Advances in X-ray Tomography for Geomaterials

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Etymologically, *tomography* means imaging by sections or sectioning. X-ray Computed Tomography (CT) enables a three dimensional reconstruction of an object from a large series of X-ray images taken around a single axis of rotation. High-resolution X-ray CT differs from conventional medical CT scanning in its ability to resolve details as small as a few microns in size, even when imaging objects are made of high density materials.

Originally developed for use in healthcare, X-ray CT is used more and more in the field of nondestructive material testing. Computed tomography is useful for studying a wide range of materials, *e.g.*, rock, bone, ceramic, metal and soft tissue. Recently, the study of Geomaterials (including granulates, soils, rocks and concrete) has become one of the more active and challenging fields for the application of high-resolution X-ray CT.

Following the first successful workshop held in Kumamoto (Japan) in November 2003 (GeoX 2003), a second international workshop (GeoX 2006) took place *in Aussois (France) on October 4-7, 2006*. The purpose of GeoX 2006 was to bring together scientists from academia and industry to address the application of X-ray CT to Geomaterials and review recent developments and challenges in the field.

This book collects a total of 48 contributions (including 5 keynote papers), which were presented at GeoX 2006. The contributions span a wide range of topics, from fundamental characterization of material behavior to applications in geotechnical and geoenvironmental engineering. Recent advances of X-ray technology, hardware and software, are also covered. The book will be rewarding for anyone interested in the frontier application of X-ray CT to Geomaterials from both fundamental and applied perspectives.
This workshop was held under the auspices of the International Society for Soil Mechanics and Geotechnical Engineering, committees TC29, TC34, TC35 (ISSMGE), the International Society of Rock Mechanics (ISRM) and the French CNRS research network “GDR 2519 – Mesure de champs et identification en mécanique des solides”. The workshop was generously supported by the following sponsors: Centre National de la Recherche Scientifique (CNRS), Institut National Polytechnique de Grenoble, Université Joseph Fourier, Région Rhône-Alpes, Ville de Grenoble, GeoX CT Center at Kumamoto University, European Synchrotron Radiation Facility, GeoFrames, SkyScan.

Jacques Desrues
Gioacchino Viggiani
Pierre Bésuelle
Keynote lectures
Micro-Characterization of Shearing in Granular Materials Using Computed Tomography

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ABSTRACT: A thorough quantitative analysis of strain localization of axisymmetric triaxial sand specimens is presented. Computed tomography technique was used to acquire detailed 3-D images of a series of Ottawa sand specimens subjected to Conventional Triaxial Compression (CTC) conditions at very low effective stresses in microgravity and terrestrial laboratories. Analysis tools were developed to track the onset, propagation, thickness and inclination angle of shear bands, and calculate the variation of void ratio within and outside shear bands. It has been found that shear bands initiate in the post-peak strength regime in CTC specimens, where a rather complex pattern of shear bands develops such that behavior is highly influenced by large-scale kinematics of the specimen. Four main deformation patterns were identified and their contribution to the overall volume change of the specimens was quantified.

KEY WORDS: Shear bands, sand, triaxial, computed tomography
1. Introduction

The mechanical behavior of granular materials is highly dependent on the arrangement of particles, particle groups and associated pore space. These geometric properties comprise the so-called structure or fabric of a material. In the literature, internal structure analysis techniques are mainly classified as destructive (e.g., specimen stabilization and thin-sectioning) and nondestructive techniques (e.g., magnetic resonance imaging (MRI), ultrasonic testing, x-ray radiography, and computed tomography (CT)). X-ray radiography has been used to trace density changes within soil specimens (e.g., Roscoe 1970; Vardoulakis and Graf 1985; Vardoulakis et al. 1985). However, it suffers from the limitation of not providing a three-dimensional (3-D) radiograph or image.

Recently, Computed Tomography has been used to study the internal density distribution of sand specimens subjected to Conventional Triaxial Compression (CTC) conditions (e.g., Desrues et al. 1996; Alshibli et al. 2000; Batiste 2001). CT is a powerful nondestructive scanning technique capable of accurately mapping the internal structure of geomaterials. In this paper, the results of CT analyses performed on sand specimens tested under CTC conditions at very low effective confining pressures in microgravity and terrestrial laboratories are presented with emphasis on tracking the development of shear bands, their characteristics (thickness and inclination angles), void ratio variation inside and outside the shear bands, and detailed analysis of the evolution of strain localization as the experiment proceeds.

