated. Surface POTs (SPOTs), in which a metal disc is directly attached to the surface (without drilling), were also performed on the marble, granites, and andesite. The results indicated that the SPOT failure is likely to occur on the epoxy-rock interface (invalid) after approximately 7.0 MPa using the Araldite AV138™. For most concrete materials, this value does not exceed the