Bulk Material Tests

1. Uniaxial Compression Tests

The uniaxial compression test used cubes of the bulk 3D-printed material (density = 1335 kg/m^3) with a side length of 60mm. Eight specimens were tested. The applied load is measured using a 100 kN capacity load cell while displacements are monitored using a three-dimensional Digital Image Correlation (3D-DIC) system, with two cameras capturing the movement of the specimen during testing.

Two loading protocols were applied to the specimens, each consisting of a force-controlled phase followed by a displacement-controlled phase. The loading speed was 0.1MPa/s in the force-controlled phase. Rates of 0.1mm/minute and 0.25mm/minute were used in the displacement-controlled phase of loading protocols 1 and 2, respectively.

The force-controlled phase was common between the two loading protocols and included two sets of three cycles (See Figure 1):

- Three cycles between the preload level (5% of the expected compressive strength) and a stress level of 15% of the expected compressive strength.
- Three cycles between 15% of the expected compressive strength and a stress level of 33.3% of the expected compressive strength. The third loading cycle in this set was used to calculate elastic properties such as elastic modulus, Poisson's ratio, and shear modulus.

In all cycles, after reaching the minimum and maximum stress levels, the force was held constant for five seconds before loading or unloading (Figure 1). After completing the first set of cycles, the force was held constant at 5% of the expected compressive strength for sixty seconds. After reaching the amplitude of the 6th total cycle, the specimen was unloaded to the minimal load of 1% of the expected compressive strength, before the displacement-controlled phase was started.

During the displacement-controlled phase, two different loading schemes were implemented:

• Loading Protocol 1 (Monotonic in the displacement-controlled phase): Three specimens were monotonically loaded in the displacement-controlled phase until failure.

• Loading Protocol 2 (cyclic in the displacement-controlled phase): For the remaining 5 specimens, the displacement-controlled phase was carried out with cyclic loading. For every cycle, the displacement amplitude was increased by a displacement increment. After reaching the amplitude of a cycle, the specimen was unloaded to a displacement that corresponds to 1% of the expected compressive strength.

The stress, vertical strain (in the direction of loading), and horizontal strain for the 8 specimens are provided in the file *BulkMaterialTestData.zip* under Input Data. Naming of the files is "SpecimenName.txt" where "SpecimenName" is according to the first column in Table 1. Each text file contains three columns as follows:

Column1: stress in MPa

Column 2: vertical strain (in the direction of loading)

Column 3: horizontal strain

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Table 1 summarizes the results of the uniaxial compression tests. It includes compressive strength, elastic and shear moduli, and Poisson's ratio for the eight specimens, as well as the coefficient of variation, CoV. The CoV is calculated as the standard deviation divided by the mean. Figure 2 depicts the stress-vertical strain and stress-horizontal strain for the tested specimens. The stress-strain curves plot horizontal and vertical strains in the negative and positive directions, respectively.

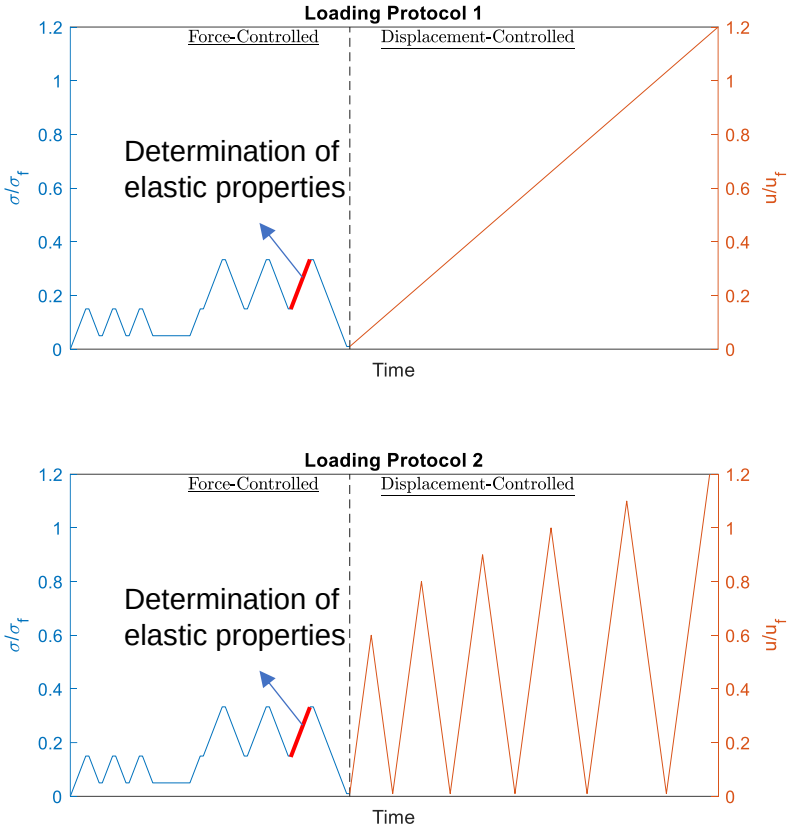

Figure 1. Loading protocols - bulk material compression test.