2. Materials and Methods

The specimens were comprised of Ottawa sand, which is a fine-grained, uniform, sub-rounded to rounded silica (quartz) material, commonly denoted as F-75 banding sand, with mean particle size of 0.22 mm, maximum void ratio of 0.805, minimum void ratio of 0.486, and specific gravity of 2.65. The specimens were prepared in a terrestrial laboratory by dry pluviation (raining) in air of the sand into a cylindrical mold under controlled intensity and velocity, which was achieved respectively, by the opening of the funnel from which the sand is poured and the distance between the funnel and the mold. This ensured uniform specimen density. A thin latex membrane (0.27 mm-thick) was used to encase and isolate the sand from the surrounding confining medium (water). The latex membrane was placed along the inside of a split mold and held aligned by a controlled negative pressure (vacuum) relative to the atmospheric pressure. The mold was then attached to the bottom pedestal of the experimental cell; the membrane stretched over the bottom end-platen and sealed using two o-rings. The sand was rained into the mold, and the top end platen was then attached by stretching the membrane over the end platen.
and sealing it using two o-rings. The vacuum (negative pressure) was then removed from the membrane-mold interface and applied to the inside of the specimen to prevent its collapse as the mold was removed. The external experimental cell was then assembled around the specimen, filled with de-aired, deionized water, and pressurized. The internal vacuum was then removed and the specimen pore space vented to the atmosphere.

The experiments were conducted on cylindrical specimens (75 mm in diameter and 150 mm long) using hardware specially developed for the purpose to conduct conventional quasi-static and cyclic triaxial experiments with very precise measurements and controls for the axial load, axial displacement, confining pressure, bulk volumetric changes, ambient temperature, etc. in both the terrestrial and microgravity environment (see Alshibli et al. 1996 for further experimental hardware details). Eleven specimens were examined (Table 1). In each of the three F2 experiments, five axial compression unloading and reloading cycles were completed at regular 5% axial strain intervals to a 25% final nominal axial strain level. F3 experiments were subjected to cyclic loading and were terminated at 3.3% axial strain. These F2 and F3 experiments were performed in the microgravity environment aboard the Space Shuttle during the NASA STS-89 mission in January 1998; six specimens were launched in a Space Shuttle Orbiter, with storage confining pressures maintained at 103 kPa for maintaining stability of the specimens.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$\sigma^1_1$ (kPa)</th>
<th>$D^2_1$ (%)</th>
<th>Maximum Axial Strain</th>
<th>Test Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>F2 007</td>
<td>0.05</td>
<td>64.8</td>
<td>25%</td>
<td>μ-g STS-89</td>
</tr>
<tr>
<td>F2 075</td>
<td>0.52</td>
<td>62.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2 189</td>
<td>1.30</td>
<td>65.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3 007</td>
<td>0.05</td>
<td>66.7</td>
<td>3.3%</td>
<td></td>
</tr>
<tr>
<td>F3 075</td>
<td>0.52</td>
<td>66.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3 189</td>
<td>1.30</td>
<td>66.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KSC5</td>
<td>1.30</td>
<td>82.3</td>
<td>4.6%</td>
<td>Terrestrial</td>
</tr>
<tr>
<td>KSC9</td>
<td>1.30</td>
<td>80.7</td>
<td>9.2%</td>
<td></td>
</tr>
<tr>
<td>KSC12</td>
<td>1.30</td>
<td>78.8</td>
<td>12.0%</td>
<td></td>
</tr>
<tr>
<td>KSC16</td>
<td>1.30</td>
<td>82.3</td>
<td>16.1%</td>
<td></td>
</tr>
<tr>
<td>F3 UD</td>
<td>NA</td>
<td>62.3</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of the experiments and their test conditions

