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A Large-Scale Shear Apparatus for Rock Discontinuities and Interfaces

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Abstract

Characterizing the shear behavior of rock discontinuities, whether natural, reinforced, or associated with engineered interfaces, is a key issue for the design of rock engineering structures. However, conventional laboratory tests are limited by scale effects and simplified loading conditions.

In this context, the large-scale shear apparatus developed by the Cerema enables testing of large specimens with natural roughness and material heterogeneities under controlled stress conditions. The device also allows the investigation of complex configurations, such as reinforced discontinuities and bonded concrete–rock interfaces.

This paper presents the main characteristics of the apparatus, together with selected experimental studies that illustrate its capabilities. These experimental studies include tests on passive rock bolts and instrumented concrete–rock interfaces using optical fiber and acoustic sensors. These studies highlight the value of large-scale testing for improving the understanding of shear and failure mechanisms at a representative scale.

The apparatus thus represents an essential intermediate tool between laboratory testing and in situ observations, opening up important perspectives for improving mechanical models and design practices in rock mechanics.

Keywords

Metric direct shear test, Scale effect, Rock joint.

1 Introduction

Rock slopes and structures interacting with rock masses, such as foundations, dams, retaining structures, and stabilized slopes, are strongly governed by the behavior of rock discontinuities. These discontinuities, whether natural, infilled, open, or associated with engineered interfaces, constitute preferential weakness planes. The mechanical response of these planes, particularly under shear loading, largely controls the stability of structures. However, characterizing this behavior remains challenging due to the inherently heterogeneous, anisotropic, and discontinuous nature of rock masses.

The shear behavior of discontinuities is the result of a combination of several mechanisms, including friction, roughness-induced, interlocking, and, in some cases, adhesion when infilling materials or bonded interfaces are present. This behavior depends on numerous parameters, such as surface morphology, mechanical properties of the materials involved, contact conditions, and the level of normal stress. In the case of reinforced discontinuities, particularly those stabilized by rock bolts, additional load transfer mechanisms are mobilized, further increasing the complexity of the overall response and failure modes.

Despite the importance of these mechanisms for engineering design, they remain challenging to characterize experimentally using conventional laboratory devices. These are generally limited to small-scale specimens and simplified geometries, often less representative of real conditions. Such approaches do not allow accurate reproduction of the geometry of natural discontinuities or the variability of mechanical properties at the rock mass scale. In particular, scale effects represent a significant challenge as parameters measured on small specimens may differ considerably from those mobilized at the scale of engineering structures, leading to uncertainties in design approaches.

In this context, the use of large-scale experimental devices is essential to better capture the actual behavior of rock discontinuities and associated systems. The large-scale shear apparatus developed by the CEREMA addresses this need. It allows testing of large specimens incorporating natural or reconstructed rock surfaces and reproducing loading conditions close to in situ situations. This paper presents the main characteristics of the apparatus together with experimental studies illustrating its capabilities.

2 Large-Scale shear Apparatus

2.1 Description

The shear apparatus was designed to perform direct shear tests on rock discontinuities reinforced with one or several rock bolts. It operates according to the principle of a Casagrande shear box. The devise is presents on Fig.1. The lower box remains fixed, while the upper box, moves horizontally. The upper box is constrained laterally, but free to move in the longitudinal direction through a system of articulated links. This configuration allows rotations and tilting induced by either the discontinuity morphology or by the deformation of the reinforcement elements. The dimensions of the machine enable the testing a joint specimen composed of two blocks with dimension 150 cm in length, 100 cm in width and 62.5 cm in thickness

The tangential displacement is imposed at a controlled rate ranging from 0.1 to 1 mm/min. The maximum horizontal displacement of the upper box is 350 mm. Two horizontal hydraulic jacks apply a tensile to the upper box via a guided shear beam, which is transmitted through articulated links. These jacks are double-acting hydraulic cylinders, each capable of delivering a maximum force of 2.5 MN. The vertical normal load is applied vertically using two hydraulic jacks mounted on a base resting on the upper block. The maximum normal force is 2 MN. These jacks are designed to elevate a loading beam, with its external arms integrated into a cradle system. The connection between the beam and the cradle is articulated, ensuring that the load is always applied normal to the upper surface of the block.

