MASTER

Influence of the interface between layers on the tensile properties of 3D printed concrete

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INFLUENCE OF THE INTERFACE BETWEEN LAYERS ON THE TENSILE PROPERTIES OF 3D PRINTED CONCRETE

Graduation Thesis

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Preface

This Graduation Thesis is the result of my graduation project *Influence of the interface between layers on the tensile properties of 3D printed concrete*. This research is conducted at the Department of the Built Environment of the Eindhoven University of Technology and is the last part for completing the master Architecture, Building and Planning with the specialization Structural Design.

The developed 3D concrete printer at the Department gave the opportunity to contribute to a research into a new and innovative way of manufacturing concrete structures. This topic is chosen because fundamental knowledge of material properties of printed concrete is necessary to guarantee structural safety of printed structures.

This research is carried out under the supervision of prof.dr.ir. T.A.M. (Theo) Salet, prof.dr.ir. A.S.J. (Akke) Suiker and R.J.M. (Rob) Wolfs MSc. I want to thank the supervisors for their feedback and discussions during this research. In addition, great gratitude goes out to the employees of the Structural Design Laboratory of the Department of the Built Environment. With their support and expertise, I could carry out a lot of successful experiments, which are the basis of this research. I also want to express my gratitude to fellow students, who supported me with discussions and feedback.

Finally, I want to thank my parents and my girlfriend for their support during my study, especially during this graduation project.

Gosse Slager

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Abstract

3D Concrete Printing (3DCP) is a new manufacturing technique that has a lot of potential advantages, compared to the current way of constructing. From the several possible printing methods, the Contour Crafting technique is used at the Eindhoven University of Technology. This technique uses a robot that places layers of concrete on each other. Because of this printing method, the density of the concrete may be influenced and an interface between the printed layers is created. This may influence the tensile properties, like the tensile strength and the fracture energy. Knowledge of material properties and behavior of printed concrete is important to guarantee structural safety of printed structures. Therefore, the influence of the interface between the layers on the tensile properties of 3D printed concrete in the hardened stage is studied in this research. This is done in an experimental way and in a numerical way.

The tensile properties of plain concrete were studied to understand the behavior of concrete subjected to tensile loading. A load-deformation relation of a specimen subjected to a direct tensile load consists of a pre-peak and post-peak branch. The pre-peak branch may be expressed in a stress-strain relation because on macro-level, stresses and strains are uniformly distributed. It is incorrect to express the post-peak branch in a stress-strain relation because macrocracks are developed whereby the deformation of the specimen consists of strains and crack openings. The post-peak branch may be expressed in a stress-crack opening relation whereby the area below this branch represents the fracture energy.

A direct tensile test setup is developed for the experiments. A test setup with rotating loading platens was already available. However, with this test setup, deformations in the specimen are very non-uniform, followed by high peak stresses due to eccentricity in the applied load caused by macrocracks. This results in a lower tensile strength of the specimen compared to a test setup with non-rotating loading platens. In addition, a realistic value for the fracture energy cannot be obtained due to non-uniform deformations with rotating loading platens. With a direct tensile test setup with non-rotating loading platens, non-uniform deformations, and thereby eccentricity during the crack development, are reduced to a minimum.

From the direct tensile tests with non-rotating loading platens, the tensile strength, fracture energy and modulus of elasticity can be obtained. Differences in tensile strengths were found between tests with rotating loading platens and non-rotating loading platens, between specimens with and without interface, and between specimens with and without time interval. The fracture energy of different specimens also differs from each other, whereby the crack surface seems to have a large influence on the fracture energy. The modulus of elasticity from the specimens was relatively low due to the measuring length of the LVDT’s, which also measured the deformation of the loading platens and glue layers. This had a larger influence on the results than was expected before. Cylinder compressive tests were carried out to obtain the modulus of elasticity of the concrete. From these tests can be concluded that the initial modulus of elasticity is higher than the measured modulus of elasticity from the direct tensile tests.

Three different types of specimens are modeled with a Finite Element Method (FEM) model which can describe discrete cracking. The aim of this model is to reproduce the crack surfaces from the specimens to understand the crack behavior of the specimen. A 2D Cohesive Zone Model (CZM) is created whereby the cohesive elements were given different tensile strengths defined by a normal distribution which was obtained from the experimental results. This resulted in a variation in tensile strengths and in non-uniform crack openings. The cohesive elements were given a constant value for the fracture energy. Multiple simulations were carried out with each model. For each simulation, the elements were random given a tensile strength from the normal distribution. This resulted for every simulation in a new crack surface. The theory about fracture of concrete, starting with a fracture process zone, followed by macrocracks, and finally resulting in a crack surface, is described very well by the model. In addition, the numerical simulations described the crack surfaces from the experimental research very well.
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1 Introduction

1.1 Scope

In the last decades, a lot of attention is paid to sustainability in the built environment. Materials and the way of constructing buildings may have a large influence on the sustainability of a building. Concrete is one of the most used materials in the built environment. Cement, water and aggregates, like sand and gravel, are constituents of basic concrete. Cement has a large contribution to the CO$_2$ emissions. 5% of the anthropogenic CO$_2$ emissions worldwide are due to the production of cement (Flower and Sanjayan, 2007). To reduce the CO$_2$ emissions due to the cement production, the amount of cement may be reduced or the material may be changed to a more sustainable product, like green cement.

At the Eindhoven University of Technology, research into a more sustainable way of constructing is carried out by means of 3D Concrete Printing (3DCP). A printer has been developed and build in the Structural Design Laboratory of the Department of the Built Environment. With this printer, this new and innovative way of construction is researched. The most important advantage from the sustainable point of view of the 3D Concrete Printer is that the user has a large influence on where to put the material. Due to this fact, the material can be placed where it is needed, resulted in saving a lot of material, and thus cement. Other important advantages of 3DCP are: no need of framework during construction, more freedom in designing structures and less heavy labor.

Several methods can be distinguished in 3D printing. Contour Crafting, Concrete Printing, and D-Shape are some of these methods. A State-of-the-art of these methods is provided by R. Wolfs (2015). The printing method used at the University of Eindhoven is Contour Crafting. With this method, layers of concrete are placed on each other whereby a shape is created. Figure 1.1 illustrates the developed printer at the Structural Design Laboratory.

Figure 1.1 3D concrete printer at the Structural Design Laboratory of the Department of the Built Environment, TU/e (Rien Meulman).
This 3D printer consists of a gantry robot, a mixer and pump and a control unit. The gantry robot can move in 3 directions and can rotate around its vertical axis, a total of 4 degrees of freedom. The print area is 9*4.5 m² with a height of 2.8 m. Concrete is mixed with water and pumped through a hose that is connected on one side at the mixer-pump and on the other side at the bottom of the vertical arm of the gantry robot, called the printer head. The concrete flows, under pressure, to the printer head, to which a nozzle is mounted. A variety of nozzles, with different shapes, can be used for printing. A control unit controls the settings of the mixer-pump and it controls the speed and movement of the gantry robot. A more extensive discussion about the 3D printer is provided by Bos, Wolfs, Ahmed and Salet (2016a).

1.2 Aim

Creating geometries with 3DCP differs a lot from the conventional way of making concrete geometries. The structural safety of the 3D printed geometries must be guaranteed. Therefore, fundamental knowledge about the structural properties of 3D printed concrete is necessary. At the department of Built Environment, the 3DCP research is mostly focusing on gaining this fundamental knowledge. Salet, Bos, Wolfs & Ahmed (2016b) are presenting an extensive discussion about the research that already has been done to this topic and key results.

As mentioned before, with the Concrete Crafting method, layers of concrete are printed on each other. Because of this printing method, the composition of the concrete, and thereby the mechanical properties, may be influenced. Between the printed layers of concrete, an interface is created. This interface may also have an influence on the mechanical properties. It is plausible that the mechanical properties are different from the mechanical properties of the same concrete when it is casted.

The aim of this research is determining the influence of the interface between the layers on the tensile properties of 3D printed concrete. In addition, material properties of printed concrete in the hardened stage are obtained and the crack behavior of printed concrete is studied.

1.3 Methodology

Obtaining tensile properties of concrete in the hardened stage is done by means of experimental research. A new test setup for direct tensile tests on concrete specimens is developed for this research. This test setup can describe the post-peak behavior of concrete.

Experiments are carried out in the Structural Design Laboratory of the Department of the Built Environment at the Eindhoven University of Technology. Concrete specimens for the experiments are printed with the 3D concrete printer at the Structural Design Laboratory and tested in the hardened stage. Specimens with 1 layer (without interface) and with multiple layers (with interface) are tested. Specimens with a time interval of 7 days, whereby the top layers are printed 7 days later than the bottom layers, are also tested to research the influence of printing on cured concrete.

Numerical research is carried out, by means of finite element method (FEM), to get a better understanding of the influence of the interface on the crack behavior of printed concrete. The FEM model must be capable to describe discrete cracking.
Tensile properties of concrete

The material properties of general concrete subjected under tensile stresses are discussed in this section.

2.1 Load-deformation relation

Figure 2.1a illustrates the load-deformation relation of a specimen loaded under direct tension. Almost to the peak load, the specimen behaves linear elastic. On macro-level, stresses and strains are uniformly distributed over the specimen and therefore a stress-strain relation can be created (Hordijk, 1991), see figure 2.1b. At the peak load, a fracture process zone with microcracks is developed, followed by macrocracks in the weakest section of the specimen (Hordijk, 1991).

The post-peak behavior can be explained by a proposed model by Hillerborg, Modeer and Petersson (1976). This model describes the fracture behavior of concrete and is known as the “Fictitious Crack model”. The basic idea of this model can be explained as follows. When a crack tip reaches the ultimate tensile strength, the crack propagates and the crack width increases with a decreasing stress. At crack width \( w_1 \) (see figure 2.1c) stresses cannot be transferred anymore (Hillerborg et al., 1976). Due to macrocracks in the specimen, it is not correct to use a stress-strain relation after the peak load, because the deformation of the specimen in the softening zone consists of strains and crack openings. The softening zone is expressed in a stress-crack opening relation (Hillerborg et al., 1976). Figure 2.1c illustrates a stress-crack opening relation of a specimen loaded under direct tension.

Van Mier (in Hordijk, 1991) considered that the softening behavior was a structural phenomenon instead of a material property. He believed that the decreasing load in the softening branch was due to a decreasing effective area (in Hordijk, 1991). Hordijk (1991) however stated that there is no reason to believe that the softening behavior is not a material property. It is explained by Hordijk (1991) that the load capacity after the peak load is a combination of the strength and stiffness of the mortar and the aggregates and the bond capacity between these and interlocking of the aggregates (i.e. sliding friction due to aggregates pulled out the mortar). Another contribution of the load capacity is explained by van Mier (in Hordijk, 1991) as bridges between overlapping cracks.
2.2 Tensile strength

As generally known, the tensile strength of concrete is very low in comparison with its compressive strength. The cause of the relatively low tensile strength is due to the presence of microcracks. The effective tensile strengths of isotropic materials in general might be increased at least 10 to 20 times when microcrack are prevented (Griffith, 1920). Neville (2012) even stated that the theoretical strength of cement paste has been estimated as high as 10,500 MPa.

2.2.1 Microcracks

If concrete is loaded under tension, it is assumed that the tensile stress is uniform, i.e. a stress is calculated from a load divided by a surface and is therefore assumed to be equal over the whole surface. According to Neville (2012), high stress concentrations occur due to microcracks in very small volumes while the average stress over a surface is comparatively low. This means that the stress over a surface is very non-uniform. High concentrated stresses lead to failure on a lower average strength than the theoretical strength.

According to Neville (2012), microcracks (cracks that cannot be seen with the naked eye and smaller than about 100 µm) already exist in concrete before a load is applied. It is likely that these microcracks are the result of differences in mechanical properties between aggregate and hydrated cement paste, shrinkage and thermal movement (Neville, 2012).

Microcracks remain stable when a specimen is subjected to a load of about 30 percent of the ultimate load. From this point, cracks start to grow in width and length. Also, the number of cracks increases. When 70 to 90 percent of the ultimate load is reached, a continuous crack pattern, also known as a fracture process zone, is formed (Neville, 2012). The fracture process zone is followed by the crack tip of a macrocrack. When a 70 to 90 percent of the ultimate load is maintained, failure may take place in time (Neville, 2012).

2.2.2 Influence specimen size on the tensile strength

The strength of a specimen depends on its size, this is called size effect. It is reasonable to assume that the larger a specimen is, the greater the chance of containing a weaker link. When the specimen size increases, the measured strength and variation in strength decrease (Neville, 2012). According to Bažant (2000), this hypothesis, also called Weibull theory, is valid when a microscopic crack propagates to a macroscopic crack and causes failure. In this way, a small part of the specimen behaves like a chain where the weakest link fails. However, when a large fracture process zone and/or long stable crack develops in which the maximum force is not reached, stress redistributions occurs and therewith energy releases. The weakest link theory, where links are coupled in series, cannot be applied anymore and another effect than the statistical size effect of Weibull occurs (Bažant, 2000). This other effect is known as energetic size effect and can be defined as follows:

The source of the energetic size effect, briefly stated, is a mismatch between the size dependence of the energy release rate and the rate of energy consumption by fracture. A significant part of the former increases as the square of the structure size, while the latter increases in proportion. Therefore, the nominal stress must decrease to reduce the energy release rate of structure so as to achieve a match. (Bažant, 2000, p. 73)

In figure 2.2 (Rossi et al., in Neville, 2012, p. 606), results are given from experiments of direct tensile tests with different diameters of cylinders. This figure shows that (1) the size effect is large on specimen with a compressive strength of 35 MPa and (2) the larger specimen size, the smaller the size effect becomes.
Chapter 2 Tensile properties of concrete

2.2.3 Influence aggregate size on the tensile strength

The aggregate size has influence on the tensile strength of concrete. Elices & Rocco (2008) carried out three-points bend tests and indirect splitting tests to determine the influence of aggregate size on the tensile properties of concrete. 44 experiments were carried out on specimen with different mortar strengths, aggregate-matrix interfaces and aggregate sizes on normal concrete. From these experiments, it can be concluded that (1) the tensile strength of concrete is lower than the tensile strength of the mortar matrix and (2) the tensile strength seems to decrease when the aggregate size increases. On high-strength concretes, tensile strengths increase with an increasing size of aggregates. These conclusions were also found by other research (Elices & Rocco, 2008).
2.3 Fracture energy

Concrete is known as a quasi-brittle material. If concrete was perfectly brittle, tensile stresses close to a microcrack will cause a running crack which can lead to failure (Hillerborg, 1985). Due to toughness of concrete, tensile stresses can still be transferred after fracture. This toughness can be described by the fracture energy. The fracture energy is the specific energy that is required for crack growth (Bažant, 1987).

The fracture energy $G_f$ is represented by the area below the stress-crack opening relation, see figure 2.1c. This is the amount of energy per unit area ($J/m^2$) of the fracture surface, perpendicular to the tensile direction (Hillerborg, 1985). An increase in fracture energy means an increase in toughness, and vice versa.

2.3.1 Influence specimen size on the fracture energy

According to Bažant (1987), although the fracture energy is a material property that should be a constant value, results sometimes differs by several hundred percent due to differences in test methods, specimen shapes, and specimen sizes.

Wittmann, Mihashi and Nomura (1990) carried out compact-tension tests on different sizes of specimen to show the influence of size effect on the fracture energy, see figure 2.3a (Wittman et al., 1990, p. 109). Experiments were carried out on three different specimen sizes with ligament lengths 150, 300 and 600 mm (length b from figure 2.3a). From these experiments, it seems that the fracture energy in this case increases with an increasing ligament length until 300 mm. The fracture energy seems to be constant with a ligament length of 300 mm and longer, see the results in figure 2.3b (Wittmann et al., 1990, p. 112).

Further analysis of the results by Wittmann et al. (1990) shows that the crack width increases with an increasing ligament length. Because the width of the fracture process zone is not constant over the ligament length, it is assumed that the crack width is also not constant over the ligament length (Wittmann et al., 1990). It can be seen from these experiments that the pre-peak behavior may be influenced by the shape of the fracture process zone, and thereby, the fracture energy may be influenced by the size and shape of the specimen (Wittmann et al., 1990).
2.3.2 Influence aggregate size on the fracture energy

Hordijk (1991) indicates that the aggregates have influence on the fracture energy. Figure 2.4 (Hordijk, 1991, p. 68) illustrates three different types of concrete and their post-peak behavior. Fiber reinforced concrete (FRC) is outside the scope of this research and is therefore not considered. In a normal weight concrete (NC), cracks develop around aggregates, creating a rough crack path with an increased contribution of interlocking. In a lightweight concrete (LC), cracks run through aggregates creating a smoother crack path (Hordijk, 1991).

![Figure 2.4 influence of aggregates on the fracture energy. Reprinted from “Local approach of fatigue of concrete”, by Hordijk, 1991, p. 68.](image)

It is reasonable to assume that the ductility, and thus the fracture energy, increases with an increasing size of aggregates. This assumption is confirmed by Elices & Rocco (2008), they researched the influence of aggregate size on the fracture energy. The first conclusions that were drawn are (1) the fracture energy of concrete is higher than the fracture energy of the mortar matrix and (2) the fracture energy increases with an increase of aggregate size. This is both the case with a strong mortar-matrix where aggregates break and with a weak mortar-matrix where aggregates do not break. In the latter case, the fracture energy is higher because of an increasing fracture surface due to more roughness. Other researchers found comparable results on normal and high-strength concretes (Elices & Rocco, 2008).

2.4 Modulus of elasticity

2.4.1 Modulus of elasticity under compressive- and tensile loading

It may be assumed that the modulus of elasticity in tension is equal to the modulus of elasticity in compression (Neville, 2012). This is confirmed by experiments from Galloway and Harding (1976) and from Lydon and Balendran (1986). Galloway and Harding (1975) carried out experiments on lean and pavement concrete and found no observable differences in the modulus of elasticity of concrete under tension and compression. Experiments on normal weight concrete and lightweight concrete were carried out by Lydon and Balendran (1986). Also from these experiments, very similar results were found in modulus of elasticity under tension and under compression.

2.4.2 Aggregate size on the modulus of elasticity

Elices & Rocco (2008) also researched the influence of aggregate size on the modulus of elasticity. When aggregates are added to a mortar, the modulus of elasticity is lower compared to the modulus of elasticity of the same mortar without aggregates. In the case of a strong bond between mortar and aggregates, the modulus of elasticity seems to decrease with an increase of aggregate size. When the bond between mortar and aggregates was weak, no clear trend was found (Elices & Rocco, 2008).
3 Experimental technique

3.1 Influence of the print process on the tensile properties

A 3D printed concrete geometry consists of layers of bulk material and interfaces between the layers. The bulk material itself is isotropic, but due to the print printing method, the printed geometry is most likely anisotropic. Observing the printed layers from figure 3.1, distinction can be made in three directions. The tensile properties in x- and y-direction (figure 3.1b) have probably no significance difference, the tensile properties in z-direction are probably decreased due to the interface.

![Figure 3.1 (a) Printed layers of concrete with bulk material and interfaces and (b) schematically representation.](image)

3.1.1 Bulk material

The bulk material is a concrete mix that is developed for printing by SG Weber Beamix. The dry bulk material is composed of:

- Portland cement (CEM I 52,5 R)
- Siliceous aggregate with an optimized particle size distribution
- Limestone filler and specific additives for ease of pumping
- Rheology modifiers for obtaining thixotropic behavior of the fresh mortar, and
- A small amount of polypropylene fibers for reducing crack formation due to early drying.

It is likely that the process method has influence on the tensile properties of the bulk material. Doomen (2016) gives a list of variables in the 3D concrete printing process. Some important variables that may influence the tensile properties of hardened concrete are listed here:

- Duration of mixing, and thereby the age of the concrete
- Pump pressure, influencing the flow of concrete, pump temperature and the density of concrete
- Temperature of the water and the environment, likely influencing the setting time
- Print speed, influencing the density of the concrete
- Nozzle shape and/or size, influencing the density of the concrete

3.1.2 Interface

The interface, created by the printing process, describes the bond between the layers. Some variables that may influence the interface are listed here:

- Time interval between layers, influencing the bond between layers due to curing of the concrete
- Height of the nozzle, influencing the bond by placing concrete on top of the previous layer or press concrete partly in the previous layer
- Nozzle size, may influence the bond by the amount of weight of concrete layer and thereby compression of the layers
- Nozzle type, may influence the bond by using a straight nozzle (placing material from above) or a nozzle with a 90-degree angle (placing material from the print direction)
3.2 Test setup

3.2.1 Introduction

According to Neville (2012), there are three different tensile tests: the direct tensile test, the flexure test and the splitting test. Direct tensile tests were carried out to obtain material properties of printed concrete. Doomen (2016) developed a setup for a direct tensile test with rotating loading platens to obtain tensile strengths from printed concrete. Rotating loading platens, or hinges, are used to ensure that there is no (or a small) eccentricity in the applied load.