1 Nominal confining pressure
2 Initial relative density
On orbit, the confining pressures were reduced to the desired experiment pressures (0.05, 0.52, or 1.30 kPa) and specimens were compressed to the prescribed nominal axial strain levels. Following the experiments, the confining pressures were restored to 103.5 kPa for Orbiter re-entry and landing. The specimens were subsequently retrieved and subjected to extensive post-flight analysis including computed tomography (CT) measurements. A control specimen (F3 UD), which was prepared along with the other F2 and F3 specimens, was not subjected to the above-described loading histories yet it also underwent CT measurements to provide initial-state information. In addition, four more experiments were conducted in a terrestrial laboratory ("KSC" experiments in Table 1) to further investigate the effects of gravity and confining pressure on the strength properties and deformation characteristics of F-75 Ottawa sand. A correction in the confining pressure value was made to account for the induced radial stresses due to membrane stretching. Also, in order to compare the microgravity to terrestrial experiments, a correction was made in the 1g experiments to account for the specimen self weight and non-uniform confining pressure due to the confining water static pressure head. Detailed reporting of constitutive behavior of these experiments is published elsewhere (Sture et al. 1998). This paper is aimed at describing the onset and progress of shear bands and the change in the internal structure of CTC sand specimens in relation to loading and axial strain levels.

3. Computed Tomography System Parameters

Computed Tomography (CT) was used to study the spatial density variation within the specimens. CT is a technique in which an incident beam of electromagnetic radiation (x- or γ-rays) passes through an object and is collected with an array of detectors. When performed from several angles across a single plane, the collected attenuation data may be transformed into a two-dimensional density map, thus reconstructing a slice image of the specimen's internal structure. When combined with data from adjacent slices, a 3D map is obtained CT is a powerful nondestructive probing technique for investigating the internal composition of a wide range of objects.

The NASA/Kennedy Space Center (KSC) Industrial Computed Tomography System, which uses a CITA-201 scanner manufactured by Scientific Measurement Systems, Inc., was used to perform the scans reported in this paper. A Cobalt-60 gamma ray source was used, with an energy level of approximately 1.25 MeV and source spot size of 2.5 mm. The data acquisition spacing (rayspacing) was specified at 0.5 mm. Second generation data acquisition was used, with time per datum of 0.2 seconds, thus requiring approximately 1 hour acquiring data per complete slice. Slice spacing was 1 mm. For further information on the CT system see Engel (1998).
Calibration of CT data concentrated on length-voxel relationships and CT number to density correlations. First, a relation between length and voxel size was established by measuring voxel values of objects within the tomographic images, whose physical dimensions were known.

Programs were written by the authors using Interactive Data Language (IDL) software that was developed by Research Systems- a Kodak Company, in order to analyze the CT images. The hardware incorporated an end platen support of ring-patterned weight-relieved aluminum. The image was first doubled in size using bilinear interpolation and the array locations of the center of the platen support and midpoints of each ring was found using an IDL function which indicates the position of the interactive graphics cursor (mouse position) in array coordinates from the screen-display image. This was done three times each for two different end platens for the purpose of averaging results. The second hardware feature used for calibration was the stainless steel cross-rods in the test cell (Figure 1), which are located at a known distance apart. The locations of the centers of the cross-rods were found with the same IDL function. The center-to-center distance was measured in CT voxels and physical distance, as with the end platen. The voxel distance was then calculated as straight-line difference and compared to physical distances from mechanical drawings and physical measurements of the end platens for a voxel to length calibration. As the two sets of measurements agreed, no further length-voxel calibration methods were used.

Figure 1. Cross section of the test cell
Spatial resolution was also measured using the ASTM E1695-95 standard. The interface between three aluminum objects and their surrounding media were examined separately. The three objects, a top platen support, a rod, and a medical phantom (an aluminum standard), were chosen because they were all scanned separately and provide as a check on consistency between scans. The top platen is a piece of test cell hardware, machined from a solid piece of aluminum. The rod was a piece of aluminum available at the scan facility and could also show similar non-uniformities as the platen. The medical phantom was a palm-sized disc made for the sole purpose of measuring CT resolution. Thus, it may be assumed to yield reliable results. The modulation transfer function was found using an edge response function of a least-square fit of 25 bilinear-interpolated edge profiles evenly distributed around each calibration standard.