The two half-cradles are connected by two HEB steel sections, which are subjected to compression between the cradle and the underside of the lower box. Contact between these sections and the lower box is ensured by roller pads in order to eliminate parasitic friction during translation.



Fig.1 General view of the large-scale shear apparatus: (1) upper half-box; (2) lower half-box; (3) cradle; (4) hydraulic jack; (5) normal force distribution plate.

2.2 Data Acquisition and Processing

The tangential (horizontal) displacement of the upper box is measured using two magnetostrictive displacement sensors installed on the shear jacks. Due to the large dimensions of the apparatus, the elastic deformation of the upper box is not negligible, particularly under high shear loads. Therefore, an additional LVDT captor is installed at the center of the rear plate of the upper box to provide a displacement measurement independent of the applied shear force.

The normal (vertical) displacement is measured using four LVDTs positioned at the four vertical edges of the upper block. These sensors allow quantification of tilting, rotation, and dilatancy. The tangential force is measured for each shear jack using a load cell placed in compression between the jack head and the distribution plate of the shear beam. Similarly, the normal force is measured for each vertical jack using load cells installed between the actuator heads and the normal loading beam.

2.3 Advantages Compared to Conventional Devices

The Cerema large-scale shear apparatus overcomes several key limitations of conventional laboratory testing devices. Firstly, the dimensions of the specimens allows a better representation of rock discontinuities, thereby preserving natural roughness and heterogeneities. This approach significantly reduces scale effects. In contrast to standard devices, which generally rely on simplified planar surfaces, the apparatus facilitates observation of realistic interlocking mechanisms and shear localization processes.

Secondly, the system allows the application of controlled normal stresses up to approximately 1 MPa. This level of stress can be categorized as moderate to high, depending on the context. It is representative of many near-surface conditions and engineering applications, although it is lower than stresses encountered at greater depths. Nevertheless, it is sufficient to meaningfully investigate the influence of confinement on shear strength and dilatancy.

Another key advantage lies in the instrumentation capabilities. In addition to conventional measurements (forces and displacements), samples can be equipped with advanced monitoring techniques such as:

- Distributed fiber optic sensors for strain measurement,
- Acoustic sensors for damage and microcracking identification.

These tools provide valuable insight into internal processes, particularly during the initiation and propagation of failure. The apparatus is designed to serve as an intermediate experimental scale, bridging the gap between laboratory tests and in situ conditions. It facilitates a more realistic and detailed analysis of the mechanical behavior of rock discontinuities and reinforced systems.

3 Experimental studies

This section presents a selection of experimental studies carried out using the large-scale shear apparatus developed by the Cerema. The present studies address representative issues related to rock mechanics, including reinforced discontinuities and bonded interfaces. Two primary subjects are emphasized: first, the examination of shear tests on plane discontinuities reinforced by rock bolts; and second, the investigation of concrete–rock interfaces, with the objective of characterizing their shear behavior under varying contact and confinement conditions. These examples illustrate the apparatus's capability to reproduce complex configurations and to provide insight into fundamental mechanisms governing shear behavior.

3.1 Rock joints reinforced by fully grouted bolts

Experimental campaigns were carried out to investigate the shear strength of a rock discontinuities reinforced with passive rock bolts. The tests examined the influence of several parameters, including bolt properties such as diameter and inclination, group effects, grout characteristics, and the initial aperture of the discontinuity. The planar discontinuity was modelled using two concrete blocks measuring 150 × 100 × 62.5 cm. The diameter of the bolts that were tested ranged from 25 to 40 mm. A part of this work has been previously reported in other studies, notably by Bidaut et al. (2006)and Maiolino & Pellet (2015; 2018).