The fracture energy is represented by the area below the stress-deformation relation post-peak branch, see figure 2.1c. Uniform deformations in the fracture zone are required if a stress-deformation relation as a material property must be obtained (Hordijk, 1991). Figure 3.2 gives the load-deformation relations of two different direct tensile tests. Figure 3.2a illustrates the locations of the Linear Variable Differential Transformers (LVDT), which measure the deformation. Figures 3.2b and 3.2c illustrate the load-deformation relations of a direct tensile test with rotating loading platens and non-rotating loading platens respectively.

When rotating loading platens are applied, the difference in deformation in the pre-peak branch on each side of the specimen are relatively large, but they are still all positive (i.e. the whole specimen is subjected to tensile stresses), see figure 3.2b. In the post-peak branch, three sides undergo a positive deformation while one side (LVDT 07 in this case) undergoes a negative deformation (i.e. this side of the specimen is subjected to compressive stresses). The deformations are very non-uniform when rotating loading platens are applied. Therefore, this test setup is not suitable to obtain the fracture energy.

Besides non-uniform deformations, rotating loading platens cause eccentricity in the applied load when macroracks are developed. Due to this eccentricity, high peak stresses are introduced whereby a lower ultimate strength is measured. When non-rotating loading platens are applied, eccentricity during the crack development is reduced (Wolinski, Hordijk, Reinhardt & Cornelissen, 1987).

It can be seen that deformations in the pre-peak branch are uniform when non-rotating loading platens are applied, see figure 3.2c. In the first part of the post-peak branch deformations are slightly non-uniform, this behavior was also found by Hordijk (1991).

Figure 3.2 Load-deformation relation of a direct tensile test with (a) LVDT’s on each side of the specimen, (b) deformation LVDT’s with rotating loading platens and (c) deformation LVDT’s with non-rotating loading platens.
3.2.2 Test setup non-rotating loading platens

The experiments were carried out in The Structures Laboratory Eindhoven of the Unit Structural Design of the Department of the Built Environment of the Eindhoven University of Technology. The testing system that is used for the experiments is the Instron 5985 test bench with a load cell of 250 kN, see figure 3.3a.

Figure 3.3 Developed test setup with (a) testing system Instron 5985 with a 250 kN load cell and (b) a schematically representation of the test setup with non-rotating loading platens.

Figure 3.3b illustrates schematically the developed test setup with non-rotating loading platens. In practice, the loading platens are not infinite stiff and small rotations may still occur, but for the sake of clarity, the loading platens are called non-rotating. With this test setup, the following material properties can be obtained:

- Tensile strength
- Fracture energy
- Modulus of elasticity

The tests were executed with an increasing deformation of a certain rate (deformation-controlled). With an increasing load (load-controlled), the specimen fails after the peak load is reached and post-peak behavior cannot be described. The test setup must be very stable to obtain the post-peak branch and the deformation must increase slowly without sudden jumps. The development of the test setup is discussed in appendix A.
The test setup with non-rotating loading platens can be found in figure 3.4. Figure 3.4a is an overall view with the grips. Figure 3.4b is enlarged whereby loading platens and the LVDT’S can be seen.

![Figure 3.4 (a) Overview of the test setup with non-rotation loading platens and (b) enlargement of the specimen.](image)

**3.2.3 Test setup rotating loading platens**

Several tests are carried out with rotating loading platens, in the same manner Doomen (2016) carried out experiments, to compare results from the two test setups. Figure 3.5 illustrates this test setup. Relatively long rods are used to reduce eccentricity in the applied load, see figure 3.5a. 4 LVDT’s are used to measure the deformation between the steel blocks (figure 3.5b).

![Figure 3.5 (a) Overview of the test setup with rotation loading platens and (b) enlargement of the specimen.](image)
3.3 Influence of the test setup on the results

A lot of variables of the test setup may influence the results. The most important variables are discussed in this chapter.

3.3.1 Measuring

The deformation is measured by 4 LVDT’s. For these tests, LVDT’s with a length of 40 mm and a total range of 2 mm are used.

The measuring length of the LVDT’s has influence on stress-deformation relation, see figure 3.6 (Hordijk, 1991, p. 10). This stress-deformation relation corresponds with a normal-weight concrete. From a direct tensile test, the crack opening remains constant over the measuring length, but the elastic deformation increases with an increasing measurement length (Hordijk, 1991). Applying a large measuring length for the control LVDT’s may cause snap-back behavior. The test may become unstable and the result of the post-peak branch is not representative for the material behavior (Hordijk, 1991).

![Figure 3.6 Influence of the measuring length on the stress-deformation relation. Reprinted from “Local approach of fatigue of concrete”, by Hordijk, 1991, p. 10.](image)

The measuring length is chosen from a practical point of view. The LVDT’s are measuring the deformation over the total length of the specimen including a part of the steel loading platens (see figure 3.11b). The measuring length of the experiments is between 50 and 80 mm. It can be seen from figure 3.6 (Hordijk, 1991, p. 10) that the measuring length has a small influence on the actual post-peak behavior and it is assumable that this measuring length not causes snap-back behavior.

3.3.2 Deformation rate

The deformation was controlled by the average deformation of the 4 LVDT’s.

According to Neville (2012), the deformation rate may have a large influence on experimental results. However, Hordijk (1991) carried out direct tensile tests with different rate’s and concluded that there was no significant difference in the results. The used deformation rate of the pre-peak branch in the experiments of Hordijk (1991) was 4.8 µm/m with a measuring length of 50 mm. Because the measuring length on the specimen of this research is comparable with the measuring length that was used by Hordijk (1991), this deformation rate is used as a starting point for the direct tensile tests.
3.3.3 Rotational stiffness

The influence of the rotational stiffness of the specimen and the loading platens of the test setup may have an influence on the results. The rotational stiffness of a specimen can be expressed by $EI/L$ whereby a shorter length of the specimen causes a higher rotational stiffness. The influence of the rotational stiffness is experimentally researched by Hordijk (1991), whereby there was varied with the length of the specimens. The results by means of the stress-deformation relation of specimens with different lengths can be found in figure 3.7 (Hordijk, 1991, p. 47). In this figure, the continuous line belongs to the shortest specimen of 50 mm.

It can be seen from these experiments that (1) results on shorter specimens deviate from results on longer specimens, see figure 3.7 (Hordijk, 1991, p. 47), and (2) a decrease in specimen length, and thereby an increase in rotational stiffness results in a more uniform crack opening (Hordijk, 1991). The first observation is explained by Hordijk (1991) as the influence the stiffness of loading platens (preventing lateral deformation) on shorter specimens. Due to the more uniform crack opening of shorter specimens, the descending branch of stress-deformation relation of shorter specimens is smoother than the descending branch of longer specimen (Hordijk, 1991).

![Figure 3.7 Stress-deformation relation of specimens with different lengths. Reprinted from “Local approach of fatigue of concrete”, by Hordijk, 1991, p. 47.](image)

In this research, the dimensions of the specimens depend on the printer. Specimens with a length of 40 mm are used in this research, whereby the loading platens possibly influence the results.

3.3.4 Preloading specimen

During the drying process of the glue, a pre-load of 100 N is applied on the specimen, see section 3.4.5. This is about 0.5% of the cube compressive strength. A pre-load this small is probably neglectable, but for the sake of completeness, the effect of a compressive preload is discussed here. Hordijk (1991) carried out direct tensile tests on specimen with a preload of 0%, 10%, 30% 50% and 75% of the cube compressive strength. Conclusions that were drawn are (1) a flatter peak was found in the stress-deformation relation from the preloaded specimen, (2) the preload had no significance influence on the tensile strength, (3) the fracture energy increased slightly at the preloaded specimen and (4) the modulus of elasticity decrease with an increased compressive preloading (Hordijk, 1991).
3.4 Specimens

3.4.1 Manufacturing method

Shapes and dimensions of specimens and making and curing of specimen are defined in standards NEN-EN 12390-1 and NEN-EN 12390-2. To obtain the influence of the print process on the material properties, specimens are not mixed and molded prescribed in these standards, but are printed instead. Because of this alternative method of creating specimen, shapes and dimensions are depending on the print process and the used nozzle.

Four different methods to make specimen from printed concrete were researched by Dolkemade and Williams (2016). The different methods were sawing after curing, cutting directly after printing, printing through a mold and capping after curing with gypsum. The methods were compared to each other and judged on manufacturing and reliability. It was concluded by Dolkemade and Williams (2016) that sawing after curing is the most reliable method because surface roughness is removed.

3.4.2 Printing

Two different nozzles were used to print concrete layers for the specimens, see figure 3.8. The most used nozzle for printing is a steel nozzle with dimensions 40*10 mm². With this nozzle, specimens with interfaces are printed (figure 3.8a). For specimens without interface, a nozzle of 45*45 mm² is used (figure 3.8b). With this nozzle, more concrete is printed, and therefore, the pump speed is maintained while the print speed is reduced with 4 to 5 times in compared to the print speed that is applied with the former nozzle.

![Printed concrete layers for specimens with (a) nozzle 40*10 mm² and (b) nozzle of 45*45 mm².](image)

The specimens were printed in three print sessions. Figure 3.9 gives a graphic of the pump temperature during the print sessions. Table 3.1 shows the dates and average pump temperatures of the print sessions. The temperature of print sessions 2 and 3 are relatively high compared to print session 1. It is possible that the pump is stiffer tightened in print sessions 2 and 3. This will cause more friction, and thereby a higher temperature. This may influence the curing process of the concrete and the material properties. The relatively humidity in the laboratory was around 60 percent during printing.

![Pump temperature during printing.](image)

<table>
<thead>
<tr>
<th>Table 3.1 Print sessions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Session</strong></td>
</tr>
<tr>
<td>Print session 1</td>
</tr>
<tr>
<td>Print session 2</td>
</tr>
<tr>
<td>Print session 3</td>
</tr>
<tr>
<td>Laboratory</td>
</tr>
</tbody>
</table>
3.4.3 Curing

After printing, the printed material was covered with plastic, and wet tissues were placed under the plastic to prevent dehydration. After about 24 hours, the printed material was placed in a water tank stored in the laboratory with an environmental temperature of about 20 °C.

Strength tests should be carried out after 28 days of curing. Because of the duration of one test, this requirement cannot be met for every test series. Because of the many variables of the printing process, it is chosen to reduce the number of print sessions and print the specimen in as little as possible print sessions. Due to this, not every test series can be tested after 28 days of curing.

3.4.4 Notches

The specimens are provided with notches to reduce the surface. Without notches, the specimens will fail on the glue layer between the steel block and the specimen. Doomen (2016) did research on the influence of notches in a numerical fashion, see figure 3.10 (Doomen, 2016, p. 62). Peak stresses were calculated with different shapes of notches. The notches from figure 3.10e resulted in the lowest peak stress. This shape looks like a dog-bone shape that is commonly used for direct tensile tests. It is difficult to create this shape of notches, and thus for practical reasons the notches of figure 3.10d will be used.

![Figure 3.10 Influence of notches on peak stresses calculated numerically. Reprinted from "The Effect of Layered Manufacturing on the Strength Properties of Printable Concrete", by Doomen, 2016, p. 62.](image)

3.4.5 Preparation specimen and test procedure

The day before testing, the specimens were sawn from the printed material. The specimens have dimensions of 40*40*40 mm$^3$ with a notch on two sides of the specimen with a radius of 6 mm, see figure 3.11a. After fabrication of the specimens, the dimensions and weight of the specimens were determined. After that, the specimens were placed back in the water tank. On the test day, one side of the specimen was glued outside the test bench, and the other side was glued inside the test bench, see figure 3.11b. In this way, imperfections of the specimen and the loading platens of the test bench are smoothed with the glue layer. When the specimen was glued in the test bench, a compressive load of 100 N was applied to prevent tensile stresses in the specimen due to shrinkage of the glue. After 30 minutes of drying, the test was started. Appendix B shows an extensive discussion of the specimen preparation and testing procedure.

![Figure 3.11 (a) Specimen with notches and (b) specimen glued in the test setup.](image)
3.5 Test series

4 types of specimens were created for testing. Figures 3.12a and 3.12b illustrate the printed sections with the nozzle of 40*10 mm$^2$. The time interval between the layers was about 30 seconds (called without interval), except for the middle interface of the section from figure 3.12b. This time interval was 7 days, whereby new layers were printed on cured concrete. Figures 3.12c and 3.12d illustrate the printed sections with the nozzle of 45*45 mm$^2$. The time interval between the layers was about 2 minutes (called without interval). This is 4 times longer due to the decrease in print speed as discussed in section 3.4.2. Figure 3.13 illustrates the different sawn specimens from the printed material.

![Figure 3.12 Printed sections, with (a) 6 layers without interval, (b) 6 layers with 7-day interval, (c) 1 layer and (d) 2 layers without interval.](image)

![Figure 3.13 Specimens after sawing, with (a) 4 layers without interval, (b) 4 layers with 7-day interval, (c) 1 layer and (d) 2 layers without interval.](image)

The specimens were given codes which consists of 4 parts, divided by underscores. An example of a specimen code is 5_4_7d_06. The explanation of the specimen code is given below:

- **Test series**: (1 to 8)
- **Number of layers**: (1, 2 or 4)
- **Time interval in days**: (0 days of 7 days)
- **Serial number**: (1 to 12)

After several the pre-tests for the development of the test setup with non-rotating loading platens, a total of 8 test series were carried out on different days. A total of 12 test could be carried out per day. An overview of the test series is given in table 3.2. Specimens of test series 1 and 7 are carried out on the test setup with non-rotating and rotating loading platens.

<table>
<thead>
<tr>
<th>Test setup</th>
<th>4 layers (without interval)</th>
<th>4 layers (7-day interval)</th>
<th>1 layer</th>
<th>2 layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-rotating</td>
<td>1_4_0d (1-7)</td>
<td>5_4_7d (1-12)</td>
<td>4_1_0d (1-12)</td>
<td>6_2_0d (1-12)</td>
</tr>
<tr>
<td>Rotating loading</td>
<td>2_4_0d (1-4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>platens</td>
<td>3_4_0d (1-12)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8_4_0d (1-8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotating loading</td>
<td>1_4_0d (8-12)</td>
<td></td>
<td>7_1_0d (7-12)</td>
<td></td>
</tr>
<tr>
<td>platens</td>
<td>-</td>
<td></td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.2 Overview test series per test setup
3.6 Mortar prisms

As mentioned before, a lot of variables in the print process may influence the material properties of hardened concrete. Mortar prisms were used to determine if the strength properties of hardened concrete of every print session are comparable. At the start of every print session, mortar prisms of 40*40*160 mm$^3$ were molded. On the days that the direct tensile tests were carried out, flexure and compression tests on the mortar prisms were carried out.

Strength tests of mortar are standardized by the NEN-EN-196-1:2005. The material was mixed and pumped by the 3D printer and collected at the end of the hose. The steel molds were filled half, compacted, then filled completely and again compacted. After that, the molds were covered with plastic to prevent dehydration.

According to standard NEN-EN 196-1:2005, the test must be carried out after 28 days of curing, with a limit of ± 8 hours, to determine the strength properties of the hardened concrete. Because not every test series was tested after 28 days of curing, the mortar prisms were also not always tested after 28 days.

A total of 34 mortar prisms were tested on the days the direct tensile tests were carried out. The names of the mortar prisms consist of three parts. The first part is the number of the test series of the direct tensile tests, the second part is the number of the print session (s1, s2 or s3), and the third part is the serial letter (A, B or C).

3.6.1 Density

Figure 3.14a illustrates three mortar prisms. The prisms were first tested on flexure, causing the crack in the middle of the prism, thereafter tested on compression, causing the crack on the left side of the specimen. Figure 3.14b gives the average density of the mortar prisms on the different test days.

Figure 3.14b shows that the density of the mortar prisms of print session 1 (1_s1) is relatively low in comparison with the other results. The mortar prisms of print session 1 were not directly molded after the material was collected. Because of the fast curing time, the density and other material properties of this mortar prisms may be influenced. In addition, the pump temperature during print session 1 was lower than the pump temperature during print sessions 2 and 3, see figure 3.9. The lower pump temperature of print session 1 indicates that there was less friction in the pump and possibly less compaction of the material in the pump. This also may influence the results.

The average density of the prisms from print session 2 and 3 are comparable with each other. The average density of print sessions 1, 2 and 3 are 2009 kg/m$^3$, 2081 kg/m$^3$ and 2071 kg/m$^3$ respectively. The total average density is 2065 kg/m$^3$.
3.6.2 Flexural strength

Figure 3.15a (Doomen, 2016, p. 26) shows the flexure test on a mortar prism. Figure 3.15b gives the average results of the flexural strengths per test series. The differences in flexural strength are relatively small. The average flexural strengths per print session are 4.97 MPa for print session 1, 5.48 MPa for print session 2 and 5.43 MPa for print session 3. The average value for print session 1 is slightly lower, possibly due to the same reasons mentioned in section 3.6.1. The total average flexural strength is 5.37 MPa.

3.6.3 Compressive strength

Figure 3.16a (Doomen, 2016, p. 27) shows the compressive test on a mortar prism. After the flexure test, one side of the mortar prism is used for the compressive strength. Figure 3.16b gives the average results of the compressive strengths per test series. Also for the compressive strength, the results of the tests are comparable. Average compressive strengths for the print sessions are 29.96 MPa for print session 1, 31.95 MPa for print session 2 and 29.30 MPa for print session 3. The total average compressive strength is 30.66 MPa.
4 Experimental results

The results of the direct tensile tests will be discussed in this section. Multiple test series have been carried out to obtain the mechanical properties of printed concrete. The results of test series 1 to 7 are discussed here. Additional test series 8 is discussed in section 4.3.3. An overview of the properties of the specimens can be found in appendix C. Results per experiment, as well as load-deformation-, stress-strain- and stress-crack opening diagrams per experiment can be found in appendix F.

4.1 Tensile strength

The average tensile strengths and the range (i.e. smallest and largest value) of the different test series can be found in figure 4.1. Specimens of test series 1 and 7 were carried out on the test setup with non-rotating-, and rotating loading platens. The other test series were carried out the test setup with non-rotating loading platens.

![Average tensile strength](image)

**Figure 4.1 Average tensile strength and range per test series.**

4.1.1 Deformation rate

As mentioned before, the deformation is controlled by the average of the four LVDT’s. At test series 1, with non-rotating loading platens, a deformation rate of 10 µm/min was applied. With this deformation rate, the specimens failed after about 50 seconds after the start of the test. At test series 2 to 7 with non-rotating loading platens, a deformation rate of 5 µm/min was applied whereby the specimens failed after about 100 seconds.

A part of test series 1 and 7 was carried out with rotating loading platens. At test series 1 with rotating loading platens (test 1_4_0d_8 to 1_4_0d_12), the deformation was controlled by the test bench with the same rate of the experiments from Doomen (2016) so that results can be compared. The applied deformation rate of the test bench was 100 µm/min whereby specimens failed after about 200 seconds. Due to a larger deformation of the test bench in comparison with the LVDT’s, the deformation rate of the test bench is much higher.

At test series 7 with rotating loading platens (7_1_0d_7 to 7_1_0d_12), the deformation rate was adapted due to a different measuring length of the LVDT’s (see figure 3.5). A rate of 2.5 µm/min was applied. This resulted in a failure of the specimen after about 120 seconds. After the peak, the deformation rate of all tests was increased to accelerate the experiments.

