FIBER-GRAINS INTERACTION MECHANISMS IN TRIAXIAL TESTS DETECTED WITH X-RAY TOMOGRAPHY

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1. Abstract

Fiber orientation plays a key role in fiber reinforcement. Fibers must undergo tensile stress to be effective and must be oriented along the minimum principal stress direction to ensure maximum interaction with the shear band. When fibers are well oriented, during shearing, porosity and strain fields are more homogeneous in the specimen, and the shear band thickness is larger. The present study is focused on the detection of the interaction mechanism between sand grains and fibers, to link the behavior observed at the macroscale with the microscale. An investigation of the soil-fibers contact would disclose the mechanisms that take place locally and affect the global behavior of the soil assembly, providing great benefits for the reinforcement's design and performance predictions.

Fiber-reinforced sand is subjected to miniature triaxial compression test and X-ray imaging. Continuum and discrete Digital Image Correlation analysis is performed to detect fiber-grain interaction mechanisms.

1. Introduction

The use of fiber reinforcement in sands to enhance shear strenght in soil structures has been extensively studied in geotechnical engineering. Previous research has focused on parameters such as fiber characteristics (material, diameter, length), concentration, and soil type to understand their impact on the macroscopic behavior of fiber-reinforced sands (FRS) [2, 3, 4].

Laboratory experiments traditionally examine the mechanical response of FRS under various stresses, with interpretations based on phenomenological approaches [2, 3, 4]. Recent advances in X-ray tomography and image analysis now allow researchers to investigate materials at a particle scale, providing deeper insights into the underlying mechanisms governing their mechanical behavior.

This study integrates traditional phenomenological analysis with microscale investigation facilitated by X-ray tomography. By combining direct shear and triaxial tests with detailed X-ray tomographic imaging, the interaction between fibers and sand grains and its impact on the mechanical response of fiber-reinforced sand (FRS) is elucidated.

The study focuses on the interaction between fibers and shear bands within soil samples subjected to direct shear and triaxial compression tests. Fibers are strategically oriented to maximize interaction with shear bands, aiming to enhance the overall performance of the reinforced sand structure. Experimental analyses are performed on Hostun sand reinforced with fluorocarbon fibers, initially randomly distributed and subsequently strategically positioned to ensure effective interaction with shear bands.

Microscale investigations using X-ray tomography provide insights into modifications of sand structure, grain rearrangement, and strain distribution induced by fiber reinforcement.

The findings of this microscale study contribute to a comprehensive understanding of FRS behavior and serve as a validation tool for developing models that capture fiber-grain interactions at different scales, bridging the gap between macroscopic mechanical responses and microscopic phenomena.

2. Macroscopic response

Preliminary direct shear tests were conducted in two steps: the first to determine the optimal fiber length and content, and the second to analyze the role of fiber orientation. From the first investigation, it appears that the optimal fiber length is the one that maximizes the fiber aspect ratio (l_f/D_{50}) by imposing the relation of fiber length over the minimum sample size less or equal to 1 (see Table 1) [1].

	Dimension		**Size in pixels***
*DS** *TX**	*Fiber length,* l_f *(mm)*	10, 30 10	500, 1500 666
DS *TX*	*Fiber diameter,* d_f *(mm)*	0.10	5 6.6
DS *TX*	*Fiber aspect ratio,* l_f/d_f	100, 300 100	-
DS *TX*	*Sand mean size diameter,* D_{50}*(mm)*	0.32	16 21.3
DS *TX*	*Sample characteristic dimension*,* D_{sample} *(mm)*	30 11	1500 730
DS *TX*	*Sample Aspect Ratio,* D_{sample}/H_{sample}	0.5 0.5	-
DS *TX*	D_{sample}/l_f	3, 1 1	-

*DS – Direct Shear; TX – Triaxial
*The size in pixels is based on a resolution of 20 μm/px (DS) and 15 μm/px (TX)
*The sample characteristic dimension corresponds to the minimum dimension of the sample.

Table 1. Characteristics of fibers, sand, and samples used in this study [1].

In ongoing research, fiber orientation is regarded as a critical parameter. Fibers must withstand tensile stress to become activated; therefore, they are oriented to effectively interact with the shear band. Given the predefined horizontal direction of the shear band in direct shear tests, the fibers are positioned randomly and at a 45° angle relative to the shear band direction. Afterward, miniature triaxial test specimens are prepared with fibers placed on horizontal planes, along the minimum principal stress direction.

In direct shear tests, specimens with fibers oriented at 45° give rise to a significant increase in material dilatancy, which is reflected in a substantial increase in peak and end-of-test shear stress compared to the non-reinforced sand (see Figure 1a). These findings are further validated by miniature triaxial tests, detailed in the following paragraphs. Fiber-reinforced sand specimens packed with fibers oriented along the horizontal direction exhibit an enhanced mechanical response, resulting in increased dilatancy and peak and end-of-test strength (see Figure 1b).