Calibration of density was performed using ASTM Guidelines (ASTM-E1935, 1997). Water and Lexan available in scans of the triaxial experimental cells, were used as standards. An aluminum standard was also scanned. Mean CT numbers (CTN) were found through selection of several rectangular representative areas of the Lexan, water, and aluminum. Rectangular areas were used for the ease of selection as simple routines utilizing built-in IDL functions would also be used for shear band investigations. Areas were as large as possible without nearing edges to avoid any possible edge effects. A linear relation between the CTN provided in the scans and their individual attenuation coefficients (Ca) [cm⁻¹], retrieved from National Institute of Standards and Technology (NIST) (Hubbell and Seltzer, 1997), was calculated. To convert to void ratio, the mass coefficient of attenuation for quartz (Mca = 0.05687 cm²/g) was used. For quartz sand, due to the negligible attenuation of air the dry density is the ratio of Ca to Mca, allowing the conversion from CTN directly to void ratio. To verify the calibration, 14 scanned specimens were examined. The mean CTN of all array points within each specimen was found and converted to void ratio, giving a measure of bulk density. This was then compared to the bulk densities calculated from initial mass and volume measurements, with corrections for volume change during experimentation.

A length calibration of 0.387 mm/voxel was found through examination of hardware from the triaxial test cell that also appeared in some CT scans. Spatial resolution was also measured using scans of an aluminum standard, which showed that data have 50% modulation at 0.275 line pair per millimeter (lpm), and 10% at 0.53 lpm. Thus, objects separated by 1.8 mm can be identified with 50% modulation, and objects 0.94 mm apart can be identified with 10% modulation. These characteristics affect data interpretation both in length and void ratio measurements. One cannot resolve features below 3 voxels (0.94 mm/0.387 mm/voxel = 2.4 voxel) at 10% modulation. While considering the fact that the average grain size of the material is 0.22 mm, one cannot resolve features below 5.3 grain diameters at 10% modulation, or below 8 grain diameters at 50% modulation.
The CTN vs. void ratio ($e$) relation found was $e = (0.2995 - \text{CTN})/(0.03900 + \text{CTN})$. A standard deviation of the void ratio error was found to be 0.033 when compared with the bulk densities of the scanned specimens.

4. Shear Band Properties

Two types of shear bands were present in the specimens, which will be referred to as axial conical and radial-planar. Conical bands appear as a set of thin annuli of low-density material in horizontal cross sections and as two straight lines, forming a ‘V’ shape, in vertical cross sections. The conical formations are located against the two end platens, with the tip pointed toward the middle of the specimen (Figure 2). The second type of shear bands are radial-planar which are more abundant. These bands are generally planar but oriented at an angle to the central axis, perhaps best being described as a set of ‘turbine blades’ oriented at an angle, or rotating about the central axis clockwise from top to bottom, while others are oriented or angle counter-clockwise. As one follows a single shear band down through several slices, it may be viewed crossing several other shear bands, which are “rotating” in the opposite direction. This is illustrated in Figure 3, where a single shear band, identified by a black stripe, is followed through a vertical plane a given specimen (image 1 is at the top of the specimen moving down to images 2, 3,…). Following the slices, the slow counter-clockwise rotation of the shear band is evident. In addition, the crossing of clockwise-rotating shear bands can be identified, not only in the highlighted band, but others as well. Due to this rotation, radial shear band patterns can vary significantly from one slice to another. It appears that the specimen is divided into active “blocks” with multiple shear bands that try to move against each other in a compression-shear mode. As compression proceeds, deformation patterns become more complex creating kinematic constraints, and the numerous number of shear bands appear to change from active to inactive modes and vice versa during the overall specimen compression process.

4.1 Inclination angle

The inclination angles ($\theta$) of a selection of shear bands were measured in several specimens. $\theta$ was measured from the direction of the minor principal stress (i.e., horizontal plane). For each specimen, two shear bands with good traceability were chosen. Using a vertical cross-section, a line was drawn on the shear band of the displayed image such that the line would appear on the image as well as change voxel values to “1” in a blank array that have the same size as the image array in the same locations. Then, several horizontal cross-section images were examined individually. On each image, the line drawn on the vertical cross section could be viewed, indicating the shear band of interest. The shear band was also marked on
each of these images, which also changed the values in the blank array. This resulted in several of the points in the plane of the shear band to be identified in 3-D space in the blank array. Using a least-square fit on the identified points, the equation of the plane and the inclination angle were found.