Figure 4.1 shows that there is no significance difference in the average tensile strength of test series 1, 2, and 3, while the deformation rate of test series 1 was two times higher than the deformation rate of test series 2 and 3. It can be concluded that the deformation rate has no significance influence on the tensile strength.
4.1.2 Statistical analysis

Combining the test series with similar specimens results in larger sample sizes whereby a more reliable result is obtained. However, tests were carried out on different days, sometimes with different deformation rates and sometimes specimen were printed on different days. Therefore, the results must be examined before test series can be combined. This was done by the Shapiro-Wilk test and by studying Q-Q plots. These tools can determine if the test series came from a normal distributed population and if results are comparable. From the Shapiro-Wilk test can be concluded, with a significance level of $\alpha = 0.05$, that the test series are not significantly different from a normal distribution. Therefore, normality is assumed. A discussion and the results the Shapiro-Wilk test can be found in appendix D.

A graphical reproduction of normality can be given with Q-Q plots. These plots also can compare results. Test series 1, 2 and 3 are similar, each containing specimens with four layers, printed without significant time interval and tested with non-rotation loading platens. However, test series 1 and 2 were printed on a different day than test series 3 and there is a difference in curing age at the time of testing. Test series 1, 2, and 3 were tested with a curing age of 28 days, 33 days, and 27 days respectively. Figure 4.2a illustrates Q-Q plots from test series 1, 2 and 3. The results and slopes of the plots of the test series are comparable. Therefore, the tensile strengths of test series 1, 2 and 3 can be combined in one test series, Figure 4.2b illustrates the Q-Q plot of this combined test series.

Test series 4 and 7 are also similar. The specimens from both test series have one printed layer of concrete, but are printed on different days. Test series 4 and 7 were tested with a curing age of 28 days of 29 days respectively. These test series can also be combined after studying the Q-Q plot. The Q-Q plots of all test series can be found in appendix D.

Figure 4.3 and table 4.1 showing average tensile strengths of the specimen types after combining several test series. Names of the specimen types consists of the number of layers followed by the time interval in days.

![Figure 4.2 Q-Q plot of average tensile strength of (a) test series 1, 2 and 3 and (b) test series 1, 2 and 3 combined.](image)

![Figure 4.3 Average tensile strength and range per specimen type.](image)

### Table 4.1 Average tensile strengths

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Tensile strength $f_t$ [MPa]</th>
<th>Standard deviation [MPa]</th>
<th>Density $\rho$ [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1_0d</td>
<td>1.49</td>
<td>0.11</td>
<td>1983</td>
</tr>
<tr>
<td>1_0d rotating</td>
<td>1.19</td>
<td>0.16</td>
<td>1944</td>
</tr>
<tr>
<td>2_0d</td>
<td>1.48</td>
<td>0.16</td>
<td>1963</td>
</tr>
<tr>
<td>4_0d</td>
<td>1.36</td>
<td>0.13</td>
<td>1966</td>
</tr>
<tr>
<td>4_0d rotating</td>
<td>1.08</td>
<td>0.16</td>
<td>1966</td>
</tr>
<tr>
<td>4_7d</td>
<td>0.76</td>
<td>0.19</td>
<td>1984</td>
</tr>
</tbody>
</table>
The density of the different specimen types can also be found in Table 4.1. As expected, no significance difference in density between the specimen types is found. The average density of all specimens is 1969 kg/m$^3$. Compared to the average density of the mortar prisms, a decrease of only 5 percent was found. This decrease in density is due to the printing process.

Figure 4.4 illustrates stress – deformation relations of different tests that are representative for their type of tests. The pre-peak behavior of experiments ‘4_0d rotating’ could not be described because the deformation was controlled by the test bench, this is discussed in appendix A. The post-peak behavior of ‘1_0d rotating’ is very rough due to a non-uniform crack opening (see figure 3.2a) and is therefore not suitable for obtaining the fracture energy. It can be seen from figure 4.4 that the stiffness of the experiments with rotating loading platens is higher than the stiffness of the experiments with non-rotating loading platens. This is discussed in section 4.3.

\[ \text{Stress - deformation relation of representative tests} \]

\[ \sigma \] [MPa] \hspace{1cm} \[ \delta \] [µm]

\[ \text{1_0d rot.} \hspace{1cm} \text{1_0d} \hspace{1cm} \text{2_0d} \hspace{1cm} \text{4_0d} \hspace{1cm} \text{4_0d rot.} \]

\[ \text{Figure 4.4 Stress – deformation relations of tests that are representative for their type of test.} \]

4.1.3 Comparing rotating and non-rotating loading platens

Experiments on specimens with 1 and 4 layers were carried out on the test setup with non-rotating and rotating loading platens, see figure 4.5. Figure 4.3 shows that the tensile strength of specimens carried out on the test setup with rotating loading platens is lower. Specimens with 1 layer have average tensile strengths of 1.49 MPa and 1.19 MPa when tested with rotating and non-rotating loading platens respectively. For specimens with 4 layers, the average tensile strengths are 1.36 MPa and 1.08 MPa respectively. In both cases, this is a decrease of 20 percent in tensile strength. During the tests, the deformation of specimens with 1 layer were controlled by the LVDT’s while the deformation of specimens with 4 layers were controlled by the test bench, causing a difference in deformation rate. It seems that the deformation rate had no influence on the results because the decrease in tensile strength is in both cases comparable.

\[ \text{Figure 4.5 Tensile tests on specimen with 4 layers with (a) non-rotating loading platens and (b) rotating loading platens.} \]
An explanation of the decrease in tensile strength may be the eccentricity in the applied load causing rotating of the loading platens. Due to rotating of the loading platens, compressive stresses on one side and tensile stresses on the other side of the specimen occurs, causing failure at a lower measured tensile strength. Figure 4.6 illustrates the influence of the eccentricity on the tensile strength. Both specimens were tested with rotating loading platens.

Figure 4.6 illustrates the influence of the eccentricity on the tensile strength. Both specimens were tested with rotating loading platens.

**Figure 4.6 Stress-deformation diagram of two tests with rotating loading platens with (a) a large eccentricity and a relatively low tensile strength and (b) a small eccentricity and a relatively high tensile strength.**

Figure 4.6a shows a large eccentricity whereby the left side of the specimen (LVDT 6) is subjected to compressive stresses. Due to a continues crack pattern (the fracture process zone) that is formed after 70 to 90 percent of the ultimate tensile load (Neville, 2012), more rotation in the loading platens occur and the deformation increases (or decreases in the case of compressive stresses) with no (or a very small) increase in stress. The ultimate tensile strength of the specimen from figure 4.6a is 0.90 MPa and is significant lower than the ultimate tensile strength of the specimen from figure 4.6b with a tensile strength of 1.36 MPa, whereby the eccentricity is very small (figure 4.6b). The tensile strength of the specimen from figure 4.6b is comparable with the average tensile strength of specimens with 4 layers tested with non-rotating loading platens. This suggests that rotating loading platens may have a large influence on the measured tensile strength. When rotating of the loading platens is retained, no (or a very small) eccentricity occurs whereby the measured tensile strength increases.

Doomen (2016) carried out experiments with rotating loading platens and found an average tensile strength of 1.32 MPa for specimens with 4 layers. This is higher than the average tensile strength found in this research (1.08 MPa). A lot of variables during printing, curing and testing may influence the result and therefore it is difficult to explain the cause of this difference.

### 4.1.4 Bulk material and interface

Specimens with and without interface were tested to determine the influence of the interface on the tensile strength. Figure 4.3 shows that the tensile strength of the specimens with 4 layers is lower than the tensile strength of specimens with 1 layer. However, the tensile strength of specimens with 4 layers is only 9 percent lower. There is also a difference in the crack surface of both specimens, see figure 4.7. The crack surface of the specimen with 4 layers (figure 4.7a) is smoother than the crack surface of the specimen with 1 layer (figure 4.7b). This surface is very rough and the weakest section is clearly not the smallest section. Figure 4.7a shows that the weakest section is the interface, or nearby the interface. Still a small roughness can be seen which may indicate that the specimen did not completely fail on the interface but failed on a combination of the interface and the bulk material due to the variance in the interface strength and bulk material strength. As a result, at each point in the fracture process zone, the weakest link of the interface and bulk material is chosen.
Chapter 4 Experimental results

Figure 4.7 crack surface of (a) a specimen with 4 layers and (b) a specimen with 1 layer.

Figure 4.8 illustrates the normal distributions of the tensile strength of specimens with 1 layer (1_0d), specimens with 2 layers (2_0d), specimens 4 layers (4_0d), and specimens with 4 layers with a 7-day interval (4_7d). The variance in tensile strength of specimens with 1 layer (1_0d) is smaller, related to the variance in tensile strength of specimens with 4 layers (4_0d).

Specimens with 2 layers (printed with the same nozzle as the specimen with 1 layer) were tested to determine if the tensile strength differs from the tensile strength of specimen with 4 layers. It turns out that the tensile strength of specimens with 2 layers is not significant lower than the tensile strength of specimens with 1 layer. However, the variation of specimens with 2 layers is larger, see figure 4.8.

Figure 4.9 illustrates the crack surface of specimens with 2 layers. Approximately half of the specimens with 2 layers did not fail on the interface, but failed on the bulk material of a combination of both. Figure 4.9a illustrates a specimen that failed on the interface while figure 4.9b illustrates a specimen that failed on the bulk material (or a combination of both). A possible explanation for the crack behavior and the small difference in tensile strength between specimens with 1 layer and 2 layers may be due to the weight of the second layer of the specimens with 2 layers (see figure 3.12a and 3.12d). The layers are possibly pressed together whereby the tensile strength of the interface of specimens with 2 layers increases.
4.1.5 Comparing print interval of 0 days and 7 days

Printing with a time interval between the layers may have a large influence on the tensile strength, depending on the print time between the layers and the curing time of the concrete. With an interval of 7 days, it may be assumed that the new layers of concrete are printed on cured concrete. The tensile strength of the interface with an interval of 7 days is 0.76 MPa, this is 56 percent of the tensile strength of specimens with 4 layers without interval. The normal distribution of the tensile strength of specimens with 4 layers with- and without time interval can be found in figure 4.8.

Figure 4.10 illustrates the crack surface of specimens with 4 layers with- and without time interval. The crack surface of the specimen without time interval (figure 4.10a) is probably a combination between interface and bulk material as discussed before. The crack surface of the specimen with a time interval of 7 days (figure 4.10b) is very smooth and obviously failed completely on the interface.
4.2 Fracture energy

The fracture energy was calculated from the results of the tests. This was done by calculating the area below the stress – crack opening relation, see figure 2.1c. Regularly, the peak of the stress-deformation branch was relatively width; this can be seen in figure 4.4. Therefore, it was sometimes difficult to determine the exact peak of the stress-deformation relation and thus to calculate the fracture energy. The results can be found in figure 4.11 and in table 4.2. The average tensile strengths are added to table 4.2 for the sake of completeness.

4.2.1 Average results

There is no significance difference in fracture energy and tensile strength of specimens with 1 layer and 2 layers (1_0d and 2_0d respectively). The fracture energy of specimens with 4 layers (4_0d) is 30 percent lower than the fracture energy of specimens with 1 layer. This implies that the interface has a large influence on the fracture energy. Possibly, there are less aggregates at the interface due to the printing process. Aggregates may have a large influence on the fracture energy, as discussed in section 2.3.2.

The fracture energy of specimens with 4 layers with an interval of 7 days between the layers (4_7d) decreases with 78 percent with respect to specimens with 4 layers without time interval (4_0d).

Table 4.2 Average tensile properties

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Fracture energy $[J/m^2]$</th>
<th>Tensile strength $[MPa]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1_0d</td>
<td>30.99</td>
<td>1.49</td>
</tr>
<tr>
<td>2_0d</td>
<td>32.98</td>
<td>1.48</td>
</tr>
<tr>
<td>4_0d</td>
<td>21.46</td>
<td>1.36</td>
</tr>
<tr>
<td>4_7d</td>
<td>4.71</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Figure 4.11 Average fracture energy and range per specimen type.

4.2.2 Crack behavior

Figure 4.11 shows a large variation in the results. The crack behavior of specimens with 1 layer is analyzed to find out if there is a relation between the crack behavior and the fracture energy. A total of 16 experiments were carried out on specimens with 1 layer. The lowest and highest value for the fracture energy that was found is 20.1 J/m$^2$ and 43.6 J/m$^2$ respectively. Figure 4.12 illustrates the crack surface of specimens with a relatively low fracture energy (20.1 and 20.9 J/m$^2$). Figure 4.13 illustrates the crack surface of specimens with a relatively high fracture energy (42.9 and 43.6 J/m$^2$). The crack surface of the specimens of figures 4.12 and 4.13 have a comparable inclination. However, the crack surface of the specimens with a relatively low fracture energy are smoother than the crack surface of specimen with a relatively high fracture energy. This indicates that the crack surface has an influence on the fracture energy. When the crack surface is rough, the ductility of concrete increases. This confirms the influence of aggregate size on the fracture energy, as discussed in section 2.3.2.

Figure 4.14 illustrates the stress – deformation relation of specimens from figures 4.12 and 4.13. For specimens with a smooth crack surface (figure 4.12), the descending branch lies lower related to the descending branch of specimens with a rough crack surface (figure 4.13). There was no correlation found between the tensile strength and fracture energy of individual specimens. i.e., a relatively high tensile strength did not necessarily result in a relatively high fracture energy and vice versa. This can be seen in figure 4.14, where the tensile strength of specimen 7_1_0d_4 is lower than the other specimens from figure 4.14, while the fracture energy is higher than the fracture energy of specimens 4_1_0d_04 and 4_1_0d_11.
Influence of the interface between layers on the tensile properties of 3D printed concrete

Figure 4.12 Crack surface of specimens with a relatively low fracture energy, with (a) $G_F = 20.1 \text{ J/m}^2$ and (b) $G_F = 20.9 \text{ J/m}^2$.

Figure 4.13 Crack surface of specimens with a relatively high fracture energy, with (a) $G_F = 42.9 \text{ J/m}^2$ and (b) $G_F = 43.6 \text{ J/m}^2$.

Figure 4.14 Stress – deformation relation of specimens with 1 layer.
4.3 Modulus of elasticity

As mentioned in section 2.4, the modulus of elasticity of concrete can be experimental obtained from a direct uniaxial tensile test and a uniaxial compressive test.

4.3.1 Tensile test series 1 to 7

The modulus of elasticity is determined from the stress – strain relation of tensile tests, by taking 10 percent and 40 percent of the tensile strength. The LVDT’s are also measuring small deformations of the glue layers, the steel blocks, and the loading platens. The strain is calculated by taking the height of the specimens whereby the deformation of the glue layers, steel blocks, and loading platens is neglected. The results can be found in figure 4.15 and table 4.3.

The average modulus of elasticity of tests with rotating loading platens on specimens with 1 layer and specimens with 4 layers are 17444 MPa and 28069 MPa respectively. There was one difference in test method between these test series: the deformation during the test of test series 1_0d rotating was controlled by the test bench while the deformation of test series 4_0d rotating was controlled by the LVDT’s, see section 4.1.1. This difference may have influenced the measured modulus of elasticity. The variation of the modulus of elasticity from tests carried out with rotating loading platens are larger than the variation from non-rotating loading platens.

The modulus of elasticities of specimens carried out with non-rotating loading platens are significant lower compared to the modulus of elasticities of specimens carried out with rotating loading platens. However, there is no significance difference in the modulus of elasticity between the test series that were carried out with non-rotating loading platens. This suggests that the type of specimen has no influence on the modulus of elasticity. The average modulus of elasticity of the tests with non-rotating loading platens is 11282 MPa.

![Figure 4.15 Average modulus of elasticity and range per specimen type.](image)

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Modulus of elasticity E [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1_0d</td>
<td>11823</td>
</tr>
<tr>
<td>1_0d rotating</td>
<td>17444</td>
</tr>
<tr>
<td>2_0d</td>
<td>11103</td>
</tr>
<tr>
<td>4_0d</td>
<td>11393</td>
</tr>
<tr>
<td>4_0d rotating</td>
<td>28069</td>
</tr>
<tr>
<td>4_7d</td>
<td>10556</td>
</tr>
</tbody>
</table>

Doomen (2016) determined the modulus of elasticity of the same material from compressive tests and direct tensile tests with rotating loading platens on specimen of 40*40*40 mm³. From the compressive tests, values around 4500 MPa were found. From the direct tensile tests perpendicular to the interface, values between 14300 – 27300 MPa were found (Doomen, 2016). Like the results with rotating loading platens from figure 4.14, the variation in modulus of elasticity from the results of Doomen (2016) is relatively large.

Because of the large variation in modulus of elasticity of tests carried out with rotating loading platens and the significant lower modulus of elasticity of tests carried out with non-rotating loading platens, a clear value for the modulus of elasticity cannot be determined based on the uniaxial tensile tests. Reasons that possibly causing the difference in modulus of elasticity are the influence of the notches from the specimens and the difference in measuring length of the LVDT’s of the test setup with non-rotating- and rotating loading platens, see figure 3.4 and 3.5. The measuring length of the LVDT’s with non-rotating loading platens is larger whereby a lower stiffness is measured. In section 3.3.3, the influence of the loading platens on short specimens is discussed. This may also influence the measured stiffness, but the difference in stiffness between tests carried out with non-rotating- and rotating loading platens is thereby not explained.
4.3.2 Cylinder compressive tests

To determine the modulus of elasticity, experiments on cylinders were carried out according to standards NEN-EN 12390-1, NEN-EN 12390-2 and NEN-EN 12390-13. The cylinders have a diameter of 100 mm and a length of 250 mm.

The cylinders were, due to the printing process, fabricated in an alternative manner than described in the standard NEN-EN 12390-1. The material was mixed and pumped by the 3D printer and collected at the end of the hose. The steel molds were filled half and compacted for 10 seconds on a vibrating table. After that, the molds were filled completely and again compacted for 10 seconds. The molds were covered with plastic to prevent dehydration. After about 24 hours, the molds were removed and the specimens were placed in water with a temperature of 22 °C (NEN-EN 12390-2). After 28 days of curing, the specimens were taken out of the water and the nuts for mounting the LVDT’s were glued on the surface of the specimens. A total of four LVDT’s were used for measuring the deformation during the test. The measuring length of the LVDT’s was around 60 mm and the LVDT’s were placed on the middle section of the specimens.

A total of 5 experiments were carried out to obtain the modulus of elasticity, named E1 to E5. The experiments were carried out in The Structures Laboratory Eindhoven. The testing system that is used for the experiments was a hydraulic test bench with a load cell of 2.5 MN.

At 3 experiments, two load cycles were carried out, see figure 4.16. For the first load cycle, the deformation rate of the test bench varied from 0.1 mm/min for the first test, to 0.3 mm/min for second to fifth test. For the second load cycle, the applied deformation rate was 0.8 mm/min. With this deformation rate the specimens failed after about 90 seconds.

Modulus of elasticity

Figure 4.16 illustrates the stress – strain relation of test E1. From this figure, the initial- and second modulus of elasticity can be found. The modulus of elasticity is calculated between 15 and 40 percent of the cylindrical compressive strength and is defined by:

\[ E_0 = \frac{\Delta \sigma}{\Delta \varepsilon} = \frac{\sigma_b - \sigma_a}{\varepsilon_a - \varepsilon_b} \]

For the initial modulus of elasticity

\[ E_1 = \frac{\Delta \sigma}{\Delta \varepsilon} = \frac{\sigma_b - \sigma_a}{\varepsilon_a - \varepsilon_b} \]

For the second modulus of elasticity

![Figure 4.16 Stress – strain relation of cylinder E1 with two load cycles.](image-url)
The results of the cylindrical compression tests can be found in table 4.4. For comparing the results with the direct tensile tests, the initial modulus of elasticity is taken because at the direct tensile tests, only one load cycle is carried out. For sake of completeness, the second modulus of elasticity of the cylindrical compressive tests is also given in table 4.4.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Density $\rho$ [kg/m$^3$]</th>
<th>Cylinder strength $f_{c,cyl}$ [MPa]</th>
<th>Initial modulus $E_0$ [MPa]</th>
<th>Second modulus $E_1$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>2028</td>
<td>23.73</td>
<td>17106</td>
<td>20970</td>
</tr>
<tr>
<td>E2</td>
<td>2025</td>
<td>23.31</td>
<td>18000</td>
<td>-</td>
</tr>
<tr>
<td>E3</td>
<td>2036</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>E4</td>
<td>2032</td>
<td>20.77</td>
<td>18256</td>
<td>23664</td>
</tr>
<tr>
<td>E5</td>
<td>2024</td>
<td>24.84</td>
<td>15981</td>
<td>21388</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>2029</strong></td>
<td><strong>23.16</strong></td>
<td><strong>17336</strong></td>
<td><strong>22007</strong></td>
</tr>
</tbody>
</table>

From the direct tensile tests with non-rotating loading platens, an average modulus of elasticity of 11282 MPa was found. Compared to the initial modulus of elasticity of the cylindrical compressive tests of 17336 MPa, this is a decrease of 35 percent. This concludes that the measured modulus of elasticity of the direct tensile tests with non-rotating loading platens is significant lower.