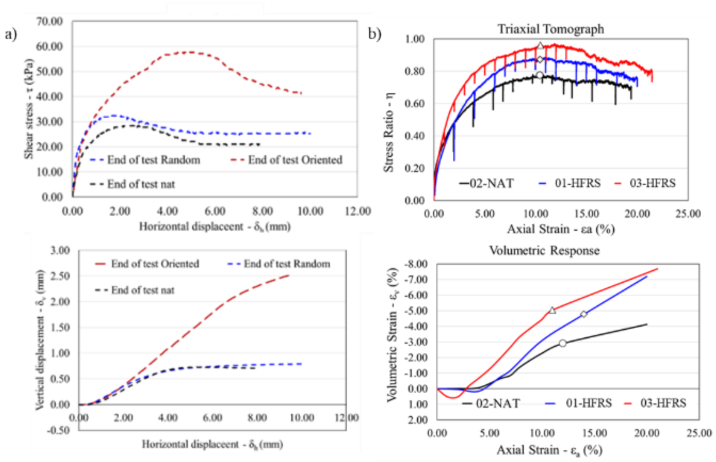

Figure 1. Direct shear test response (a) and miniature triaxial test response (b).

3. Microscale analysis

Miniature triaxial tests are being conducted in the X-ray tomograph, enabling digital image correlation studies using either continuum or discrete approaches. Images and Continuum DIC analyses reveal that strain fields and porosity maps from natural and fiber-reinforced sand (FRS) samples show more diffuse and homogeneous deformation in the FRS sample, with a thicker shear band [1].

Discrete analysis of the fiber-reinforced sample is underway to examine grain kinematics, aiming to understand the impact of fiber presence and characterize fiber-grain interaction. Displacements and rotations of grains from 0 to 10% axial deformation are being analyzed using SPAM functions [5].

There is no discernible effect attributable to fibers, with no observed localization or change in displacement values due to their presence.

The analysis of grain rotations indicates that rotation values increase progressively with each deformation step (see Figure 2 and Figure 3). Beginning at a 4% axial strain, rotations show an increase in the upper left area of the sample, propagating downward and toward the center with continued shearing, outlining the initial formation of a shear band. However, rotations are not confined to a distinct visible band but propagate across the sample, in agreement with the observations from continuum DIC [1]. Evaluation of displacements and rotations up to the 20% deformation step is necessary to confirm enhanced homogeneity and provide a more comprehensive understanding of shear band development.

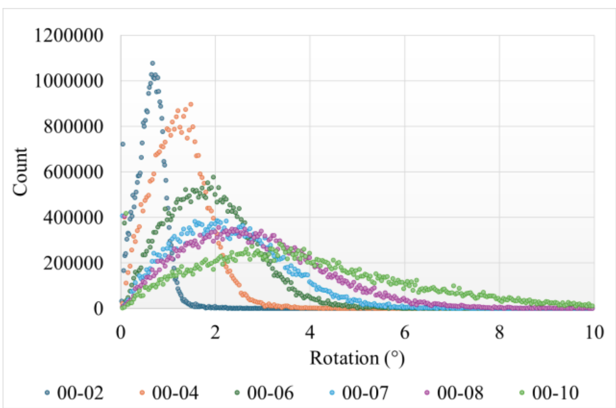

Figure 2. Histogram of grains rotation evolution during shearing.