Fig.2 show the maximum contribution of sheared bolts in an isolated configuration as a function of diameter and inclination (Maiolino & Pellet 2015). The results show that bolts inclined in the direction of shear displacement, typically 45° to 60°, provide the highest contribution. In this configuration, the bolts are rapidly mobilized in tension from the earliest stages of displacement, leading to efficient load transfer. In contrast, vertical bolts are initially subjected to bending, developing a crank-like mechanism before progressively reorienting at the discontinuity plane and mobilizing tensile resistance. This phenomenon leads to a reduction in the contribution and a significant increase in displacements, which are typically 3 to 4 times higher. The results demonstrate a roughly linear rise in bar contribution with diameter, highlighting the dominant role of the resisting cross-section in load mobilization.

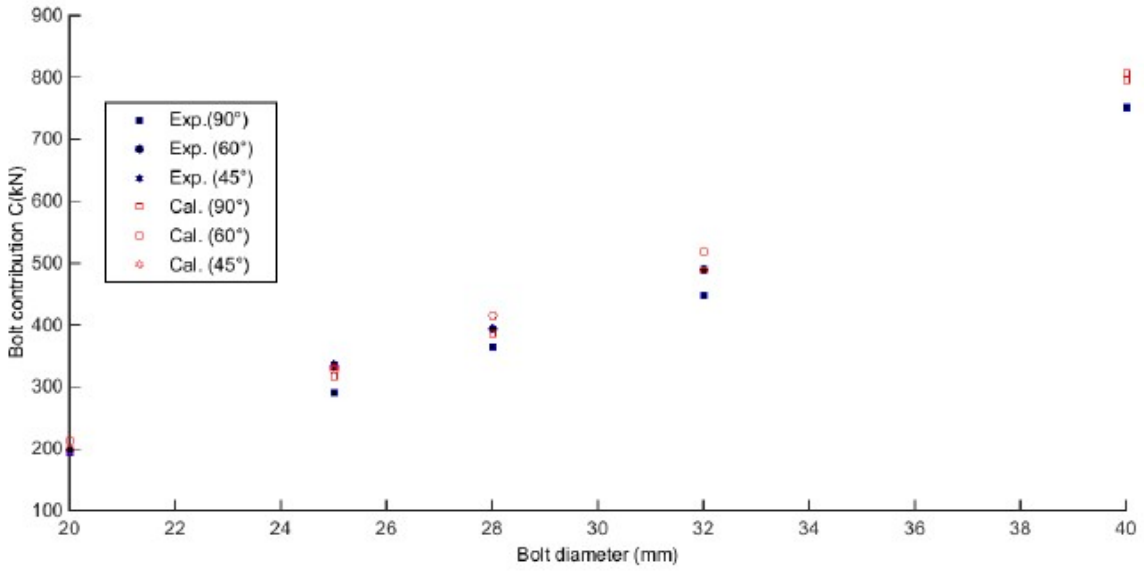


Fig. 2 Ultimate bolt contribution as a function of bolt diameter for different bolt inclinations (Maiolino & Pellet, 2015).

3.2 Study of a Bonded Concrete–Rock Interface

This study focuses on the shear behavior of bonded concrete–granite interfaces at the metric scale, in the context of gravity dam stability assessment. Five direct shear tests were performed on large-scale interfaces with an area of 1.5 m² (Bost et al. 2020).In addition to the standard instrumentation of the machine (force and displacement measurements), the samples were equipped with acoustic sensors and optical fiber (Fig. 3), enabling detailed monitoring of damage processes and strain distribution during shearing.