A third load cycle should be carried out to determine the stable modulus of elasticity. In general, a small difference is found between the second modulus of elasticity and the stable modulus of elasticity (NEN-EN 12390-13).

**Compressive strength cylinders**

The compressive strength of the cylinders can be found in table 4.4. The average cylinder compression strength is lower than the average compression strength of the mortar prisms (section 3.6.3). This can be explained by size effect, i.e. the size of the specimen. According to Van Boom and Kamerling (1978), an important cause of this effect is the influence of the loading platens. When a cube (in this case, a mortar prism of 40*40*40 mm$^3$) is subjected to a compressive load, friction between the loading platens and the cube provides resistance against lateral expansion. Because of this resistance, a relatively high compressive strength is measured (Van Boom & Kamerling, 1978). Due to the height of the cylinders, the friction of the loading platens does not affect the middle zone of the specimen. Other causes of size effect can be the ratio between the specimen size and the aggregate size and difference in temperature and humidity between the core and the surface of the specimen which causes internal stresses (Neville, 2012).

When the cylinder compressive strength does not exceed 50 MPa, the relation between the compressive strength of cubes and cylinders can be defined by (Neville, 2012):

$$f_{c,cyl} = 0.8 \cdot f_{c,cube}$$

This formula can be used for validation of both compressive tests. Applying this formula with average cube compressive strength from section 3.6.3 gives the following result:

$$f_{c,cyl} = 0.8 \cdot 30.66 = 24.53 \text{MPa}$$

The difference between this calculated value and the average cylindrical compressive strength of 23.16 MPa from table 4.4 is relatively small.
4.3.3 **Tensile test series 8**

As discussed in section 4.3.1, the measuring length of the LVDT’s with the test setup with non-rotating loading platens may have an influence on the relatively low modulus of elasticity. The modulus of elasticity from the test setup with non-rotating loading platens and from the cylinder compressive tests are 11282 MPa and 17336 MPa respectively. To find out if the measuring length has influence on the measured stiffness, an additional test series was carried out with non-rotating loading platens whereby the measuring length was adapted. Figure 4.17 illustrates the difference in measuring length between test series 1 to 7 and additional test series 8. The current measuring length measures between the loading platens (figure 4.17a), while the adapted measuring length measures between the glued steel blocks (figure 4.17b). Due to this adjustment, the deformation of the loading platens does not affect the LVDT’s anymore. Like the test setup with rotating loading platens, the glue layers and a small part of the steel blocks may still affect the LVDT deformation.

![Figure 4.17 Change of measuring length, with the measuring length of (a) test series 1 to 7 and (b) test series 8.](image)

A total of 8 tests were carried out in test series 8. The first 4 tests were carried out whereby LVDT’s 11 and 12 (front and back) were positioned between the loading platens, and LVDT’s 6 and 7 (left and right) were positioned between the glued steel blocks. Figure 4.18 illustrates the difference between the LVDT’s by means of a stress – deformation relation. The strain is calculated by taking the height of the specimen. Table 4.5 shows the modulus of elasticity of both measurements. Figure 4.18 shows that the modulus of elasticity increases when the LVDT’s measure between the steel blocks (figure 4.17b). Because of the high stiffness of the loading platens, it was assumed that the position of the LVDT’s from figure 4.17a would not influence the results. Because of the adapted measuring length from figure 4.17b, the average measured modulus of elasticity was increased with about 34 percent. The measuring length of the LVDT’s had a much greater influence on the results than expected.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Modulus of elasticity (LVDT’s 11, 12) [MPa]</th>
<th>Modulus of elasticity (LVDT’s 6, 7) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8_4_od_01</td>
<td>10927</td>
<td>14084</td>
</tr>
<tr>
<td>8_4_od_02</td>
<td>12084</td>
<td>15202</td>
</tr>
<tr>
<td>8_4_od_03</td>
<td>11455</td>
<td>16219</td>
</tr>
<tr>
<td>8_4_od_04</td>
<td>11968</td>
<td>16636</td>
</tr>
</tbody>
</table>

![Figure 4.18 stress – strain relation of test 8_4_od_03 with different measuring lengths.](image)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Modulus of elasticity (all LVDT’s) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8_4_od_05</td>
<td>15958</td>
</tr>
<tr>
<td>8_4_od_06</td>
<td>16097</td>
</tr>
<tr>
<td>8_4_od_07</td>
<td>13935</td>
</tr>
<tr>
<td>8_4_od_08</td>
<td>15962</td>
</tr>
</tbody>
</table>

The last 4 tests were carried out with all the LVDT’s positioned between the glued steel blocks, see figure 4.17b. Table 4.6 shows the results of these tests. The average modulus of elasticity with the adapted measuring length is 15512 MPa.
4.3.4 Discussion

The modulus of elasticity from test series 8 is still lower than the initial modulus of elasticity from the cylindrical compressive tests with 17336 MPa. This difference may be explained by the glue layers and the small part of the steel blocks that is still measured by the LVDT’s and by the notches of the specimens. The deformation of an elastic body can be defined as:

$$\Delta L = \frac{FL}{EA}$$

When a body consists of parts with different loads, lengths, modulus of elasticities, and/or surfaces, the parts can be added together to calculate the total deformation. Because only the length and modulus of elasticity of the parts differ from each other and the total modulus of elasticity is calculated, this can be defined as:

$$\frac{L_{tot}}{E_{tot}} = \frac{L_{specimen}}{E_{specimen}} + \frac{L_{glue}}{E_{glue}} + \frac{L_{steel}}{E_{steel}}$$

Where $E_{tot}$ the total modulus elasticity is and $L_{tot}$ the length of the specimen. The load and surface are excluded from the formula because these are the same for each part. For the specimen length, a value of 40 mm is chosen with a modulus of elasticity of 17336 MPa (from the cylinder compressive tests). For the glue layers, a total thickness of 1 mm is chosen with a modulus of elasticity of 5000 MPa (Hoffman, 1996). For the steel blocks, a total thickness of 14 mm is chosen (per steel block about 7 mm) with a modulus of elasticity of 210000 MPa. The thickness of the glue layer and steel blocks was for every test different, but it is believed that a good approximation is made. For the total length, a value of 40 mm is chosen. This length is also used for calculating the modulus of elasticity from the experiments. This results in:

$$E_{tot} = \frac{40}{\left(\frac{40}{17366} + \frac{1}{5000} + \frac{14}{210000}\right)} = 15564 \text{ MPa}$$

The result of this calculation is very close to the average modulus of elasticity of test series with 15512 MPa, while for concrete the modulus of elasticity from the cylinder compressive tests with 17366 MPa is used. From this calculation can be seen that the influence of the glue layer and the steel blocks is relatively large. This calculation also proofs that the initial modulus of elasticity obtained from the cylindrical compressive tests is the right value.

The influence of measuring over the loading platens is larger than before was believed. This can be seen from the results from the direct tensile tests. The modulus of elasticity from tests whereby the LVDT’s measured between the loading platens (4.17a) and between the glued blocks (4.17b) are 11282 MPa and 15512 MPa respectively, while the initial modulus of elasticity from the cylindrical compressive tests is 17336 MPa.

The influence of rotating loading platens on the modulus of elasticity is hereby not explained. The relatively high modulus of elasticity of these tests (17444 MPa and 28069 MPa) are possibly due to rotating of the specimen during the test but a reasoned explanation was not found.
5 Numerical research

From the experimental research, tensile properties and crack surfaces were obtained. Figure 5.1 illustrates the crack surface of 3 representative specimens. Crack surfaces of specimens with 1 layer (figure 5.1a) and 4 layers (figure 5.1b) are very non-uniform while the crack surface of the specimen with 4 layers with a time interval of 7 days (figure 5.1c) is very smooth.

These types of specimens were modeled with the Finite Element Method (FEM) to reproduce the crack behavior and crack surface of the different specimens. This is done to get a better understanding of the crack behavior of printed concrete. This model can describe discrete cracking. Graphical user interface Abaqus 6.12-3 is used for this numerical research.

![Figure 5.1 Crack surface of specimens with (a) 1 layer, (b) 4 layers without time interval and (c) 4 layers with time interval of 7 days.](image)

The non-uniform crack surface of figure 5.1a and 5.1b suggests that there is variation in the tensile properties of the material because the specimens did not fail on the smallest section. This variation can also be seen in the tensile strengths of the specimens (figure 4.3 and figure 4.8). The variation in tensile strengths from figure 4.8 is given to the cohesive elements as described in this chapter to obtain comparable crack surfaces from the FEM simulations and from the experiments. The cohesive elements are given a constant value for the fracture energy.

5.1 Discrete cracking

There are two different ways of modeling discrete cracking in Abaqus: by means of the Extended Finite Element Method (XFEM) and by means of a Cohesive Zone Model (CZM) (Cid Alfaro, Suiker & de Borst, 2010). From benchmark studies, carried out by Schoenmakers (2013), it was concluded that the theoretical crack pattern was better described with a CZM. The CZM is based on the “Fictitious Crack model” (Hillerborg et al., 1976), see section 2.1.

There are two methods of modeling bond properties with a CZM in Abaqus: with cohesive surfaces, whereby the bond properties are assigned to a surface between the continuum elements, and with cohesive elements, whereby the bond properties are assigned to a cohesive element (Schoenmakers, 2013). Schoenmakers (2013) concluded after a benchmark study that a CZM with cohesive elements gives a more accurate result. Cohesive elements can be used with and without a physical thickness. For elements with physical thickness, the calculation time is significantly shorter. (Schoenmakers, 2013).

A CZM with cohesive elements with a physical thickness is used for modelling the bond between the concrete layers.
5.2 Cohesive Zone Model

A Cohesive Zone Model consists of continuum elements and cohesive elements. The cohesive elements describe the bond behavior between the continuum elements. Figure 5.2 illustrates the basic principle of a CZM with cohesive elements with a physical thickness.

Figure 5.2 Basic principle of a Cohesive Zone Model, with continuum and cohesive elements.

Figure 5.2a illustrates schematically a 2D model, in this case the section of a specimen with 4 layers. Figure 5.2b is an enlargement part with continuum elements and cohesive elements. The cohesive elements can be divided in bulk elements and interface elements. The cohesive bulk elements describe the bond behavior of the material while the cohesive interface elements describe the bond between the layers. The bond is described by a traction separation diagram, see figure 5.3. To the peak, the material behaves linear elastic. At the peak, damage is initiated. From this point, damage is evolving with a decreasing stress to the point where the damage is complete and no stress can be taken anymore.

Figure 5.3 Traction – separation diagram with linear softening.

Figure 5.4 illustrates 3 main directions: normal- (mode I), shear parallel- (mode II), and shear perpendicular direction (mode III). In the case of a 3D model, the traction – separation relation must be defined for these 3 directions. For a 2D model, only mode I and mode II must be defined.

Figure 5.4 Main stress directions Mode I, Mode II, and Mode III.
5.2.1 Damage initiation

There are 4 different damage initiation criteria available in Abaqus 6.12-3. These criteria can be distinguished by stress criterion and strain criterion. The applied damage law is named QUADS and is defined as (Abaqus User manual):

\[
\left( \frac{t_n}{t_0^n} \right)^2 + \left( \frac{t_s}{t_0^s} \right)^2 + \left( \frac{t_t}{t_0^t} \right)^2 = 1
\]

Where \( t \) represents the value of the actual stress, \( t_0 \) represents the value of the peak stress and subscript \( n, s \) and \( t \) represent the normal and the two shear directions (see figure 5.4). This criterion is stress based whereby damage is initiated when the quadratic interaction function reaches a value of 1 (Abaqus User manual). This damage law is chosen for its stress based criterion and because it relates the different directions to each other.

5.2.2 Damage evolution

After initiation, damage start to evolve. This damage evolution can be defined as (Abaqus User’s Manual):

\[
t_n' = \left( 1-D \right) \cdot \overline{t}_n, \quad \overline{t}_n \geq 0
\]

\[
t_s' = \left( 1-D \right) \cdot \overline{t}_s
\]

\[
t_t' = \left( 1-D \right) \cdot \overline{t}_t
\]

Where \( \overline{t} \) represents the value of the predicted stress without damage, calculated with the elastic part of the traction – separation behavior with the current stains and \( D \) represents the damage variable. The initial value of the damage variable is 0 (material is undamaged) and evolves to 1 (material is completely damaged). The damage variable for linear softening can be defined as (Abaqus User’s Manual):

\[
D = \frac{v_0 \cdot \left( v_i - v_0 \right)}{v_i \cdot \left( v^s - v_0 \right)}
\]

Where \( v_0, v_i, \) and \( v^s \) represent the values for separation as illustrated by figure 5.3.

Abaqus defines several forms for a combination of stresses in different directions (mixed mode behavior). The applied form for mixed mode behavior is a power law criterion (Abaqus User’s Manual):

\[
\frac{G_n}{G_n^\alpha} + \frac{G_s}{G_s^\alpha} + \frac{G_t}{G_t^\alpha} = 1
\]

Where \( G^\alpha \) represent the critical fracture energy for the main directions and \( \alpha \) is the power, and in this case \( \alpha = 1 \).

5.2.3 User Material

In addition to the standard defined material models by Abaqus, a user material (UMAT) can also be used for the bond behavior of cohesive elements. Cid Alfaro, Suiker, De Borst and Remmers (2009) presented the following formulation for the traction - separation relation:

\[
t_i = \left( 1-d \right) \cdot C_i \cdot v_j - d \cdot C_j \cdot \delta_{ij} \langle v_i \rangle
\]

The available UMAT at the TU/e is based on this formulation. A discussion about this formulation is given by Cid Alfaro et al. (2009). From a benchmark study, it can be concluded that the material model of Abaqus and the UMAT give the same results. This conclusion was also drawn by Schoenmakers (2013).
5.3 2D Cohesive Zone Model

Three different specimens were modeled to describe the crack behavior: specimens with 1 layer, specimens with 4 layers without time interval and specimens with 4 layers with a time interval of 7 days. The 2D model has the same dimensions as the specimens: 40*40 mm² with notches. The nodes on the bottom of the model were supported by hinges. The nodes on the top of the model were given a deformation of 1 mm.

To obtain a non-uniform crack opening in the Cohesive Zone Model, the cohesive elements were given different tensile strengths. This resulted in a variation in tensile strengths and in non-uniform crack openings.

5.3.1 Geometry and mesh

The mesh of a CZM consists of continuum elements and relatively small cohesive elements between the continuum elements. It is not possible to create this type of mesh directly in Abaqus. Schoenmakers (2013) created a Python script that places cohesive elements between continuum elements. This Python script is used for creating the CZM. First, the geometry and meshes were generated with the program Gmsh. The coordinates and elements from the geometry were used as input for the Python script. A discussion about this method and about the Python script is presented by Schoenmakers (2013).

Figure 5.5 illustrates 3 different meshes. The first mesh (figure 5.5a) is a random mesh with cohesive elements with a straight orientation at the location of the interfaces between the layers. With this mesh, a uniform crack was created at the smallest section of the model due to the orientation of the cohesive elements. The variation in tensile strength has no influence on the crack behavior. The second mesh (figure 5.5b) is also a random mesh, but without the straight orientation of cohesive elements. With this mesh, a more non-uniform crack was created due to the variation in tensile strength of the cohesive elements, but the orientation of the cohesive elements had still a large influence on the crack formation. Therefore, it was decided to create a structured mesh (figure 5.5c) whereby the orientation of the mesh had no influence on the crack formation. With this mesh, the crack formation depends on the variation in tensile strength. Because of this mesh, the notches have no circular shape anymore. This shape may result in peak stresses on other places in the section then when a circular shape is applied.

![Figure 5.5 2D model with 3 different meshes](image)

Figure 5.5 2D model with 3 different meshes, (a) random mesh with straight interfaces, (b) random mesh with random interface elements and (c) structured mesh with structured interface

The mesh of figure 5.5c consists of 3510 continuum elements and 5173 cohesive elements. The size of the continuum elements is about 1 mm and is based on the maximum aggregate size in the concrete.
5.3.2  Material properties

The cohesive elements were given different tensile strengths to create non-uniform cracks. Figure 5.6 illustrates the cohesive interface elements that describe the bond between the layers. The other cohesive elements describe the bond in the bulk material. The variation of tensile strength in the cohesive elements is defined by the normal distributions of figure 4.8, whereby:

- The bond in the bulk material is presented by results of specimen type 1_0d
- The bond of the interface without interval is presented by results of specimen type 4_0d
- The bond of the interface with 7-day interval is presented by results of specimen type 4_7d

The material properties of the cohesive elements and the continuum elements are given in table 5.1 and table 5.2 respectively. The cohesive elements are given a variation in tensile strength while a constant value is given for the fracture energy (table 5.1). The continuum elements are given constant material properties (table 5.2).

![Figure 5.6 CZM with 4 layers, with cohesive interface elements colored red.](image)

<table>
<thead>
<tr>
<th>Table 5.1 Material properties cohesive elements</th>
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<tbody>
<tr>
<td>Cohesive elements</td>
</tr>
<tr>
<td>Bulk material</td>
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<tr>
<td>Interface (7-day interval)</td>
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<tr>
<td>Interface (without interval)</td>
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<table>
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<tr>
<th>Table 5.2 Material properties continuum elements</th>
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<tr>
<td>Continuum elements</td>
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</table>

The cohesive elements were given a random tensile strength from a normal distribution by a written Python script. This Python script discretized a normal distribution of the tensile strength in different steps. For each step an element set is created whereby the size of the element set depends on the normal distribution. The cohesive elements are randomly assigned to the element sets. Table 5.1 gives a range on tensile strengths. The element sets were given a tensile strength within this range.

3 different CZM were created:

- 1 layer: This model has no interface. Therefore, all the cohesive elements describe the bulk material.
- 4 layers with 7-day interval: The cohesive interface elements describing the interface with a 7-day interval. The other cohesive elements describing the bulk material.
- 4 layers without time interval: The cohesive interface elements describing the interface without time interval. The other cohesive elements describing the bulk material.

Multiple simulations were carried out with each model. For each simulation, the elements were given tensile strengths with the Python script. Results of the simulations are discussed in the next chapter.
5.4 Results

5.4.1 Cohesive zone model with 1 layer

Figure 5.7 illustrates the crack behavior of a specimen with 1 layer. The blue zones in the figures illustrate the damaged cohesive elements. When the damage is completed, the elements are deleted as can be seen in figure 5.7c. To give a good demonstration of the crack behavior, a scale factor of 2000 and 1500 is applied to the figure 5.7a and 5.7b respectively.

At the peak, a fracture process zone is developed with multiple microcracks (figure 5.7a). After the peak, in the softening branch, a macrocrack runs through the fracture process zone (figure 5.7b). At that point, there is still a remaining stress capacity in the specimen. Finally, the fracture is completed and there is no stress capacity anymore (figure 5.7c). This behavior corresponds with the theory as discussed in section 2.2.1.

Figure 5.7 Crack behavior of the model with 1 layer, with (a) the fracture process zone at the peak load (scale factor 2000), (b) the fracture process zone after the peak load (scale 1500), and (c) the fracture completed.

Figures 5.8 and 5.9 show comparative cracks from the CZM and the experiments that were carried out. Figure 5.8 shows a crack at the top of the notches for both the CZM and specimen 7_1_0d_03 (figure 5.8c). Figure 5.9 shows comparable cracks between the CZM and specimen 7_1_0d_04 (figure 5.9c). This crack runs from the bottom side of the notches at the right to the top of the notches at the left.

Figure 5.8 Crack behavior of the model and a specimen with 1 layer, with (a) the fracture process zone (scale factor 1500, (b) the fracture completed, and (c) the comparative fracture of specimen 7_1_0d_03.
Influence of the interface between layers on the tensile properties of 3D printed concrete

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5.4.2 Cohesive zone model with 4 layers with 7-day interval

Figure 5.10 illustrates the crack behavior of a specimen with 4 layers with a time interval of 7 days between layer 2 and 3. At the peak, the fracture process zone is located only in the middle interface (figure 5.10a). The different tensile strengths between the bulk material and the middle interface are too large to create a fracture process zone in the bulk material. This can also be seen by figure 4.8, where the normal distribution of the 7-day interval is significant lower. It seems that the bulk material remains undamaged. After the peak, a macrocrack runs through the interface (figure 5.10b), followed by a very smooth crack at the middle interface (figure 5.10c). This crack behavior is comparable with the specimens of 4 layers with 7-day interval (figure 5.10d).