Measurements of $\theta$ are summarized in Table 2 based on a fit to a plane. Considered in these results should be the visual inspection which indicates two important characteristics: first, some shear planes appear to have a slight twist out of plane and second, new shear bands continue to form as axial strain increases and others cease activity following formation. If a shear band were to form early and then stop being active, it would likely deform due to overall specimen deformation. This could be an out-of-plane twist, planar rotation, or a combination of both. As an example, if one formed at an axial strain of 10% with an angle of 66° to the horizontal and then remain the same length but simply rotate with no shear along that band, its angle would decrease to 50°. Given the understanding that the band is nearly planar, it is reasonable to fit it to a plane and take the higher-angle shear bands as the significant bands. Though not performed in this study, further testing with a single specimen examined at multiple axial strains is suggested to increase the accuracy of shear plane inclination and shape.

![Figure 2. CT Scans for KSC Experiments](image-url)
A comparison between the measured $\theta$ values, Coulomb ($\theta_c = 45^\circ + \phi_p/2$; where $\phi_p$ is the peak friction angle), and Roscoe ($\theta_R = 45^\circ + \psi/2$; where $\psi$ represents the dilatancy angle) solutions is also presented in Table 2. The $\theta$ values range between 55 to 66° with a mean value of 60.2°. The Coulomb solution over-predicts $\theta$ by 4-6° for the ground specimens (KSC specimens) and the F2 189 microgravity experiment. However, for the other two $\mu$g experiments, the angle is greatly over-predicted (13° -21°) by the Coulomb solution. Considering the same relation, but using the measured residual friction angles ($\phi_{res}$), as it appears that shear bands develop during the residual stress condition, $\theta$ is better-predicted using the
Coulomb solution, though the prediction still overestimates the $\theta$ values (up to 6.3°) for F2 007 and F2 075 microgravity specimens. It should be noted that the F2 007 and F2 075 microgravity experiments exhibited unusually high friction angles and relatively smaller $\theta$ values for which Roscoe solution provided better predictions. It appears that as the confining pressure decreased from 1.30 to 0.05 kPa, the strain localization phenomenon in granular materials becomes increasingly kinematically governed (Roscoe solution) as opposed to statically controlled as given by the Coulomb solution.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$\theta$ (Degrees)</th>
<th>Coulomb Solution (Degrees)</th>
<th>Roscoe Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\theta_X = 45^\circ + \phi_f/2$</td>
<td>$\theta_X = 45^\circ + \phi_{\text{res}}/2$</td>
</tr>
<tr>
<td>F2 007</td>
<td>55.2</td>
<td>79.9</td>
<td>62.7</td>
</tr>
<tr>
<td>F2 075</td>
<td>56.8</td>
<td>72.9</td>
<td>63.4</td>
</tr>
<tr>
<td>F2 189</td>
<td>57.4</td>
<td>68.8</td>
<td>60.3</td>
</tr>
<tr>
<td>KSC9</td>
<td>61.3</td>
<td>70.5</td>
<td>n/a</td>
</tr>
<tr>
<td>KSC12</td>
<td>63.1</td>
<td>70.7</td>
<td>65.3</td>
</tr>
</tbody>
</table>

Table 2. Shear band inclination angle measured from the minor principal stress direction

4.2. Thickness

To determine shear band thickness, profiles were obtained across the shear bands. Due to the non-uniform appearance of the shear bands, 10-voxels wide profiles were gathered by reading into an array. The void ratio values across the 10 voxels were averaged to form the shear band profile. As shown in Figure 4, the solid line represents the profile, and the dashed line represents the average void ratio value outside the shear band, collected via gathering data in small rectangular regions near the shear band. The size of the region varied in order to take the largest area possible without overlapping onto shear bands. The region that is located inside the shear band is shaded light gray, and its thickness is represented by $t_a$ (apparent thickness). From $t_a$, the true (perpendicular) shear band thickness $t_E$ is calculated, based on the average inclination of the shear band.