Table 1. Summary of the uniaxial compression test results.

Specimen	Loading protocol	Elastic modulus [MPa]	Shear modulus [MPa]	Poisson ratio [-]	Compressive strength [MPa]
CCu_1	Protocol 1	3695.7	1567.8	0.18	7.82
CCu_2	Protocol 1	3944.7	1640.7	0.20	8.41
CCu_3	Protocol 1	4397.0	1784.8	0.23	8.66
CCu_4	Protocol 2	4027.5	1606.2	0.25	7.95
CCu_5	Protocol 2	4210.8	1710.0	0.23	7.99
CCu_6	Protocol 2	3670.1	1523.4	0.20	7.95
CCu_7	Protocol 2	3744.5	1532.9	0.22	7.41
CCu_8	Protocol 2	4221.9	1812.3	0.16	8.66
Mean		**3989.0**	**1647.3**	**0.21**	**8.1**
CoV		**0.068**	**0.068**	**0.140**	**0.054**

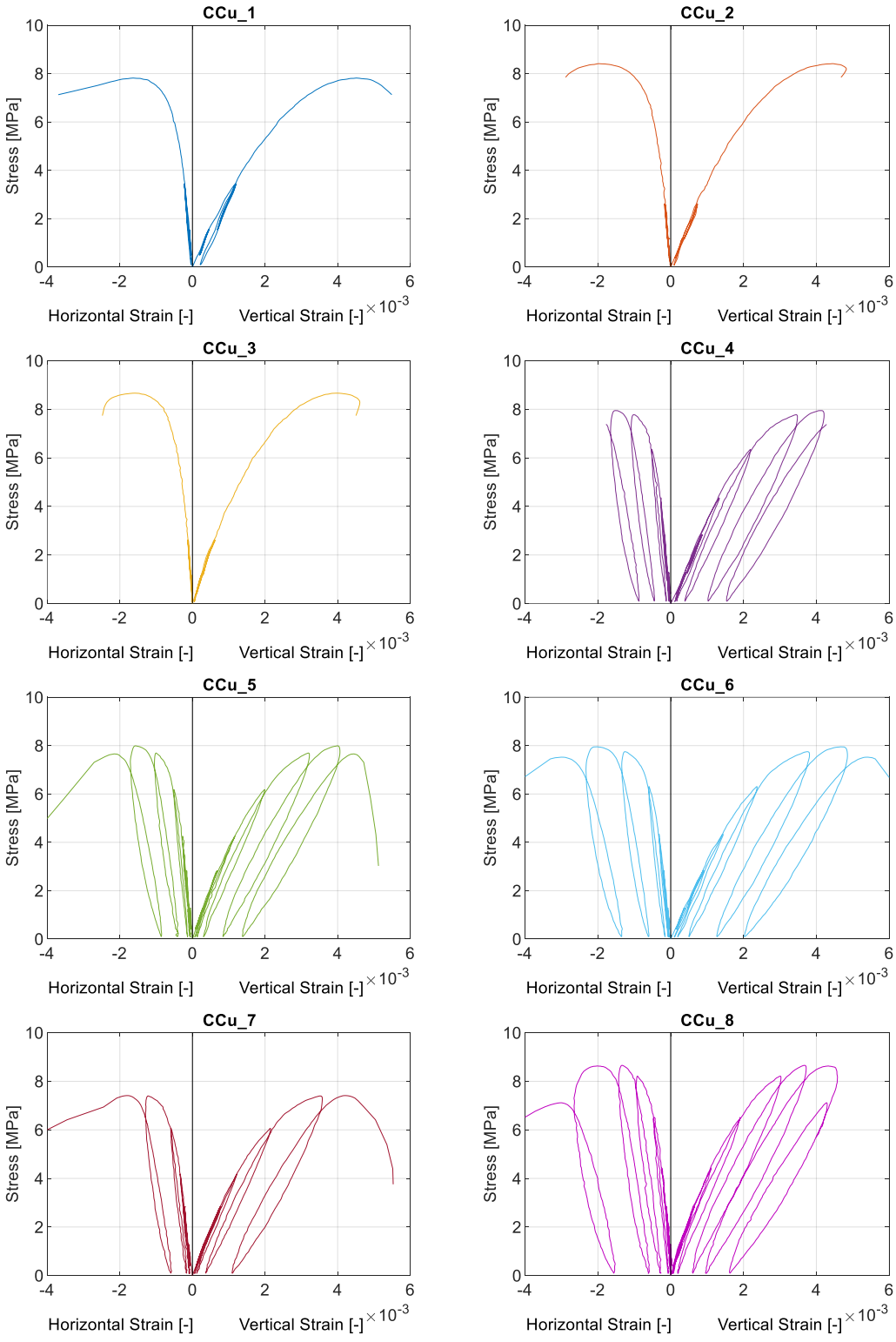

Figure 2. Stress-strain relationships for the tested cubes.

2. Four-point Bending Test

The 4-point bending test was conducted according to the norm DIN EN 12390-5 (2019). Two beam sizes were tested: one with a square cross-section of side length of *a* = 15mm and length *l* = 75mm, referred to as 'Beam15', and another with a square cross-section of side length *a* = 30mm and length *l* = 150mm, referred to as 