Figure 5.10 Crack behavior of the model and a specimen with 4 layers with 7-day interval, with (a) the fracture process zone at the peak load (scale factor 2000), (b) the fracture process zone after the peak load (scale 1500), (c) the fracture completed, and (d) the comparative fracture of specimen 5_4_7d_04.
5.4.3 Cohesive zone model with 4 layers without time interval

Figure 5.11 illustrates the crack behavior of a specimen with 4 layers. At the peak, the fracture process zone is mostly located in the middle interface, but microcrack can also be seen in the bulk material around the interface (figure 5.11a). After the peak, a macrocrack runs through the fracture process zone, located mostly on the interface (figure 5.11b). Finally, the fracture is completed (figure 5.11c). The fracture process zone is smaller than the fracture process zone from a specimen with 1 layer (figure 5.7).

Figures 5.12 and 5.13 show comparative cracks from the models and specimens. Figure 5.12a shows a running macrocrack from left to right. The crack of the model (figure 5.12b) and the specimen (figure 5.12c) are comparable, both failed on a combination of the interface and the bulk material, as discussed in section 4.1.4. Most specimens with 4 layers without interval had a comparable crack surface. Figure 5.13a shows a running macrocrack both from the left and the right to the middle. The crack from this model and specimen (figures 5.13b and 5.13c) is smoother than the crack from figure 5.12.
5.4.4 Discussion

The crack behavior of the model with 1 layer seems to correspond with the theory about fracture as discussed in section 2.2.1. The fracture process zone, followed by macrocracks, and the rough crack surface, were described very accurate by the model.

With the model with 4 layers with 7-day interval, only a small process zone was observed, whereby it seems that the bulk material was not damaged. The fracture process zone was only located in the interface, resulted in a very smooth crack surface. This smooth crack surface was also obtained with the 4-layer model with 7-day interval specimens.

The crack surface of the model with 4 layers without interval was also described very well. The model mostly failed at the interface, but at some points in the bulk material. This is comparable with the crack surface of specimens with 4 layers without interval.

With the average tensile strengths and variances of the interface without interval and of the bulk material obtained from the tests on specimens with 1 layer, the crack surface of the model with 4 layers without interface was also described very well. The model failed mostly at the interface, but at some points in the bulk material, this is comparable with the crack surface of specimens with 4 layers without interval. This implies that the average tensile strength and variance of the bulk material also applies to the specimens with 4 layers. If the average tensile strength of the bulk material of specimens with 4 layers was lower, the model would have failed more on the bulk material, resulting in a rougher crack surface, like figures 5.7, 5.8, and 5.9. If the average tensile strength was higher, the model would have failed only on the interface, like figure 5.10. Both cases do not represent the crack surface of specimens with 4 layers without interval and therefore, it may be assumed that the tensile strengths and variances of the bulk material also applies to the specimens with 4 layers.
6 Conclusions and recommendations

The aim of this research is determining the influence of the interface between the layers on the tensile properties of 3D printed concrete. Therefore, a new test setup for direct tensile tests was developed which remains stable in the post-peak branch whereby the fracture energy can be determined. With the direct tensile test setup, experiments were carried out to obtain material properties. In addition to the direct tensile tests, mortar prisms were tested on flexure and compressive to compare these strength properties from the different print sessions and cylinder compressive tests were carried out to determine the modulus of elasticity. Finally, a numerical analysis on the crack behavior of printed concrete was carried out. Conclusions and recommendations of this research are discussed in this chapter.

6.1 Conclusions

From the results of this research it can be concluded that the printing method Contour Crafting has a large influence on the tensile properties of the printed concrete. First, an overview of the material properties that are obtained in this research are given in the tables below. The conclusions are given thereafter. Table 6.1, 6.2, and 6.3 are giving the material properties of the mortar prism tests, the tensile tests, and the cylinder tests respectively.

<table>
<thead>
<tr>
<th>Table 6.1 Material properties mortar prism tests</th>
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<tbody>
<tr>
<td>Print session</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>S1</td>
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<td>S2</td>
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<td>S3</td>
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<th>Table 6.2 Material properties tensile tests</th>
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<tbody>
<tr>
<td>Specimen type</td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>1_0d</td>
</tr>
<tr>
<td>1_0d rotating</td>
</tr>
<tr>
<td>2_0d</td>
</tr>
<tr>
<td>4_0d</td>
</tr>
<tr>
<td>4_0d rotating</td>
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<td>4_7d</td>
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<table>
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<tr>
<th>Table 6.3 Material properties cylinder tests</th>
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<tr>
<td>Density ρ [kg/m³]</td>
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<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Average</td>
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</tbody>
</table>
6.1.1 Test setup direct tensile test

The developed test setup with non-rotating loading platens resulted in a stable test whereby pre-peak and post-peak behavior can be described. From literature, it was already concluded that the test setup may have a large influence on the material properties, as discussed in section 3.3. The observations that are made from the influence of the test setup on the results of these experiments are described below.

The tensile strengths of tests with rotating loading platens are with a decrease of 20 percent significant lower compared to tensile strengths of tests with non-rotating loading platens. In addition, the variation in tensile strengths increases from tests with rotating loading platens. The most important cause is the eccentricity in applied load caused by macrocracks, followed by fracture on a lower tensile strength. This is discussed in section 4.1.3. Table 6.2 gives the average tensile strengths and variations in the form of standard deviations of the different tests.

The fracture energy of the tests with non-rotating loading platens can be determined due to the stable post-peak branch. Testing with rotating loading platens resulted in unstable post-peak behavior whereby very non-uniform crack openings and deformations occurred. The specimens were partly subjected to compressive stresses due to rotating of the loading platens. Therefore, a realistic value of the fracture energy could not be given from tests with rotating loading platens.

The modulus of elasticity of the direct tensile tests was very low compared to the obtained value from the cylindrical compressive tests. The LVDT’s measured the deformation over specimens, the glue layer and a part of the steel blocks. The influence of the glue layer and steel blocks was larger than believed before. From the discussion in section 4.3.4, it can be concluded that the influence of the glue and steel block is relatively large. A reasoned explanation of the high modulus elasticity from tests with rotating loading platens was not found.

Several deformation rates were used for the direct tensile tests. A change in deformation rate did not show significance differences in the results.

6.1.2 Test procedure

During this research, a lot of attention has been payed to the test procedure of the direct tensile tests. This is important for obtaining reliable experimental results. The test procedure is discussed in appendix B. A reliable gluing procedure was developed whereby only a few specimens failed on the glue layer during testing. This procedure is also discussed in appendix B.

6.1.3 Density

The mortar prisms and cylinders were compacted during molding. This was not the case at the printed specimens for the tensile tests. There is no significance difference in the density of the mortar prisms and cylinders. The density of the printed specimens decreases with about 3 to 5 percent compared to the molded specimens because the printed specimens were not compacted after printing.

6.1.4 Tensile strength

The 1-layer and 4-layer specimens were printed with a different nozzle and a different print speed. The bulk material of these specimens is most likely comparable. There was no significance difference found between the densities of the specimens (table 6.2). This suggests that the composition of the concrete, and thereby the tensile strengths, do not differ from each other. From the crack behavior of the numerical analysis, it may be assumed that the average tensile strength in the bulk material is comparable for specimens with 1 layer and 4 layers.

The tensile strength of the interface without interval decreases with 9 percent compared to the bulk material. A short interval results also in a decrease of tensile strength. Even though the interface could not be distinguished with the naked eye from the bulk material, it is assumable that the interface contains less aggregates and that the bond of the cement in the interface is weaker compared to the bond of the cement in the bulk material.

The interface with 7-day interval results in a decrease in tensile strength of 56 percent compared to the interface without interval. This interface represents the bond between fresh and cured concrete.
6.1.5 Fracture energy

The fracture energy of the printed concrete is relatively low compared to the fracture energy of plain concrete. This may be explained by the relatively low tensile strength of printed concrete and by a small specimen size and small aggregate size as discussed in section 2.3. No other studies to the fracture energy of comparable material where found to validate the test results.

The fracture energy of 4-layer specimens without interval related to the fracture energy of 1-layer specimens decreases with 30 percent. This is due to a 9 percent lower tensile strength and most likely due to a smoother crack surface compared to 1-layer specimens.

It was found that when the crack surface increases in roughness, the fracture energy also increases. This indicates that the crack surface has an influence on the fracture energy and that the concrete behavior is more ductile when the crack surface is rough. This also may explain the relatively large variation in fracture energy.

The fracture energy of 4-layer specimens with 7-day interval decreases with 78 percent compared to 4-layer specimens without interval. This is due to a 56 percent lower tensile strength and the even smoother crack surface compared to 4-layer specimens without interval.

6.1.6 Modulus of Elasticity

As mentioned before, the measuring length of the LVDT’s had a large influence on the modulus of elasticity from the direct tensile tests. As expected, the modulus of elasticities of the different specimen types are comparable. This means that the interface has no influence on the modulus of elasticity. From test series 8, the cylinder compressive tests and the discussion in section 4.3.4, it can be concluded that the initial modulus of elasticity is about 17336 MPa.

6.1.7 Compressive strength

The average compressive strength of cubes (40*40*40 mm³) and cylinders (with a diameter of 100 mm and a length of 250 mm) are 30.66 MPa and 23.16 MPa respectively. The compressive strength of cubes is higher because the lateral deformation that is prevented at the loading platens has a larger influence on short specimens. The relation between the compressive strengths obtained from the cubes and cylinders was found in literature (Van Boom & Kamerling, 1978) and is discussed in section 3.4.2. The relation between the cubical compressive strength and cylindrical compressive strength was also found in the results from this research.

6.1.8 Cohesive Zone Model

A Cohesive Zone model was used to describe discrete cracking. Three types of specimens were modeled: specimens with 1 layer, specimens with 4 layers without time interval and specimens with 4 layers with a time interval of 7 days. Every type of specimen was simulated multiple times whereby each time a different crack surface was obtained.

From the model with 1 layer can be seen that the model describes very accurate the fracture process zone, followed by macrocracks, and the rough crack surface. This seems to correspond with the theory about fracture of concrete. From the model with 4 layers with 7-day interval, the fracture process zone was only located in the interface, resulting in a very smooth crack surface whereby it seems that the bulk material did not damage. From the model with 4 layers without interval, a rougher crack surface can be seen whereby the model mostly failed at the interface and at some points failed in the bulk material. The crack surfaces of all three types of specimens was described very accurate and comparable with the crack surfaces from the experiments.

From the crack surfaces, it can be implied that the average tensile strength and variance of the bulk material also applies to the specimens with 4 layers.

The Cohesive Zone Model is a strong tool to describe the crack behavior of printed concrete structures. It is possible to give the cohesive elements different material properties from the interface and the bulk material.
6.2 Recommendations

6.2.1 Direct tensile test setup

The developed test setup seems to give very accurate results. However, the test setup may still influence the results. Therefore, some improvements should be made for the test setup.

The last improvement was repositioning the LVDT’s to obtain a more realistic value for the modulus of elasticity. The LVDT’s are still measuring between the steel blocks whereby the modulus of elasticity is influenced by the steel blocks and the glue layer, see section 4.3.4. Therefore, it is very important to place the LVDT’s on the specimens whereby the LVDT’s are only measuring the deformation of the specimens. This can be done by using smaller LVDT’s that are taking less space or increasing the specimen length.

Another improvement on the test setup is another way of fixating the steel blocks on the loading platens. In the current situation, the steel blocks are fixed with hexagon socket screws whereby it is very important to tighten firmly the screw. If this is not done, the steel blocks may start to rotate, whereby the results may be influenced.

6.2.2 Specimens

From literature, it was found that the specimen size may have influence on the tensile properties. For this research, relatively small specimens (40*40*40 mm$^3$) were used. This small size of specimens may influence the material properties. The tensile strength should decrease and the fracture energy should increase with an increase in specimen size. This influence was not studied because there was no variation in the specimen size in this research. When the specimen size is varied, this influence may be studied.

The preparation of the specimens may also have a large influence on the results. Therefore, it is very important to place the specimens in water during curing and be careful during sawing the specimens.

6.2.3 Modulus of elasticity of test setup with rotating loading platens

From tests with rotating loading platens, a relatively high modulus of elasticity with a large variation was found. The measuring length of the LVDT’s (as discussed above) may have influenced the results, but the exact cause of these high values was not studied in this research. This may be researched by carrying out experiments on short and long specimens both with the test setup with non-rotating, - and rotating loading platens. It is advised to place the LVDT’s on the specimens to exclude influence of the steel blocks.

6.2.4 Crack surfaces

The crack surfaces of the specimens were observed with the naked eye and from pictures. To get a better view of the crack surface, the specimens may be observed with a microscope or another technology. Before testing, the interface was not recognizable with the naked eye. Possibly the interface can also be observed with a microscope.

6.2.5 Time interval

In this research, an interval time of about 30 seconds and 7 days is used to obtain material properties. For determine print strategies, more interval times should be tested to find out what the decrease of tensile strength and fracture energy is with an increase in interval time. Therefore, more interval times should be tested to find out at what the influence of the time interval on the tensile properties is.

6.2.6 Cohesive Zone Model

As mentioned before, the cohesive zone model is a strong tool for describing the crack behavior of printed concrete structures. The model is suitable for unreinforced structures. The model may be expanded with reinforcement to describe the crack behavior of printed concrete structures with fibers or other reinforcement. This gives the model more practical use.
7 References

7.1.1 Literature


7.1.2 Standards


7.1.3 Figures


Appendices

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Appendix A  Development of the direct tensile test setup

Test equipment

The experiments were carried out in The Structures Laboratory Eindhoven of the Unit Structural Design of the Department of the Built Environment of the Eindhoven University of Technology. The used testing system for the experiments is the Instron 5985 test bench with a load cell of 250 kN. Deformations during the experiment were measured with Linear Variable Differential Transformers (LVDT’s).

![Figure A.1a Instron 5985 Test bench.](image)

![Figure A.1b Linear Variable Differential Transformers.](image)

![Figure A.1c 250 kN load cell.](image)

Specimens

Printed specimens without knowledge about curing age, density, time interval between layers etcetera were used for the development of the direct tensile test setup with non-rotating loading platens. Therefore, the results of these test series cannot be used. The specimens have dimensions of 40*40*40 mm\(^3\) with circular notches with a radius of 6 mm. The middle section has a surface of approximately 40*28 mm\(^2\).
Initial test setup

Figure A.2 illustrates the initial test setup. The loading platens of 200*120*40 mm³ are directly fixed on the grips with four M10 hexagon socket screws. This results in a high rotational stiffness. The specimens are glued on steel blocks of 40*40*20 mm³. The steel blocks are fixed on the loading platens with M10 hexagon socket screws.

![Figure A.2 Representation of the initial test setup.](image)
Test series A – 2 LVDT’s

Figure A.3 shows the test setup of the first tests. The deformation was measured with two LVDT’s placed between the loading platens. The measuring height was about 75 mm and the distance between the LVDT’s was about 160 mm.

Deformation controlled by LVDT 11

The first two experiments were controlled by the deformation of LVDT 11. The used rates of these tests were 5 or 10 µm/min respectively. Figure A.4 shows a representative load – deformation relation of the first tests.
After two tests, it came clear that the test setup was not stiff enough to be controlled by one LVDT. A relative large difference in deformation was measured between LVDT 11 and LVDT 12. At the peak load, a crack was initiated, causing rotation of the loading platens. As a result, the deformation of LVDT 11 was increasing too fast, and the test bench corrected the deformation what causes a control loop (figure A.4). The load dropped to about 800 N and increased thereafter due to the remaining capacity of the specimen. After that, the loading platens rotated further and the displacement of LVDT 12 becomes negative (i.e. this side of the specimen is subjected to compressive stresses). Thereafter, the loading platens probably start to rotate back, whereby LVDT 11 was shortened, which caused the test bench to extend with a high rate because the rate was controlled by this LVDT.

For this specific test, every 0.01 second a measuring point was recorded. From the 7 measuring points between the average deformation of 20 µm and 40 µm it can be concluded that it took the test bench approximately 0.07 second to overcome this deformation. The deformation of this phase of the test is too fast to get realistic results.

**Deformation controlled by test bench**

Because the experiments became instable when the deformation was controlled by one LVDT, it was decided that the deformation was controlled by the deformation of the test bench itself. 4 tests have been carried out with this setup. The used deformation rates were 5, 10 and 20 µm/min. Figure A.5 shows a load – deformation of one of these tests. The behavior of this experiment is representative for the four experiments.

![Load - deformation graph](image)

*Figure A.5 Load-deformation relation, experiment controlled by Instron test bench.*

With this test setup, the first part of the experiment, the pre-peak behavior, was very stable. The first part of the post-peak behavior was also stable. In the specific case of figure A.5, the crack initiates on the side of LVDT 12, because the deformation of this side is larger. On the side of LVDT 11, the specimen is loaded under compression at the peak load. At the load of about 1200 N, the load drops in approximately 0.07 second to almost 0 N.

Controlling the deformation by the test bench is not suitable for obtaining the softening behavior. The deformation of the test bench keeps increasing, while the deformation of the test bench should remain the same or even decrease due to a difference in deformation between the LVDT’s and the test bench. This can be seen by figure A.11b, whereby the deformation of the test bench increases to the peak. After the peak, the deformation of the test bench decreases to a point where the deformation of the LVDT’s and the test bench are the same. From this point, the deformation of the test bench start to increase.
Test series B – 2 LVDT’s

The first important improvement to the test setup was moving the LVDT’s closer to the specimen, see figure A.6. Due to this improvement, the influence of the rotating loading platens is smaller. The used rate of these tests was 5 µm/min.

Deformation controlled by LVDT 11

Because the LVDT’s were closer to each other, a new attempt was made to control the deformation by LVDT 11. Figure A.7 shows the result this test.
The specimen of this test failed on a compression of about 10,000 N due to rotation of the loading platens. At a tensile load of about 1000 N in the ascending branch, LVDT 11 starts to shorten due to rotation of the loading platens (figure A.7b). The test bench accelerates in a very short time to correct the deformation of LVDT 11. Consequently, the specimen cracks, the loading platens rotate back in its initial position, LVDT 11 extends to 220 µm and the test bench reacts by moving back to obtain the right deformation for LVDT 11. The test bench overshoots and starts to compress the specimen. This process took about 0.12 seconds.

Figure A.7c shows a deformation - time relation of LVDT 11. The dashed line gives the rate of 5 µm/min of the experiment. Up to a deformation of 1.5 µm, LVDT 11 follows the given rate. From that point LVDT 11 starts to shorten. At about 22 seconds, the test bench extends to 220 µm (figure A.7a). At that point, the deformation should be about 1.7 µm.

The difference in deformation of the LVDT’s is smaller, but still present. The test setup is instable when controlling the deformation of the test bench by one LVDT. Therefore, the test should be controlled by the average of multiple LVDT’s.

**Deformation controlled by LVDT 05 (2 LVDT’s)**

An average deformation of LVDT 11 and LVDT 12 is calculated with software, called AnalogAverage.vi. This software is written by Eric Wijen from *The Structures Laboratory Eindhoven*. This software creates an average value from the deformations of LVDT 11 and 12. This average value is sent to the measuring unit. From here, the signal is sent to the computer for obtaining data and sent to the test bench for controlling the deformation. The test bench responds on this signal whereby the LVDT’s deform creating a new average value. This process repeats itself to the end of the test.

4 tests have been carried out with this setup. 3 of these tests failed on compression with the same reasons as explained before. Although the descending branch was longer stable in this test series due to the average signal, the test setup was still instable. One reason for the instability was probably the relative large rotation of the loading platens. After inspection on tolerances in the test bench, it turned out that there was a small tolerance in the upper and lower grip of the test bench. By screwing the grips in its own bases the movement in the grips disappeared. After this improvement, 4 new tests have been carried out. Figure A.8 shows a representative load-deformation relation of the tests.