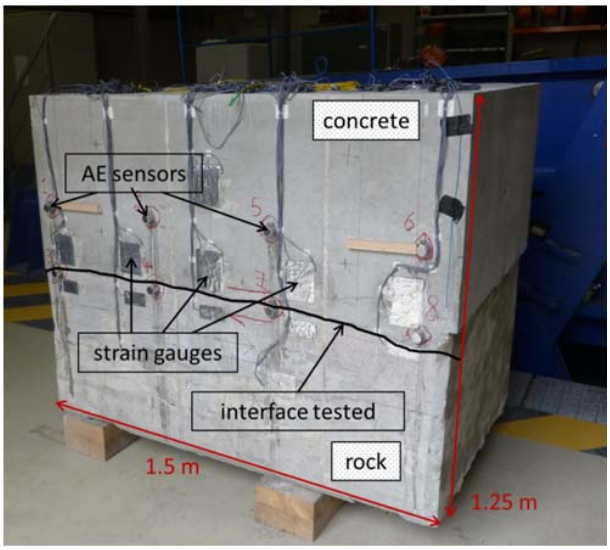


Fig.3 Lateral view of the instrumentation devices set up on a concrete-rock sample (Bost et al 2020).

Fig.4 presents the evolution of shear stress as a function of displacement. In all tests, the shear stress increases progressively up to a peak value, followed by a sharp drop, characteristic of brittle failure. The results show that failure does not occur through shear of the materials (concrete or rock) along the imposed shear plane, but rather through debonding at the concrete–rock interface. This failure mode highlights the critical role of the contact zone, whose properties (adhesion, surface preparation, roughness) directly control the overall shear resistance. These observations underline the value of large-scale testing for capturing realistic failure mechanisms that are difficult to reproduce with conventional laboratory devices.

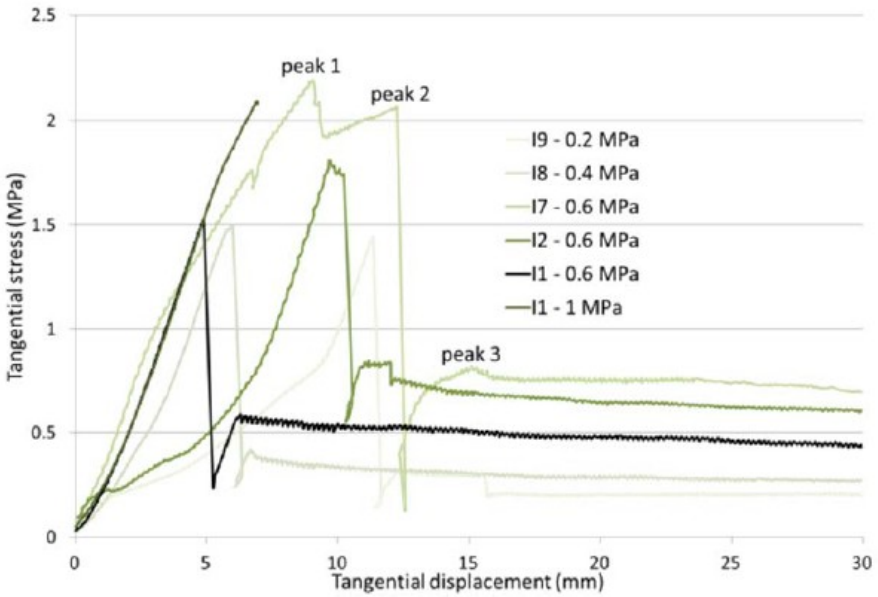


Fig. 4 Shear stress versus tangential displacement for the five direct shear tests (Bost et al 2020).

4 Conclusion

The large-scale shear apparatus developed by the Cerema represents a powerful experimental tool for investigating the shear behavior of rock discontinuities, whether natural, reinforced, or associated with engineered interfaces. The apparatus's dimensions and loading capacity, it enables testing of representative configurations that incorporate real surface roughness, material heterogeneities, and stress conditions close to field situations, while reducing scale effects.

Beyond conventional approaches, the apparatus allows the investigation of complex systems such as reinforced discontinuities, bonded interfaces, and irregular joint geometries, providing detailed insight into deformation and failure mechanisms. The integration of advanced instrumentation, including optical fiber and acoustic monitoring, also opens the way to multi-scale analysis of damage processes.

Consequently, the device constitutes an essential intermediate scale between laboratory testing and in situ conditions, offering strong potential for the development and validation of mechanical models, as well as for improving design methods for rock engineering structures.

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