'Beam30'. A total of 7 specimens were tested per size. Figure 3 illustrates the geometry of the specimens. The test setup is illustrated in Figure 4. According to the norm DIN EN 12390-5 (2019), a monotonically increasing stress rate of 0.04MPa/s was applied.

For specimens with *a* = 15mm, i.e., "Beam15", the mean and CoV of the flexural strength obtained was 2.7MPa and 0.241. For specimens with *a* = 30mm, i.e., "Beam30", the average and CoV of the flexural strength obtained was 2.9MPa and 0.149.

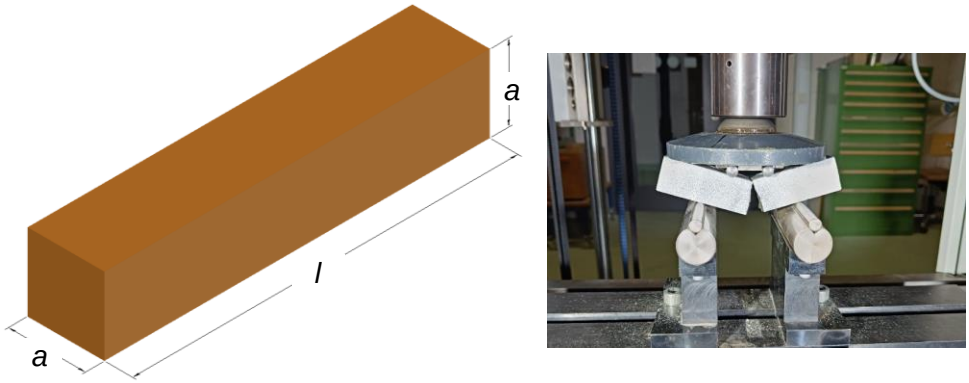

Figure 3. Four-point bending test: (left) specimen geometry, and (right) failure mode.

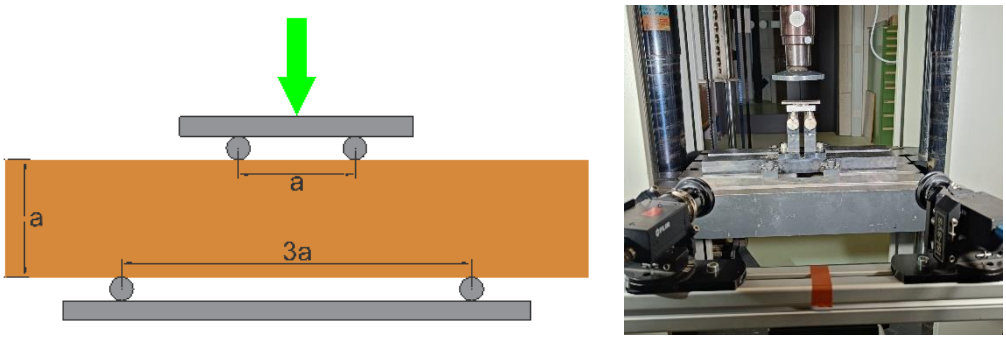

Figure 4. Four-point bending test setup.

References

EN DIN EN 12390-5. 12390-5: 2019-10: Prüfung von festbeton-teil 5: Biegezugfestigkeit von probekörpern. Deutsche Fassung EN, pages 12390‑5, 2019.

EN DIN EN 12390-13. 12390-13: 2021-09: Prüfung von festbeton‑teil 13: Bestimmung des elastizitätsmoduls unter druckbelastung (sekantenmodul). Norm, Ausgabe September, 2021.