None of the tests failed on compression anymore. However, the load still drops, followed by a control loop. This drop has a large influence on softening branch.
Test series C – 4 LVDT’s

To prevent the load from dropping, the test setup needs to be further improved by measuring the deformation on all sides of the specimen. When the deformation is measured on two sides, the rotation, and thus the crack behavior, over one axis can be determined. Because a crack can initiate on each side of the specimen, the deformation of the other sides of the specimen needs to be measured. 2 LVDT’s were added to the test setup: one on the left side of the specimen (LVDT 06) and one on the right side of the specimen (LVDT 07). Figure A.9 shows the 4 LVDT’s around the specimen.

Figure A.9a Test setup with four LVDT’s.

Figure A.9b Top view test setup.

Figure A.9c Front view test setup.

Deformation controlled by LVDT 05 (4 LVDT’s)

The deformation was controlled by LVDT 05 with these tests. This was the average deformation of LVDT 06, 07, 11 and 12. Approximately 20 tests have been carried out with this test setup. Figure A.10 shows a representative load - deformation relation of the tests.

Figure A.10 Load-deformation relation, test controlled by LVDT 05 (average of 4 LVDT’s).
Figure A.10 still shows a load drop followed by a control loop in the load deformation relation. Rates of 5 µm/min and 10 µm/min have been used for these tests. The change of rate had no influence on the load drop and the load cycle.

**Test series D – Proportional gain factor**

A possible explanation of the load drop and the control loop may be the responsiveness of the load cell of the test bench. With a closed loop feedback control, whereby the deformation is controlled by the LVDT’s, and a too low response speed of the load cell, the load cell reacts not fast enough to overcome the deformations. The response speed can be changed by overriding the default gain settings in the Instron Bluehill 3 software. The help function of this software is used as reference for changing the gain settings.

The proportional gain factor determines how fast the load cell must travel to meet the specified rate. Increasing this value means increasing the response speed of the load cell. The unit of the gain is in the case of deformation controlled [mm/mm], and is based on [deformation test bench/deformation LVDT]. The default value for the gain factor is 1 mm/mm and assumes with this value that the deformation of the test bench and the LVDT’s is the same. Figure A.10 shows that the deformation of the test bench is much larger than the deformation of the LVDT’s during a test. Therefore, the default value of the gain should be changed.

The gain can be determined by calculating the change in deformation of the test bench for 1 unit of deformation of the LVDT’s. Figure A.11a shows the measured deformations of the test bench and the LVDT’s during a test that is representative for the test series. Figure A.11b shows the load – deformation relation of the same test. In the linear elastic branch (from figure A.11b), the change of deformation of the test bench is 4 µm per unit (1 µm) of deformation of the LVDT’s. The proportional gain factor during the linear elastic branch should be 4 mm/mm, this is 4 times higher than the default value.

**Figure A.11 Test of the final test series, with (a) deformation test bench – LVDT’s and (b) Load-deformation relation.**

At the first tests that were carried out with the manual changed proportional gain, still a load drop was observed. This was caused by the change in relation between the deformations of the test bench and the LVDT’s after the linear elastic branch. After the peak, the deformation of the test bench decreased, whereby the proportional gain became too high. This resulted in overshoot whereby the test bench stared to move erratically and the load–deformation relation was also erratically. This was solved by gradually decreasing the proportional gain during the test whereby stable results as figure A.11b were obtained. The decrease of the proportional gain during the test can be found in appendix B, table B.1 and B.2.
Appendix B  Specimen preparation and test procedure

Fabricate specimens

The day before testing, the specimens were prepared. Specimens were sawn with the sawing machine from figure B.1a. Notches were drilled with the drill from figure B.1b and the gluing surface was roughening with saw cuts with the saw from figure B.1c.

The specimens have dimensions of 40*40*40 mm$^3$ with on two sides of the specimens a notch with a radius of 6 mm. Figure B.2 illustrates the sawing procedure of specimens.
In the case of figure B.2, beams with 6 layers were printed with a nozzle of 40*10 mm². The beams were sawn in slides with a thickness of 40 mm (figure B.2a). On one side the ribs were sawn from the specimen and the interface was marked (figure B.2b). Then the ribs on the other side were sawn from the specimen (figure B.2c). The top layer (figure B.2d) and bottom layer (figure B.2e) were sawn from the specimen. Two specimens were pressed together and with the drill from figure B.3b, notches were drilled on both sides of the specimen (figure B.2f). To roughen the gluing surface, sawing cuts are made on the top and bottom side of the specimen (figure B.2g).

After fabrication of the specimens, dimensions and weight of the specimens were determined. After that, the specimens were placed back in the water tank.

**Gluing specimens**

On the day of the tests, the specimens were glued on steel blocks, see figure B.3. The two-components glue X60 is used for gluing the specimen on the steel blocks. This glue consists of a powder (Plexil 7742F) and a fluid (Pleximon 801). After mixing, the glue has a very short curing time.

The dust was removed from the specimen and the steel blocks were cleaned with alcohol to ensure a proper adhesion. A relative thick layer of glue was placed on the specimen (figure B.3a). The steel block was placed on top of the specimen (figure B.3b) and glue residues were removed (figure B.3c). A small pre-load in the form of a steel block was applied to improve the adhesion.

*Figure B.3 Gluing the first steel block on the specimen.*
Aligning lower grip test bench

Before the tests could be carried out, the position of the lower grip was determined. The alignment of the upper and lower grips is very important to introduce a centric tensile load. If the alignment between the grips has a large deviation, shear stresses and possibly other mechanical phenomena can occur due to eccentric loads.

To ensure that the grips are aligned with a small deviation, the surface of the loading platens were provided with notches of 40*40 mm² with a depth of 2 mm where the steel blocks fit in. Figure B.5 shows an overview of the procedure to align the lower grip. First, the loading platens were placed and fixed (figure B.4a). Then, the upper grip was screwed in its own base to ensure that the upper grip was fixed (figure B.4.b). Then, a steel block was placed (and enclosed due to the notch) in the upper loading platen (figure B.4c). Thereafter, the upper grip was lowered until the steel block was almost in contact with the lower loading platen (figure B.4d). Now, the lower grip was positioned until the steel block fits in the notch of the lower loading platen and the lower grip was fixed (figure B.4e). At last, the lower grip was screwed in its own base to ensure that also the lower grip was fixed (figure B.4.f). Besides aligning the lower grip, the notches also prevented the specimen from moving in horizontal direction during the gluing process and during the tests.
Placing specimen in test bench

Figure B.5 illustrates the procedure for placing the specimen in the test setup. The steel block of 40*40*20 mm³ was mounted with a M10 hexagon socket screw on the upper loading platen (figure B.5a). The steel block with specimen was mounted on the lower loading platen (figure B.5b). It is important that the socket screws are properly tightened. The 2-components glue X60 (figure B.5c) was mixed and placed on the specimen (figure B.5d). Because of imperfections of the specimen, a thick layer of glue was used.

The upper loading platen was lowered on the specimen (figure B.5e). Shrinkage occurred during drying of the glue. To prevent that the specimen is loaded under tensile stresses during the drying process, the specimen was loaded with a compressive load of 100 N. This load was kept constant by another test program (figure B.5f) than the one that was used for the actual test (figure B.7). After 30 minutes, the glue was hardened and the test could be started. During this 30 minutes, the LVDT’s were placed (figure B.5f).
Figure B.6 shows a screenshot of the compressive method during hardening of the glue. The specimens were loaded with a constant compressive load of about 100 N. The bottom graphic shows the displacement of the test bench as a function of time. From this graphic can be seen that the glue is shrinking during hardening.

Test procedure

Figure B.7 is a screenshot of the software AnalogAverage.vi. As mentioned in appendix A, this software creates an average value of the LVDT's and controls the deformation of the test bench. This program must be started before testing.
Figure B.8 shows a screenshot of the testing method of the direct tensile test. The graphic shows the average load – deformation relation during the test. On the right side of the figure the deformations of the LVDT’s and average deformations can be seen.

![Screenshot test method direct tensile test](image)

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The test started when the specimen was subjected to a tensile load of 10 N. From that point, the deformations of the LVDT’s were reset.

During the test the deformation rate and the proportional gain was changed (as discussed in appendix A). Tables B.1 and B.2 give the change in rate and gain for test series 1-7 and test series 8 respectively. The values for test series 8 deviate due to the repositioning of the LVDT’s.

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<td>131.1</td>
<td>40.6</td>
<td>40.7</td>
<td>40.2</td>
<td>1980</td>
<td>28.3</td>
<td>1136.2</td>
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<td>128.8</td>
<td>40.6</td>
<td>40.5</td>
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<td>1967</td>
<td>30.2</td>
<td>1203.0</td>
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</tr>
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<td>2017-jan-12</td>
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<td>40.3</td>
<td>40.0</td>
<td>1973</td>
<td>26.5</td>
<td>1056.7</td>
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<td>2017-jan-12</td>
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<td>40.6</td>
<td>40.6</td>
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<td>1230.0</td>
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<td>2017-jan-12</td>
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<td>129.8</td>
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<td>40.5</td>
<td>40.0</td>
<td>1969</td>
<td>28.0</td>
<td>1120.0</td>
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</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>Test name</th>
<th>Print date</th>
<th>Test date</th>
<th>Initial rate</th>
<th>Mass [g]</th>
<th>Height [mm]</th>
<th>Width [mm]</th>
<th>Thickness [mm]</th>
<th>Density [kg/m³]</th>
<th>Width (crack) [mm]</th>
<th>Crack surface</th>
<th>Remarks</th>
</tr>
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<tbody>
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<td>1</td>
<td>8_4_0d_01</td>
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<td>2.5</td>
<td>121.3</td>
<td>40.4</td>
<td>40.2</td>
<td>38.5</td>
<td>1941</td>
<td>27.2</td>
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<td>119.8</td>
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<td>40.1</td>
<td>38.1</td>
<td>1943</td>
<td>29.2</td>
<td>1109.2</td>
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<td>40.5</td>
<td>40.1</td>
<td>38.2</td>
<td>1946</td>
<td>28.0</td>
<td>1067.7</td>
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<td>2017-jan-26</td>
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<td>40.2</td>
<td>38.2</td>
<td>1964</td>
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<td>1077.7</td>
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<td>40.2</td>
<td>38.7</td>
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<td>1103.5</td>
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<td>40.3</td>
<td>38.5</td>
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<td>2017-jan-31</td>
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<td>40.5</td>
<td>40.3</td>
<td>38.5</td>
<td>1959</td>
<td>27.5</td>
<td>1056.8</td>
<td>Changed gauge length</td>
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</table>
Appendix D  Statistical analysis tensile strengths

Tensile strengths

In table D.1 the tensile strength per experiment and the average strength and standard deviation per test can be found.

Table D.1 Individual results tensile strengths

<table>
<thead>
<tr>
<th>Specimen</th>
<th>1_4_0d fixed platen</th>
<th>1_4_0d rotating platen</th>
<th>2_4_0d fixed platen</th>
<th>3_4_0d fixed platen</th>
<th>4_1_0d fixed platen</th>
<th>5_4_0d fixed platen</th>
<th>6_2_0d fixed platen</th>
<th>7_1_0d fixed platen</th>
<th>7_1_0d rotating platen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[MPa]</td>
<td>[MPa]</td>
<td>[MPa]</td>
<td>[MPa]</td>
<td>[MPa]</td>
<td>[MPa]</td>
<td>[MPa]</td>
<td>[MPa]</td>
<td>[MPa]</td>
</tr>
<tr>
<td>1</td>
<td>1.59</td>
<td>1.02</td>
<td>1.22</td>
<td>1.57</td>
<td>1.74</td>
<td>1.00</td>
<td>1.51</td>
<td>1.42</td>
<td>1.06</td>
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<tr>
<td>2</td>
<td>1.35</td>
<td>0.96</td>
<td>1.25</td>
<td>1.39</td>
<td>-</td>
<td>0.55</td>
<td>1.52</td>
<td>1.48</td>
<td>1.27</td>
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<tr>
<td>3</td>
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<td>0.90</td>
<td>1.35</td>
<td>1.37</td>
<td>-</td>
<td>0.84</td>
<td>1.69</td>
<td>1.34</td>
<td>1.30</td>
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<tr>
<td>4</td>
<td>1.22</td>
<td>1.14</td>
<td>1.46</td>
<td>1.44</td>
<td>1.55</td>
<td>0.69</td>
<td>1.75</td>
<td>1.33</td>
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<tr>
<td>5</td>
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<td>1.36</td>
<td>-</td>
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<td>0.52</td>
<td>1.57</td>
<td>1.55</td>
<td>1.55</td>
<td>0.98</td>
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<td>1.46</td>
<td>1.46</td>
<td>1.46</td>
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<tr>
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<td>1.39</td>
<td>0.64</td>
<td>1.57</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>8</td>
<td>1.36</td>
<td>1.52</td>
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<td>10</td>
<td>1.09</td>
<td>1.49</td>
<td>0.70</td>
<td>1.32</td>
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<tr>
<td>12</td>
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<td>0.55</td>
<td>1.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>1.39</td>
<td>1.08</td>
<td>1.32</td>
<td>1.36</td>
<td>1.52</td>
<td>0.76</td>
<td>1.48</td>
<td>1.43</td>
<td>1.19</td>
</tr>
<tr>
<td>St. deviation</td>
<td>0.15</td>
<td>0.16</td>
<td>0.09</td>
<td>0.13</td>
<td>0.11</td>
<td>0.19</td>
<td>0.16</td>
<td>0.08</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Shapiro-Wilk test for normality of tensile strengths

To determine if the tensile strengths of the samples came from a normally distributed population, the Shapiro-Wilk test (1965) is carried out. With the following steps, a p-value per sample can be calculated.

Order the results of the sample from the smallest to the largest value.

Calculate the sum of squares of a sample:

$$SS = \sum_{i=1}^{n} (x_i - \bar{x})^2$$

Where $x_i$ is the observation and $\bar{x}$ is the sample mean.

Compute b:

$$b = \sum_{i=1}^{m} a_i (x_{m+1-i} - x_i)$$

Where $a_i$ is a coefficient obtained from the Shapiro-Wilk tables (Shapiro-Wilk, 1965, table 5).

Compute W:

$$W = \frac{b^2}{SS}$$
W values can be found in the Shapiro-Wilk table for W values (Shapiro-Wilk, 1965, table 6). The W values from the table needs to be interpolated to find the p value corresponding to the calculated W value.

The calculated p values can be found in table D.2. The chosen significance level is $\alpha = 0.05$. All calculated p values are greater than the chosen significance level. Therefore, it can be concluded with 95% confidence that the samples came from a normally distributed population.

<table>
<thead>
<tr>
<th></th>
<th>1_4_0d fixed</th>
<th>1_4_0d rotating</th>
<th>2_4_0d fixed</th>
<th>3_4_0d fixed</th>
<th>4_1_0d fixed</th>
<th>5_4_7d fixed</th>
<th>6_2_0d fixed</th>
<th>7_1_0d fixed</th>
<th>7_1_0d rotating</th>
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</thead>
<tbody>
<tr>
<td>SS</td>
<td>0.108</td>
<td>0.131</td>
<td>0.033</td>
<td>0.180</td>
<td>0.113</td>
<td>0.411</td>
<td>0.317</td>
<td>0.035</td>
<td>0.159</td>
</tr>
<tr>
<td>b</td>
<td>0.310</td>
<td>0.349</td>
<td>0.176</td>
<td>0.393</td>
<td>0.329</td>
<td>0.606</td>
<td>0.552</td>
<td>0.180</td>
<td>0.389</td>
</tr>
<tr>
<td>$W = b^2/SS$</td>
<td>0.890</td>
<td>0.931</td>
<td>0.938</td>
<td>0.860</td>
<td>0.954</td>
<td>0.895</td>
<td>0.961</td>
<td>0.941</td>
<td>0.952</td>
</tr>
<tr>
<td>Lower bound*</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.05</td>
<td>0.5</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>W value</td>
<td>0.806</td>
<td>0.927</td>
<td>0.935</td>
<td>0.85</td>
<td>0.938</td>
<td>0.883</td>
<td>0.943</td>
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<tr>
<td>Upper bound*</td>
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<td>0.9</td>
<td>0.1</td>
<td>0.9</td>
<td>0.5</td>
<td>0.9</td>
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<tr>
<td>W value</td>
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<td>0.972</td>
<td>0.943</td>
<td>0.973</td>
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</tbody>
</table>

*p values from Shapiro-Wilk table 6 with corresponding W value, depending on sample size n.

**Q-Q plots tensile strengths**

To demonstrate normality, also a graphical reproduction is made by means of Q-Q plots. On the horizontal axis, Z-values, and on the vertical axis tensile strengths are plotted. The diagonal line is the expected value, calculated with the mean and standard deviation of the given test series. Because the test series sizes are relative small, the variation in the q-q plot is large. This variation becomes smaller with larger test series.

![Q-Q plot 1_4_0d](image1)

![Q-Q plot 1_4_0d rotating platens](image2)

![Q-Q plot 2_4_0d](image3)

![Q-Q plot 3_4_0d](image4)
Appendix D Statistical analysis tensile strengths
Combined results tensile strengths

After combining results of test series 1, 2 and 3, a new Q-Q plot is reproduced.

The same applies to test series 4 and 7.

---

Appendices
Appendix E  Experimental results cylinder compressive tests

Print date 19 December 2016
Test date 16 January 2017

<table>
<thead>
<tr>
<th>Table E.1 Cylinder properties</th>
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<tbody>
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<td>Specimen</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>LVDT 2</td>
</tr>
<tr>
<td>E1</td>
</tr>
<tr>
<td>E2</td>
</tr>
<tr>
<td>E3</td>
</tr>
<tr>
<td>E4</td>
</tr>
<tr>
<td>E5</td>
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</table>

<table>
<thead>
<tr>
<th>Table E.2 Results of compressive tests on cylinders</th>
</tr>
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<tbody>
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<td>Specimen</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>E1</td>
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<td>E2</td>
</tr>
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<td>E3*</td>
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<tr>
<td>E4</td>
</tr>
<tr>
<td>E5</td>
</tr>
<tr>
<td>Average</td>
</tr>
</tbody>
</table>

*Test E3 was failed due to a small load drop in the linear elastic branch, the cause of this failure is unknown.

Deformation rate

The deformation rate at the first experiment was 0.05 mm/min. This rate was increased to 0.1 mm/min at 4 MPa. The first experiment took about 30 minutes including the load cycle. This was a lot slower than the prescribed stress rate. The second experiment took about 15 minutes with a deformation rate of 0.1 mm/min and later 0.2 mm/min. The last fourth and fifth experiment had a deformation rate of 0.3 mm/min for the first loading cycle. For the second loading cycle, a deformation rate of 0.8 mm/min was used. With this rate, specimens four and five failed after about 90 seconds.

![Figure E.1 Stress-strain relation cylinder E1.](image)
Figure E.2 Stress-strain relation cylinder E2.

Figure E.3 Stress-strain relation cylinder E3.

Figure E.4 Stress-strain relation cylinder E4.

Figure E.5 Stress-strain relation cylinder E5.
Appendix E  Experimental results cylinder compressive tests

**Figure E.6 Cylinder E1.**

**Figure E.7 Cylinder E2.**

**Figure E.8 Cylinder E3.**

**Figure E.9 Cylinder E4.**
Figure E.10 Cylinder E1.

Figure E.11 Cylinder E2.

Figure E.12 Cylinder E3.

Figure E.13 Cylinder E4.