In several specimens a minimum of nine shear bands were examined, with two profiles per band. The data was obtained by examining three slices; at 37%, 50%, and 63% of the specimen final height, with a minimum of three shear bands per slice. Considering the columnar nature of shear bands (Oda et al. 1997), there are regions where shear bands have higher void ratios, and regions where spreading of columns (due to buckling phenomena) occur. When one traces a shear band, the void ratio would be observed to fluctuate. Because of this, the apparent density of the shear band is dependent on the location where one measures the profile. While it
is possible to strike a profile right where a large void exists, which would result in high band thickness values, it is also possible to strike a profile where there are few voids, which would make the shear band appear rather narrow. Also, a thick shear band measurement could be found if more than one shear band was actually measured, as there are numerous occurrences where multiple shear bands have joined together during crossing and the overall deformation process. While the effort was made to choose single shear bands, the multitude of crossings does make this an extremely challenging task.

The KSC and F2 specimens formed shear band thicknesses with mean and median values between 8 and 16 mean particle diameter ($d_{50}$) with measurements ranging from 2 to 30 particle diameters (Table 3). While there is wide variation of shear band thickness, the mean and median values agree well, and are within the common 8-20 $d_{50}$ range, which is seen in terrestrial higher-pressure investigations. A full investigation of the use of CT scanning to measure the shear band width is called for with data which allows the viewing of individual particles. In this manner, the bands could be measured and compared on a particle-level scale as well as a scale similar to that used in this study.
### Table 3. Summary of shear band thickness measurements and void ratio values within shear bands

<table>
<thead>
<tr>
<th>Specimen</th>
<th>F2 007</th>
<th>F2 075</th>
<th>F2 189</th>
<th>KSC 9</th>
<th>KSC12</th>
<th>KSC 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean of $t_e/d_{s0}$</td>
<td>14.24</td>
<td>10.02</td>
<td>16.68</td>
<td>8.33</td>
<td>10.45</td>
<td>16.30</td>
</tr>
<tr>
<td>Median of $t_e/d_{s0}$</td>
<td>12.69</td>
<td>9.23</td>
<td>16.39</td>
<td>7.32</td>
<td>10.26</td>
<td>15.59</td>
</tr>
<tr>
<td>Minimum of $t_e/d_{s0}$</td>
<td>5.69</td>
<td>4.25</td>
<td>8.50</td>
<td>1.95</td>
<td>3.00</td>
<td>3.27</td>
</tr>
<tr>
<td>Maximum of $t_e/d_{s0}$</td>
<td>28.86</td>
<td>23.24</td>
<td>29.80</td>
<td>19.78</td>
<td>17.79</td>
<td>37.03</td>
</tr>
<tr>
<td>Mean void ratio ($e$)</td>
<td>0.883</td>
<td>0.865</td>
<td>0.885</td>
<td>0.834</td>
<td>0.817</td>
<td>0.839</td>
</tr>
<tr>
<td>$\Delta e = e - e_o$</td>
<td>0.285</td>
<td>0.258</td>
<td>0.287</td>
<td>0.286</td>
<td>0.263</td>
<td>0.297</td>
</tr>
</tbody>
</table>

#### 4.3. Void Ratio within Shear Bands

In order to establish the void ratio variation within shear bands, the same shear band profiles that were used in thickness measurements were examined. Data was gathered only on the F2 series and KSC12 and KSC16 specimens, as the shear bands are difficult to accurately isolate in the KSC 9 specimen as it is in the early stages of shear band development, and they are not present in the F3 series tests which are compressed to only 3.3% axial strain. Only the region within a shear band was examined; the profile edges were avoided, as they include a combination of data from both inside and outside the shear band due to the inclination of the shear band over the 2 mm slice thickness of the CT scanning. The values that fell within the inner portion of the shear band profile were identified and the mean void ratio was calculated (Table 3). For the F2 189 specimen, a combined mean void ratio was found to be 0.885. The mean void ratio for the KSC16 specimen is 0.839, which is slightly lower than the void ratio of the F2 189 specimen. In general, the shear bands in the KSC specimens display a lower void ratio than the F2 specimen’s shear bands.

#### 5. Volume Change Distribution

By observing the distribution of the different shear bands, as well as their densities, and comparing them to the volumetric data recorded during testing, one can trace back and determine the evolution of shear bands as specimen compression proceeded. Discretization of the specimen can be used to determine what fractions of volume change are attributed to various localization patterns. For instance, the unexpected behavior of continuous specimen volume expansion (dilation) in the post-peak regime raises questions regarding low effective stress triaxial testing, and what occurs at larger overall strain levels. Also, the large number of shear bands