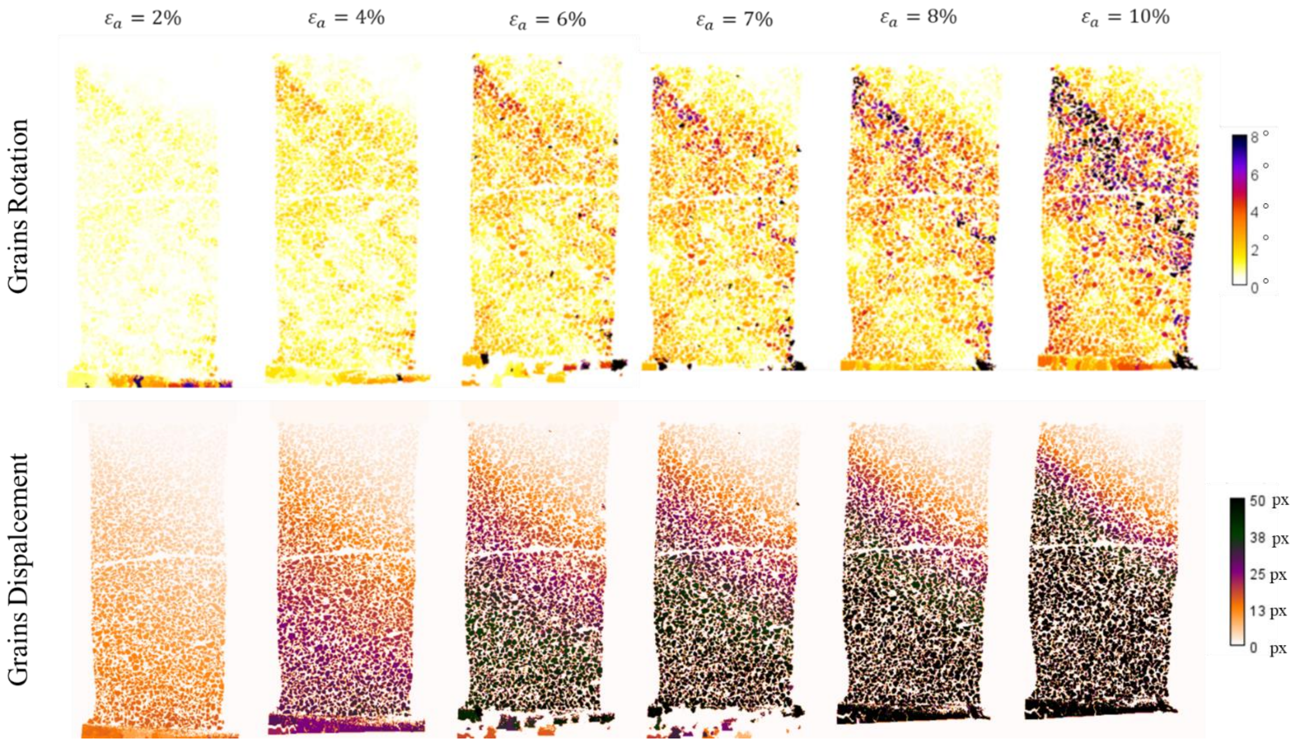

Figure 3. Grain vertical displacements and rotations.

Observing the evolution of a single fiber intersecting the shear band, its deformation is studied. Initially, the fiber displays a curved shape, with its left lateral tail lower than the right side (Figure 4). As deformation increases, the left portion rises to match the height of the right, resulting in a more straight form consistent with the vertical displacement distribution (see Figure 3). Analyzing the elongation of the fiber, it stretches by 0.8%, increasing from a length of 6.36 mm to 6.41 mm. This elongation indicates that the fiber is experiencing tensile stress, suggesting stress transmission between fibers and grains within the shear band.

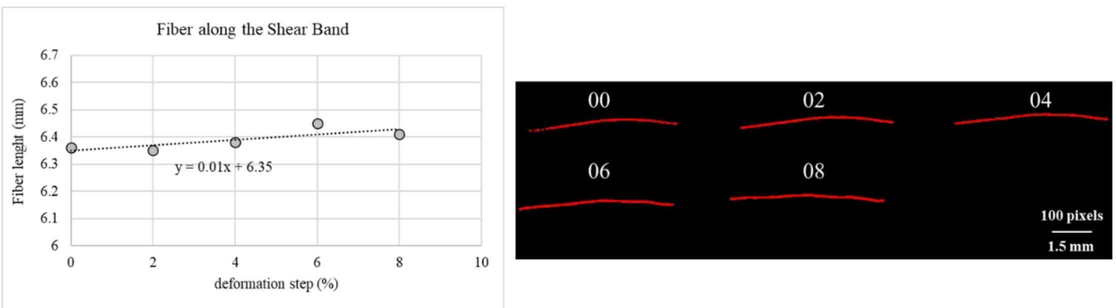

Figure 4. Fiber evolution along the shear band from 0 to 8% of axial deformation.

4. Conclusions and perspectives

Fibers promote more diffuse and homogeneous deformation within the material, resulting in a thicker shear band compared to non-reinforced sand. The discrete image correlation carried out concerning the initial condition reveals that for each loading step, the vertical displacement distribution homogenously decreases from the bottom to the top of the specimen without showing effects attributable to the presence of fibers. The analysis of rotations distribution reveals similar results. The discrete image analysis carried out on a single fiber intersecting the shear band reveals that its length increases with shearing, suggesting stress transmission between fibers and grains.

Subsequent studies must include the analysis of deformation steps beyond 10%. It is imperative to perform a comparison between the analyzed fiber-reinforced sample and natural sand, as noticeable differences attributable to the presence of fibers may emerge. Examining the evolution of the displacement field on the horizontal plane is essential to determine if it is affected by the presence of fibers. Volumetric deformations in the region localized within the shear band need to be calculated. Furthermore, repeating discrete digital image correlation (DIC) with an incremental approach would be beneficial to ascertain if there is a specific deformation step where a particular kinematic behavior is initiated.

5. References

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