Figure E.14 Cylinder E5.
Appendix F  Experimental results direct tensile tests
General information

Test name: 1_4_0d_03
Tensile test method: Non-rotating loading platens
Print date: 2016-nov-16
Test date & time: 2016-dec-14 12:51
Deformation rate: \( r = 10 \, [\mu \text{m/min}] \)

Specimen

Height: \( z = 41.2 \, [\text{mm}] \)
Width (at crack): \( x = 29.3 \, [\text{mm}] \)
Thickness (at crack): \( y = 40.2 \, [\text{mm}] \)
Density: \( \rho = 1962 \, [\text{kg/m}^3] \)

Results

Tensile force: \( F_t = 1869.0 \, [\text{N}] \)
Tensile strength: \( f_t = 1.59 \, [\text{MPa}] \)
Fracture energy: \( G_F = 36.77 \, [\text{J/m}^2] \)
Young’s modulus: \( E = 12335 \, [\text{MPa}] \)
Displacement at peak: \( \delta_{\text{peak}} = 8.4 \, [\mu \text{m}] \)

Graphics

Load - deformation 1_4_0d_03

Pre-peak

[Diagram showing stress-strain relationship pre-peak]

1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0.01
0.02
0.03
0
strain \( \epsilon \) [%\%]

1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0

Post-peak

[Diagram showing stress-crack opening relationship post-peak]

0
20
40
60
80
100
120
140
160

load \( F \) [N]

deformation \( \delta \) [\mu m]

0
20
40
60
80
100
120
140
160

stress \( \sigma \) [MPa]

0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

strain \( \epsilon \) [%\%]

0
500
1000
1500
2000

0
10
20
30
40
50
60
70
80

stress \( \sigma \) [MPa]

0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

load - deformation 1_4_0d_03

Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
General information
Test name 1_4_0d_04
Tensile test method Non-rotating loading platens
Print date 2016-nov-16
Test date & time 2016-dec-14 13:38
Deformation rate \( r = 10 \) [\( \mu \text{m/min} \)]

Specimen
Height \( z = 41.1 \) [mm]
Width (at crack) \( x = 29.8 \) [mm]
Thickness (at crack) \( y = 40.6 \) [mm]
Density \( \rho = 1965 \) [kg/m\(^3\)]

Results
Tensile force \( F_t = 1628.4 \) [N]
Tensile strength \( f_t = 1.35 \) [MPa]
Fracture energy \( G_F = 33.63 \) [J/m\(^2\)]
Young's modulus \( E = 11612 \) [Mpa]
Displacement at peak \( \delta_{\text{peak}} = 6.8 \) [\( \mu \text{m} \)]

Graphics

Appendix F Experimental results direct tensile tests
**General information**

Test name: 1_4_0d_05  
Tensile test method: Non-rotating loading platens  
Print date: 2016-nov-16  
Test date & time: 2016-dec-14 14:22  
Deformation rate: \( r \) = 10 [µm/min]

**Specimen**

Height: \( z \) = 41.2 [mm]  
Width (at crack): \( x \) = 28.2 [mm]  
Thickness (at crack): \( y \) = 40.7 [mm]  
Density: \( \rho \) = 1956 [kg/m\(^3\)]

**Results**

Tensile force: \( F_t \) = 1763.3 [N]  
Tensile strength: \( f_t \) = 1.54 [MPa]  
Fracture energy: \( G_F \) = 21.29 [J/m\(^2\)]  
Young’s modulus: \( E \) = 12288 [Mpa]  
Displacement at peak: \( \delta_{peak} \) = 7.6 [µm]

**Graphics**

---

**Load - deformation 1_4_0d_05**

![Graph showing load vs. deformation](image)

---

**Pre-peak**

![Graph showing stress vs. strain](image)

---

**Post-peak**

![Graph showing stress vs. crack opening](image)
**General information**

- **Test name:** 1_4_0d_06
- **Tensile test method:** Non-rotating loading platens
- **Print date:** 2016-nov-16
- **Test date & time:** 2016-dec-14 15:11
- **Deformation rate:** \( r = 10 \, [\mu m/min] \)

**Specimen**

- **Height:** \( z = 41.2 \, [mm] \)
- **Width (at crack):** \( x = 31.4 \, [mm] \)
- **Thickness (at crack):** \( y = 40.9 \, [mm] \)
- **Density:** \( \rho = 1949 \, [kg/m^3] \)

**Results**

- **Tensile force:** \( F_t = 1566.4 \, [N] \)
- **Tensile strength:** \( f_t = 1.22 \, [MPa] \)
- **Fracture energy:** \( G_F = 28.30 \, [J/m^2] \)
- **Young’s modulus:** \( E = 11694 \, [MPa] \)
- **Displacement at peak:** \( \delta_{\text{peak}} = 6.5 \, [\mu m] \)

**Graphics**

- **Load - deformation 1_4_0d_06**
- **Pre-peak**
- **Post-peak**
General information
Test name 1_4_0d_07
Tensile test method Non-rotating loading platens
Print date 2016-nov-16
Test date & time 2016-dec-14 16:02
Deformation rate $r \quad 10 \ [\mu m/min]$

Specimen
Height $z \quad 40.6 \ [mm]$
Width (at crack) $x \quad 31.5 \ [mm]$
Thickness (at crack) $y \quad 40.4 \ [mm]$
Density $\rho \quad 1942 \ [kg/m^3]$

Results
Tensile force $F_t \quad 1604.7 \ [N]$
Tensile strength $f_t \quad 1.26 \ [MPa]$
Fracture energy $G_F \quad 22.00 \ [J/m^2]$
Young’s modulus $E \quad 10187 \ [MPa]$
Displacement at peak $\delta_{peak} \quad 9.5 \ [\mu m]$

Graphics

Load - deformation 1_4_0d_07

Pre-peak

Post-peak
General information
Test name 1_4_0d_08
Tensile test method Rotating loading platens
Print date 2016-nov-16
Test date & time 2016-dec-16 12:55
Deformation rate \( r \) 100 \([\mu m/min]\)

Specimen
Height \( z \) 41.2 [mm]
Width (at crack) \( x \) 29.3 [mm]
Thickness (at crack) \( y \) 40.9 [mm]
Density \( \rho \) 1943 [kg/m\(^3\)]

Results
Tensile force \( F_t \) 1225.4 [N]
Tensile strength \( f_t \) 1.02 [MPa]
Fracture energy \( G_F \) - [J/m\(^2\)]
Young's modulus \( E \) 11833 [MPa]
Displacement at peak \( \delta_{peak} \) 5.4 [\(\mu\)m]

Graphics

Appendix F Experimental results direct tensile tests
General information
Test name 1_4_0d_09
Tensile test method Rotating loading platens
Print date 2016-nov-16
Test date & time 2016-dec-16 12:29
Deformation rate \( r = 100 \) [\( \mu \text{m/min} \)]

Specimen
Height \( z = 41.2 \) [\( \text{mm} \)]
Width (at crack) \( x = 30.0 \) [\( \text{mm} \)]
Thickness (at crack) \( y = 40.7 \) [\( \text{mm} \)]
Density \( \rho = 1940 \) [\( \text{kg/m}^3 \)]

Results
Tensile force \( F_t = 1174.8 \) [\( \text{N} \)]
Tensile strength \( f_t = 0.96 \) [\( \text{MPa} \)]
Fracture energy \( G_F \) [\( \text{J/m}^2 \)]
Young's modulus \( E = 16348 \) [\( \text{MPa} \)]
Displacement at peak \( \delta_{\text{peak}} = 4.6 \) [\( \mu \text{m} \)]

Graphics

Load - deformation 1_4_0d_09

Pre-peak

Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
General information

Test name: 1_4_0d_10
Tensile test method: Rotating loading platens
Print date: 2016-nov-16
Test date & time: 2016-dec-16 12:31
Deformation rate: \( r = 100 \text{ [µm/min]} \)

Specimen

Height: \( z = 41.2 \text{ [mm]} \)
Width (at crack): \( x = 32.4 \text{ [mm]} \)
Thickness (at crack): \( y = 40.6 \text{ [mm]} \)
Density: \( \rho = 1950 \text{ [kg/m}^3\text{]} \)

Results

Tensile force: \( F_t = 1176.2 \text{ [N]} \)
Tensile strength: \( f_t = 0.90 \text{ [MPa]} \)
Fracture energy: \( G_F \) [- [J/m²]]
Young’s modulus: \( E = 18183 \text{ [MPa]} \)
Displacement at peak: \( \delta_{\text{peak}} = 4.3 \text{ [µm]} \)

Graphics

Load - deformation 1_4_0d_10

Pre-peak

Appendix F Experimental results direct tensile tests

93
**General information**

- **Test name**: 1_4_0d_11
- **Tensile test method**: Rotating loading platens
- **Print date**: 2016-nov-16
- **Test date & time**: 2016-dec-16 12:32
- **Deformation rate**: \( r = 100 \text{ [µm/min]} \)

**Specimen**

- **Height**: \( z = 41.1 \text{ [mm]} \)
- **Width (at crack)**: \( x = 30.5 \text{ [mm]} \)
- **Thickness (at crack)**: \( y = 40.9 \text{ [mm]} \)
- **Density**: \( \rho = 1949 \text{ [kg/m}^3\text{]} \)

**Results**

- **Tensile force**: \( F_t = 1419.4 \text{ [N]} \)
- **Tensile strength**: \( f_t = 1.14 \text{ [MPa]} \)
- **Fracture energy**: \( G_F = - \text{ [J/m}^2\text{]} \)
- **Young’s modulus**: \( E = 22305 \text{ [MPa]} \)
- **Displacement at peak**: \( \delta_{\text{peak}} = 4.6 \text{ [µm]} \)

**Graphics**

- **Load - deformation 1_4_0d_11**
- **Pre-peak**

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Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
General information

Test name: 1_4_0d_12
Tensile test method: Rotating loading platens
Print date: 2016-nov-16
Test date & time: 2016-dec-16 12:32
Deformation rate: \( r = 100 \text{ [\mu m/min]} \)

Specimen

Height: \( z = 41.1 \text{ [mm]} \)
Width (at crack): \( x = 30.5 \text{ [mm]} \)
Thickness (at crack): \( y = 40.7 \text{ [mm]} \)
Density: \( \rho = 1939 \text{ [kg/m}^3] \)

Results

Tensile force: \( F_t = 1681.1 \text{ [N]} \)
Tensile strength: \( f_t = 1.36 \text{ [MPa]} \)
Fracture energy: \( G_f \) - \([J/m^2]\)
Young’s modulus: \( E = 18820 \text{ [MPa]} \)
Displacement at peak: \( \delta_{peak} = 5.6 \text{ [\mu m]} \)

Graphics

Load - deformation 1_4_0d_12

Pre-peak

Appendix F Experimental results direct tensile tests
General information

Test name: 2_4_0d_01
Tensile test method: Non-rotating loading platens
Print date: 2016-nov-16
Test date & time: 2016-dec-19 13:23
Deformation rate: \( r = 5 \, \mu\text{m/min} \)

Specimen

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height ( z )</td>
<td>40.8 [mm]</td>
</tr>
<tr>
<td>Width (at crack)</td>
<td>30.1 [mm]</td>
</tr>
<tr>
<td>Thickness (at crack)</td>
<td>41.2 [mm]</td>
</tr>
<tr>
<td>Density ( \rho )</td>
<td>- [kg/m(^3)]</td>
</tr>
</tbody>
</table>

Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile force ( F_t )</td>
<td>1513.0 [N]</td>
</tr>
<tr>
<td>Tensile strength ( f_t )</td>
<td>1.22 [MPa]</td>
</tr>
<tr>
<td>Fracture energy ( G_F )</td>
<td>16.65 [J/m(^2)]</td>
</tr>
<tr>
<td>Young’s modulus ( E )</td>
<td>11419 [MPa]</td>
</tr>
<tr>
<td>Displacement at peak ( \delta_{peak} )</td>
<td>6.9 [\mu m]</td>
</tr>
</tbody>
</table>

Graphics

Load - deformation 2_4_0d_01

Pre-peak

Post-peak
**General information**

Test name: 2_4_0d_02  
Tensile test method: Non-rotating loading platens  
Print date: 2016-nov-16  
Test date & time: 2016-dec-19 14:26  
Deformation rate: \( r = 5 \, [\mu\text{m/min}] \)

**Specimen**

Height: \( z = 40.8 \, [\text{mm}] \)  
Width (at crack): \( x = 29.8 \, [\text{mm}] \)  
Thickness (at crack): \( y = 41.3 \, [\text{mm}] \)  
Density: \( \rho = - \, [\text{kg/m}^3] \)

**Results**

Tensile force: \( F_t = 1541.4 \, [\text{N}] \)  
Tensile strength: \( f_t = 1.25 \, [\text{MPa}] \)  
Fracture energy: \( G_F = 19.82 \, [\text{J/m}^2] \)  
Young's modulus: \( E = 9422 \, [\text{MPa}] \)  
Displacement at peak: \( \delta_{peak} = 7.7 \, [\mu\text{m}] \)

**Graphics**

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**Appendix F** Experimental results direct tensile tests
Test name: 2_4_0d_03
Tensile test method: Non-rotating loading platens
Print date: 2016-nov-16
Test date & time: 2016-dec-19 15:11
Deformation rate: \( r = 5 \text{ [\mu m/min]} \)

Specimen:
- Height: \( z = 41.0 \text{ [mm]} \)
- Width (at crack): \( x = 30.1 \text{ [mm]} \)
- Thickness (at crack): \( y = 40.6 \text{ [mm]} \)
- Density: \( \rho \) = \([\text{kg/m}^3]\)

Results:
- Tensile force: \( F_t = 1643.4 \text{ [N]} \)
- Tensile strength: \( f_t = 1.35 \text{ [MPa]} \)
- Fracture energy: \( G_F = 19.99 \text{ [J/m}^2]\)
- Young’s modulus: \( E = 11649 \text{ [Mpa]} \)
- Displacement at peak: \( \delta_{\text{peak}} = 7.4 \text{ [\mu m]} \)

Graphics:
- Load - deformation 2_4_0d_03
- Stress - strain
- Crack opening - deformation
**General information**

- **Test name**: 2_4_0d_04
- **Tensile test method**: Non-rotating loading platens
- **Print date**: 2016-nov-16
- **Test date & time**: 2016-dec-19 16:43
- **Deformation rate**: \( r \) 5 [µm/min]

**Specimen**

- **Height**: \( z \) 41.0 [mm]
- **Width (at crack)**: \( x \) 29.7 [mm]
- **Thickness (at crack)**: \( y \) 41.2 [mm]
- **Density**: \( \rho \) - [kg/m³]

**Results**

- **Tensile force**: \( F_t \) 1780.6 [N]
- **Tensile strength**: \( f_t \) 1.46 [MPa]
- **Fracture energy**: \( G_F \) 23.31 [J/m²]
- **Young's modulus**: \( E \) 10921 [Mpa]
- **Displacement at peak**: \( \delta \) 7.5 [µm]

**Graphics**

- **Load - deformation 2_4_0d_04**
- **Pre-peak**
- **Post-peak**
**General information**
- **Test name**: 3_4_0d_01
- **Tensile test method**: Non-rotating loading platens
- **Print date**: 2016-dec-07
- **Test date & time**: 2017-jan-03 10:35
- **Deformation rate**: \( r = 5 \text{ [µm/min]} \)

**Specimen**
- **Height**: \( z = 40.3 \text{ [mm]} \)
- **Width (at crack)**: \( x = 29.0 \text{ [mm]} \)
- **Thickness (at crack)**: \( y = 40.7 \text{ [mm]} \)
- **Density**: \( \rho = 1972 \text{ [kg/m}^3\text{]} \)

**Results**
- **Tensile force**: \( F_t = 1846.4 \text{ [N]} \)
- **Tensile strength**: \( f_t = 1.57 \text{ [MPa]} \)
- **Fracture energy**: \( G_F = 18.68 \text{ [J/m}^2\text{]} \)
- **Young’s modulus**: \( E = 12313 \text{ [MPa]} \)
- **Displacement at peak**: \( \delta_{peak} = 7.6 \text{ [µm]} \)

**Graphics**

**Load - deformation 3_4_0d_01**

**Pre-peak**

**Post-peak**
**General information**

- **Test name**: 3_4_0d_02
- **Tensile test method**: Non-rotating loading platens
- **Print date**: 2016-dec-07
- **Test date & time**: 2017-jan-03 11:19
- **Deformation rate**: \( r = 5 \text{ [µm/min]} \)

**Specimen**

- **Height**: \( z = 40.2 \text{ [mm]} \)
- **Width (at crack)**: \( x = 28.6 \text{ [mm]} \)
- **Thickness (at crack)**: \( y = 40.7 \text{ [mm]} \)
- **Density**: \( \rho = 1969 \text{ [kg/m}^3\text{]} \)

**Results**

- **Tensile force**: \( F_t = 1615.4 \text{ [N]} \)
- **Tensile strength**: \( f_t = 1.39 \text{ [MPa]} \)
- **Fracture energy**: \( G_F = 25.99 \text{ [J/m}^2\text{]} \)
- **Young’s modulus**: \( E = 11484 \text{ [Mpa]} \)
- **Displacement at peak**: \( \delta_{\text{peak}} = 7.4 \text{ [µm]} \)

**Graphics**

- **Load - deformation 3_4_0d_02**
- **Pre-peak**
- **Post-peak**
**General information**

Test name: 3.4.0d.03
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07
Test date & time: 2017-jan-03 12:18
Deformation rate: \(5 \text{ [\mu m/min]}\)

**Specimen**

Height: \(z\) 40.5 [mm]
Width (at crack): \(x\) 28.7 [mm]
Thickness (at crack): \(y\) 40.5 [mm]
Density: \(\rho\) 1970 [kg/m^3]

**Results**

Tensile force: \(F_t\) 1590.2 [N]
Tensile strength: \(f_t\) 1.37 [MPa]
Fracture energy: \(G_F\) 20.39 [J/m^2]
Young’s modulus: \(E\) 11142 [Mpa]
Displacement at peak: \(\delta_{\text{peak}}\) 7.7 [\mu m]

**Graphics**

Load - deformation 3.4.0d.03

- Pre-peak
- Post-peak

Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
**General information**

Test name: 3.4.0d_04

Tensile test method: Non-rotating loading platens

Print date: 2016-dec-07

Test date & time: 2017-jan-03 13:06

Deformation rate: \( r = 5 \text{ [µm/min]} \)

**Specimen**

Height: \( z = 40.4 \text{ [mm]} \)

Width (at crack): \( x = 28.6 \text{ [mm]} \)

Thickness (at crack): \( y = 40.5 \text{ [mm]} \)

Density: \( \rho = 1959 \text{ [kg/m}^3\text{]} \)

**Results**

Tensile force: \( F_t = 1664.2 \text{ [N]} \)

Tensile strength: \( f_t = 1.44 \text{ [MPa]} \)

Fracture energy: \( G_F = 22.93 \text{ [J/m}^2\text{]} \)

Young’s modulus: \( E = 11595 \text{ [MPa]} \)

Displacement at peak: \( \delta_{\text{peak}} = 7.4 \text{ [µm]} \)

**Graphics**

Load - deformation 3.4.0d_04

Pre-peak

Post-peak

Appendix F Experimental results direct tensile tests
General information

Test name: 3.4_0d_06
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07
Test date & time: 2017-jan-03 14:31
Deformation rate: \( r = 5 \, [\mu m/min] \)

Specimen

Height: \( z = 40.4 \, [mm] \)
Width (at crack): \( x = 27.9 \, [mm] \)
Thickness (at crack): \( y = 40.7 \, [mm] \)
Density: \( \rho = 1975 \, [kg/m^3] \)

Results

Tensile force: \( F_t = 1611.1 \, [N] \)
Tensile strength: \( f_t = 1.42 \, [MPa] \)
Fracture energy: \( G_F = 13.61 \, [J/m^2] \)
Young’s modulus: \( E = 11320 \, [MPa] \)
Displacement at peak: \( \delta_{peak} = 6.9 \, [\mu m] \)

Graphics

Load - deformation 3.4_0d_06

Pre-peak

Post-peak
General information

Test name 3_4_0d_07
Tensile test method Non-rotating loading platens
Print date 2016-dec-07
Test date & time 2017-jan-03 15:25
Deformation rate $\dot{r} = 5 \ \mu\text{m/min}$

Specimen

Height $z = 40.3 \ [\text{mm}]$
Width (at crack) $x = 28.6 \ [\text{mm}]$
Thickness (at crack) $y = 40.6 \ [\text{mm}]$
Density $\rho = 1977 \ [\text{kg/m}^3]$

Results

Tensile force $F_t = 1673.0 \ [\text{N}]$
Tensile strength $f_t = 1.44 \ [\text{MPa}]$
Fracture energy $G_F = 12.60 \ [\text{J/m}^2]$
Young’s modulus $E = 10968 \ [\text{MPa}]$
Displacement at peak $\delta_{\text{peak}} = 8.1 \ [\mu\text{m}]$

Graphics

Load - deformation 3_4_0d_07

Pre-peak

Post-peak
General information
Test name 3_4_0d_08
Tensile test method Non-rotating loading platens
Print date 2016-Dec-07
Test date & time 2017-Jan-03 16:18
Deformation rate $r = 5 \, [\mu \text{m/min}]$

