On the anisotropy of mechanical properties in Grimsel granite

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Anisotropy of rock properties

- Mechanical properties
  - Elasticity
  - Seismic
  - Strength
  - Fracture toughness

- Thermal and hydraulic properties
  - Permeability
  - Thermal conductivity

Mechanical anisotropy

Strength

Elasticity
Seismic

Process
Zone

Fracture
Toughness
Elasticity anisotropy: Transverse isotropy

\[
\begin{bmatrix}
\epsilon_x' \\
\epsilon_y' \\
\epsilon_z' \\
\gamma_{x'y}' \\
\gamma_{x'z}' \\
\gamma_{y'z}'
\end{bmatrix}
\begin{bmatrix}
1/E \\
-v/E \\
-v'/E' \\
1/E' \\
1/G' \\
1/G
\end{bmatrix}
\begin{bmatrix}
\sigma_x' \\
\sigma_y' \\
\sigma_z' \\
\sigma_{x'y}' \\
\sigma_{x'z}' \\
\sigma_{y'z}' \\
\tau_{x'y}' \\
\tau_{x'z}' \\
\tau_{y'z}'
\end{bmatrix}
\]
Elasticity anisotropy: Transverse isotropy

Uniaxial compression

Ultrasonic measurements
Elasticity anisotropy: Transverse isotropy

- **Conclusions:**
  - Grimsel granite deformation can be characterized by the transverse isotropy model.
  - The isotropy plane coincides with the foliation plane.
Elasticity: Significance of anisotropy and nonlinearity

- Conclusion:
  - Elasticity of Grimsel granite is significantly anisotropic and non-linear.
Implications in GUG-Lab experiments

Mechanical anisotropy

- Elasticity
- Seismic
- Tensile Strength
- Fracture Toughness
- Process Zone
Tensile strength anisotropy

<table>
<thead>
<tr>
<th>$\varphi$</th>
<th>B [mm]</th>
<th>$P_m$ [kN]</th>
<th>$\sigma_t$ [MPa]</th>
<th>Average $\sigma_t$ [MPa]</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>39.5</td>
<td>32.39</td>
<td>5.50</td>
<td></td>
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<tr>
<td></td>
<td>38.6</td>
<td>34.3</td>
<td>5.68</td>
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<tr>
<td></td>
<td>40.3</td>
<td>36</td>
<td>5.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90°</td>
<td>38.9</td>
<td>74.2</td>
<td>16.07</td>
<td>$14.69 \pm 2.00$</td>
<td>2.61</td>
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<td></td>
<td>38.0</td>
<td>55.9</td>
<td>12.39</td>
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<td></td>
<td>37.3</td>
<td>69.1</td>
<td>15.60</td>
<td></td>
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</table>
Digital image correlation experiments

$\theta = 0^\circ$

$\varphi = 90^\circ$
Mechanical anisotropy

- Elasticity
- Seismic
- Strength
- Fracture
- Toughness
- Process
- Zone
Fracture toughness anisotropy
Fracture toughness anisotropy

Configuration $\varphi = 0^\circ$

Fracture trace

Fracture surface

$\varphi = 45^\circ$

Kink distance

Maximum offset

Foliation

$\varphi = 90^\circ$

Maximum offset

Foliation

bt: biotite  ep: epidote  f: feldspar  qz: quartz
Anisotropy of fracture process zone

Anisotropic?

Anisotropic

Tensile Strength

Process Zone

Fracture Toughness
Fracture process zone anisotropy

\( \varphi = 0^\circ \)

\( \varphi = 90^\circ \)

Uniform traction

Linear traction

Nonlinear traction

Traction free

Effective crack
Crack growth in anisotropic media

Anisotropy

Competing factors

in-situ stress
Conclusions:

- Nonlinearity and anisotropy are important features in Grimsel granite.
- Anisotropy can have significant effects of fracture growth near the borehole.
- Anisotropy must be considered in interpreting the results of DUG-Lab experiments.

Suggestion:

- We should plan laboratory measurements in the upcoming Bedretto ISC experiments.

Future research:

- Evaluate different criteria for predicting fracture growth in anisotropic rocks.
- Develop a numerical code to simulate fracture growth in anisotropic rocks.
For more details:


Thank you!