Specimen
Height $z = 40.4 \, [\text{mm}]$
Width (at crack) $x = 28.3 \, [\text{mm}]$
Thickness (at crack) $y = 40.4 \, [\text{mm}]$
Density $\rho = 1972 \, [\text{kg/m}^3]$

Results
Tensile force $F_t = 1550.1 \, [\text{N}]$
Tensile strength $f_t = 1.36 \, [\text{MPa}]$
Fracture energy $G_f = 17.24 \, [\text{J/m}^2]$
Young's modulus $E = 10968 \, [\text{MPa}]$
Displacement at peak $\delta_{\text{peak}} = 7.7 \, [\mu \text{m}]$

Graphics

Load - deformation 3_4_0d_08

Pre-peak

Post-peak

Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
**General information**

Test name: 3_4_0d_09

Tensile test method: Non-rotating loading platens

Print date: 2016-dec-07

Test date & time: 2017-jan-03 17:03

Deformation rate: $r = 5 \text{ [µm/min]}$

**Specimen**

Height: $z = 40.4 \text{ [mm]}$

Width (at crack): $x = 28.8 \text{ [mm]}$

Thickness (at crack): $y = 40.5 \text{ [mm]}$

Density: $\rho = 1979 \text{ [kg/m}^3\text{]}$

**Results**

Tensile force: $F_t = 1615.3 \text{ [N]}$

Tensile strength: $f_t = 1.39 \text{ [MPa]}$

Fracture energy: $G_F = 20.36 \text{ [J/m}^2\text{]}$

Young's modulus: $E = 11341 \text{ [Mpa]}$

Displacement at peak: $\delta_{\text{peak}} = 7.9 \text{ [µm]}$

**Graphics**

**Load - deformation 3_4_0d_09**

**Pre-peak**

**Post-peak**
**General information**
Test name 3_4_0d_10
Tensile test method Non-rotating loading platens
Print date 2016-Dec-07
Test date & time 2017-Jan-03 17:53
Deformation rate $r = 5 \text{ [}\mu\text{m/min}]$

**Specimen**
Height $z = 40.5 \text{ [mm]}$
Width (at crack) $x = 28.4 \text{ [mm]}$
Thickness (at crack) $y = 40.7 \text{ [mm]}$
Density $\rho = 1967 \text{ [kg/m}^3\text{]}$

**Results**
Tensile force $F_t = 1261.4 \text{ [N]}$
Tensile strength $f_t = 1.09 \text{ [MPa]}$
Fracture energy $G_F = 11.00 \text{ [J/m}^2\text{]}$
Young's modulus $E = 10978 \text{ [MPa]}$
Displacement at peak $\delta_{\text{peak}} = 6.5 \text{ [}\mu\text{m]}$

**Graphics**

![Load - deformation 3_4_0d_10](image-url)

Pre-peak

Post-peak
General information
Test name: 3_4_0d_11
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07
Test date & time: 2017-jan-03 18:43
Deformation rate: \( r = 5 \text{ [\mu m/min]} \)

Specimen
Height: \( z = 40.1 \text{ [mm]} \)
Width (at crack): \( x = 29.6 \text{ [mm]} \)
Thickness (at crack): \( y = 40.5 \text{ [mm]} \)
Density: \( \rho = 1986 \text{ [kg/m}^3\text{]} \)

Results
Tensile force: \( F_t = 1369.2 \text{ [N]} \)
Tensile strength: \( f_t = 1.14 \text{ [MPa]} \)
Fracture energy: \( G_F = 23.24 \text{ [J/m}^2\text{]} \)
Young’s modulus: \( E = 12073 \text{ [MPa]} \)
Displacement at peak: \( \delta_{\text{peak}} = 5.7 \text{ [\mu m]} \)

Graphics

Load - deformation 3_4_0d_11

Pre-peak

Post-peak

Appendix F Experimental results direct tensile tests
**General information**

Test name: 3_4_0d_12

Tensile test method: Non-rotating loading platens

Print date: 2016-dec-07

Test date & time: 2017-jan-04 10:12

Deformation rate: \( r = 5 \, [\mu m/min] \)

**Specimen**

Height: \( z = 40.1 \, [mm] \)

Width (at crack): \( x = 27.6 \, [mm] \)

Thickness (at crack): \( y = 40.5 \, [mm] \)

Density: \( \rho = 1958 \, [kg/m^3] \)

**Results**

Tensile force: \( F_t = 1522.6 \, [N] \)

Tensile strength: \( f_t = 1.36 \, [MPa] \)

Fracture energy: \( G_f = 21.38 \, [J/m^2] \)

Young's modulus: \( E = 12146 \, [Mpa] \)

Displacement at peak: \( \delta_{peak} = 7.3 \, [\mu m] \)

**Graphics**

Load - deformation 3_4_0d_12

Pre-peak

Post-peak
General information
Test name: 4_1_0d_01
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07
Test date & time: 2017-jan-04 11:07
Deformation rate: \( r = 5 \, \mu m/min \)

Specimen
Height: \( z = 41.5 \, [mm] \)
Width (at crack): \( x = 31.6 \, [mm] \)
Thickness (at crack): \( y = 41.1 \, [mm] \)
Density: \( \rho = 2007 \, [kg/m^3] \)

Results
Tensile force: \( F_t = 2250.6 \, [N] \)
Tensile strength: \( f_t = 1.74 \, [MPa] \)
Fracture energy: \( G_F = 43.60 \, [J/m^2] \)
Young’s modulus: \( E = 11433 \, [MPa] \)
Displacement at peak: \( \delta_{peak} = 9.6 \, [\mu m] \)

Graphics

Appendix F Experimental results direct tensile tests

Appendix F
**General information**
Test name: 4_1_0d_04
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07
Test date & time: 2017-jan-04 13:42
Deformation rate: \( r = 5 \text{ [µm/min]} \)

**Specimen**
Height: \( z = 41.4 \text{ [mm]} \)
Width (at crack): \( x = 31.1 \text{ [mm]} \)
Thickness (at crack): \( y = 40.9 \text{ [mm]} \)
Density: \( \rho = 1986 \text{ [kg/m}^3\text{]} \)

**Results**
Tensile force: \( F_t = 1971.7 \text{ [N]} \)
Tensile strength: \( f_t = 1.55 \text{ [MPa]} \)
Fracture energy: \( G_F = 20.10 \text{ [J/m}^2\text{]} \)
Young’s modulus: \( E = 11958 \text{ [MPa]} \)
Displacement at peak: \( \delta_{\text{peak}} = 8.6 \text{ [µm]} \)

**Graphics**

![Load - deformation 4_1_0d_04](image)

**Pre-peak**

![Stress-strain curve](image)

**Post-peak**

![Stress-crack opening](image)
General information
Test name: 4_1_0d_05
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07
Test date & time: 2017-jan-04 14:37
Deformation rate: \( r = 5 \, \mu\text{m/min} \)

Specimen
Height: \( z = 41.1 \, \text{mm} \)
Width (at crack): \( x = 29.5 \, \text{mm} \)
Thickness (at crack): \( y = 40.7 \, \text{mm} \)
Density: \( \rho = 1987 \, \text{kg/m}^3 \)

Results
Tensile force: \( F_t = 1744.0 \, \text{N} \)
Tensile strength: \( f_t = 1.45 \, \text{MPa} \)
Fracture energy: \( G_F = 21.39 \, \text{J/m}^2 \)
Young’s modulus: \( E = 11481 \, \text{MPa} \)
Displacement at peak: \( \delta_{\text{peak}} = 7.9 \, \mu\text{m} \)

Graphics

Appendix F: Experimental results direct tensile tests
General information
Test name: 4_1_0d_06
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07
Test date & time: 2017-jan-04 15:34
Deformation rate: \( r = 5 \, \mu\text{m/min} \)

Specimen
Height: \( z = 41.2 \, [\text{mm}] \)
Width (at crack): \( x = 30.4 \, [\text{mm}] \)
Thickness (at crack): \( y = 41.0 \, [\text{mm}] \)
Density: \( \rho = 1987 \, [\text{kg/m}^3] \)

Results
Tensile force: \( F_t = 1827.5 \, [\text{N}] \)
Tensile strength: \( f_t = 1.47 \, [\text{MPa}] \)
Fracture energy: \( G_F = 27.23 \, [\text{J/m}^2] \)
Young’s modulus: \( E = 12807 \, [\text{MPa}] \)
Displacement at peak: \( \delta_{\text{peak}} = 7.6 \, [\mu\text{m}] \)

Graphics

Load - deformation 4_1_0d_06

Pre-peak

Post-peak
**General information**

Test name: 4_1_0d_07  
Tensile test method: Non-rotating loading platens  
Print date: 2016-dec-07  
Test date & time: 2017-jan-04 16:26  
Deformation rate: \( r \) 5 [\( \mu \text{m/min} \)]

**Specimen**

Height: \( z \) 41.3 [mm]  
Width (at crack): \( x \) 28.7 [mm]  
Thickness (at crack): \( y \) 40.6 [mm]  
Density: \( \rho \) 2001 [kg/m\(^3\)]

**Results**

Tensile force: \( F_t \) 1615.7 [N]  
Tensile strength: \( f_t \) 1.39 [MPa]  
Fracture energy: \( G_F \) 24.87 [J/m\(^2\)]  
Young’s modulus: \( E \) 12316 [Mpa]  
Displacement at peak: \( \delta_{\text{peak}} \) 6.4 [\( \mu \text{m} \)]

**Graphics**

*Load - deformation 4_1_0d_07*

*Pre-peak*

*Post-peak*
### General information

**Test name**: 4_1_0d_08  
**Tensile test method**: Non-rotating loading platens  
**Print date**: 2016-dec-07  
**Test date & time**: 2017-jan-04 17:19  
**Deformation rate**: \( r = 5 \, [\mu \text{m/min}] \)

### Specimen

- **Height**: \( z = 41.0 \, [\text{mm}] \)
- **Width (at crack)**: \( x = 30.6 \, [\text{mm}] \)
- **Thickness (at crack)**: \( y = 41.1 \, [\text{mm}] \)
- **Density**: \( \rho = 2017 \, [\text{kg/m}^3] \)

### Results

- **Tensile force**: \( F_t = 1907.7 \, [\text{N}] \)
- **Tensile strength**: \( f_t = 1.52 \, [\text{MPa}] \)
- **Fracture energy**: \( G_F = 35.96 \, [\text{J/m}^2] \)
- **Young’s modulus**: \( E = 12956 \, [\text{MPa}] \)
- **Displacement at peak**: \( \delta_{\text{peak}} = 7.0 \, [\mu \text{m}] \)

### Graphics

**Load - deformation 4_1_0d_08**

---

**Pre-peak**

**Post-peak**
General information

Test name: 4_1_0d_09
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07
Test date & time: 2017-jan-04 18:15
Deformation rate: \( r = 5 \ [\mu \text{m/min}] \)

Specimen

Height: \( z = 41.4 \ [\text{mm}] \)
Width (at crack): \( x = 31.1 \ [\text{mm}] \)
Thickness (at crack): \( y = 41.3 \ [\text{mm}] \)
Density: \( \rho = 1987 \ [\text{kg/m}^3] \)

Results

Tensile force: \( F_t = 1774.1 \ [\text{N}] \)
Tensile strength: \( f_t = 1.38 \ [\text{MPa}] \)
Fracture energy: \( G_F = 34.69 \ [\text{J/m}^2] \)
Young’s modulus: \( E = 12436 \ [\text{MPa}] \)
Displacement at peak: \( \delta_{\text{peak}} = 6.9 \ [\mu \text{m}] \)

Graphics

Load - deformation 4_1_0d_09

Pre-peak

Post-peak

Appendix F
Experimental results direct tensile tests
**General information**

- **Test name**: 4_1_0d_10
- **Tensile test method**: Non-rotating loading platens
- **Print date**: 2016-dec-07
- **Test date & time**: 2017-jan-04 18:59
- **Deformation rate**: \( r = 5 \, [\mu m/min] \)

**Specimen**

- **Height**: \( z = 41.2 \, [mm] \)
- **Width (at crack)**: \( x = 26.8 \, [mm] \)
- **Thickness (at crack)**: \( y = 41.0 \, [mm] \)
- **Density**: \( \rho = 1987 \, [kg/m^3] \)

**Results**

- **Tensile force**: \( F_t = 1629.0 \, [N] \)
- **Tensile strength**: \( f_t = 1.49 \, [MPa] \)
- **Fracture energy**: \( G_F = 28.12 \, [J/m^2] \)
- **Young’s modulus**: \( E = 12247 \, [Mpa] \)
- **Displacement at peak**: \( \delta_{\text{peak}} = 7.8 \, [\mu m] \)

**Graphics**

**Load - deformation 4_1_0d_10**

- Pre-peak
- Post-peak
General information
Test name 4_1_0d_11
Tensile test method Non-rotating loading platens
Print date 2016-dec-07
Test date & time 2017-jan-05 11:12
Deformation rate $r \ 5 \ \mu m/min$

Specimen
Height $z \ 41.3 \ [mm]$
Width (at crack) $x \ 27.7 \ [mm]$
Thickness (at crack) $y \ 40.7 \ [mm]$
Density $\rho \ 1991 \ [kg/m^3]$

Results
Tensile force $F_t \ 1813.0 \ [N]$
Tensile strength $f_t \ 1.61 \ [MPa]$
Fracture energy $G_F \ 20.89 \ [J/m^2]$
Young’s modulus $E \ 12321 \ [Mpa]$
Displacement at peak $\delta_{\text{peak}} \ 8.0 \ \mu m$

Appendix F Experimental results direct tensile tests

Graphics

Load - deformation 4_1_0d_11

Pre-peak

Post-peak

Appendix F Experimental results direct tensile tests
General information
Test name 4_1_0d_12
Tensile test method Non-rotating loading platens
Print date 2016-dec-07
Test date & time 2017-jan-05 12:15
Deformation rate $r = 5 \, \mu m/min$

Specimen
Height $z = 41.2 \, [mm]$
Width (at crack) $x = 30.9 \, [mm]$
Thickness (at crack) $y = 41.1 \, [mm]$
Density $\rho = 2000 \, [kg/m^3]$

Results
Tensile force $F_t = 2070.7 \, [N]$
Tensile strength $f_t = 1.63 \, [MPa]$
Fracture energy $G_F = 29.43 \, [J/m^2]$
Young's modulus $E = 12316 \, [MPa]$
Displacement at peak $\delta_{peak} = 6.9 \, [\mu m]$

Graphics

Load - deformation 4_1_0d_12

Pre-peak
Post-peak

Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
**General information**

- **Test name**: Tensile test method
- **Print date**: 2016-dec-07; 2016-dec-14
- **Test date & time**: 2017-jan-10 10:18
- **Deformation rate**: \( r = 5 \, [\mu \text{m/min}] \)

**Specimen**

- **Height**: \( z = 40.5 \, [\text{mm}] \)
- **Width (at crack)**: \( x = 29.1 \, [\text{mm}] \)
- **Thickness (at crack)**: \( y = 37.7 \, [\text{mm}] \)
- **Density**: \( \rho = 1972 \, [\text{kg/m}^3] \)

**Results**

- **Tensile force**: \( F_t = 1095.8 \, [\text{N}] \)
- **Tensile strength**: \( f_t = 1.00 \, [\text{MPa}] \)
- **Fracture energy**: \( G_F = 5.30 \, [\text{J/m}^2] \)
- **Young’s modulus**: \( E = 11053 \, [\text{MPa}] \)
- **Displacement at peak**: \( \delta_{\text{peak}} = 4.7 \, [\mu \text{m}] \)

**Graphics**

- **Load - deformation 5_4_7d_01**
- **Pre-peak**
  - **stress** \( \sigma \) vs. **strain** \( \varepsilon \)
  - **Post-peak**
  - **stress** \( \sigma \) vs. **crack opening** \( w \)
General information
Test name 5_4_7d_02
Tensile test method Non-rotating loading platens
Print date 2016-dec-07; 2016-dec-14
Test date & time 2017-jan-10 11:10
Deformation rate \( r \) 5 [\( \mu \text{m/min} \)]

Specimen
Height \( z \) 40.3 [mm]
Width (at crack) \( x \) 26.5 [mm]
Thickness (at crack) \( y \) 37.3 [mm]
Density \( \rho \) 1968 [kg/m\(^3\)]

Results
Tensile force \( F_t \) 541.7 [N]
Tensile strength \( f_t \) 0.55 [MPa]
Fracture energy \( G_F \) 3.40 [J/m\(^2\)]
Young’s modulus \( E \) 9631 [MPa]
Displacement at peak \( \delta_{\text{peak}} \) 6.3 [\( \mu \text{m} \)]

Graphics

Load - deformation 5_4_7d_02

Pre-peak

Post-peak

Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
**General information**

- **Test name**: 5_4_7d_03
- **Tensile test method**: Non-rotating loading platens
- **Print date**: 2016-dec-07; 2016-dec-14
- **Test date & time**: 2017-jan-10 11:58
- **Deformation rate**: $r = 5 \, [\mu m/min]$

**Specimen**

- **Height**: $z = 40.1 \, [mm]$
- **Width (at crack)**: $x = 28.3 \, [mm]$
- **Thickness (at crack)**: $y = 36.9 \, [mm]$
- **Density**: $\rho = 1981 \, [kg/m^3]$

**Results**

- **Tensile force**: $F_t = 875.3 \, [N]$
- **Tensile strength**: $f_t = 0.84 \, [MPa]$
- **Fracture energy**: $G_F = 5.25 \, [J/m^2]$
- **Young’s modulus**: $E = 11209 \, [MPa]$
- **Displacement at peak**: $\delta_{peak} = 4.3 \, [\mu m]$

**Graphics**

**Load - deformation 5_4_7d_03**

![Load - deformation graph](image)

**Pre-peak**

- **Stress vs. strain**
- **Post-peak**

- **Stress vs. crack opening**

---

**Appendix F** Experimental results direct tensile tests
General information

Test name: 5_4_7d_04
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07; 2016-dec-14
Test date & time: 2017-jan-10 12:47
Deformation rate: \( r = 5 \text{ [\mu m/min]} \)

Specimen

Height: \( z = 40.4 \text{ [mm]} \)
Width (at crack): \( x = 27.0 \text{ [mm]} \)
Thickness (at crack): \( y = 37.3 \text{ [mm]} \)
Density: \( \rho = 1987 \text{ [kg/m}^3 \text{]} \)

Results

Tensile force: \( F_t = 692.4 \text{ [N]} \)
Tensile strength: \( f_t = 0.69 \text{ [MPa]} \)
Fracture energy: \( G_F = 4.50 \text{ [J/m}^2 \text{]} \)
Young's modulus: \( E = 10194 \text{ [MPa]} \)
Displacement at peak: \( \delta_{\text{peak}} = 4.1 \text{ [\mu m]} \)

Graphics

Load - deformation 5_4_7d_04

Pre-peak

Post-peak

Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
General information
Test name 5_4_7d_05
Tensile test method Non-rotating loading platens
Print date 2016-dec-07; 2016-dec-14
Test date & time 2017-jan-10 13:37
Deformation rate \( r = 5 \, \mu\text{m/min} \)

Specimen
Height \( z = 40.4 \, \text{mm} \)
Width (at crack) \( x = 28.6 \, \text{mm} \)
Thickness (at crack) \( y = 36.0 \, \text{mm} \)
Density \( \rho = 1994 \, \text{kg/m}^3 \)

Results
Tensile force \( F_t = 532.1 \, \text{N} \)
Tensile strength \( f_t = 0.52 \, \text{MPa} \)
Fracture energy \( G_F = 4.32 \, \text{J/m}^2 \)
Young’s modulus \( E = 10261 \, \text{MPa} \)
Displacement at peak \( \delta_{\text{peak}} = 5.2 \, \mu\text{m} \)

Graphics

Load - deformation 5_4_7d_05

Pre-peak

Post-peak

Appendix F Experimental results direct tensile tests
General information

Test name: 5_4_7d_06
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07; 2016-dec-14
Test date & time: 2017-jan-10 14:34
Deformation rate: \( r = 5 \, [\mu m/min] \)

Specimen

Height: \( z = 40.7 \, [mm] \)
Width (at crack): \( x = 26.6 \, [mm] \)
Thickness (at crack): \( y = 36.1 \, [mm] \)
Density: \( \rho = 1977 \, [kg/m^3] \)

Results

Tensile force: \( F_t = 994.7 \, [N] \)
Tensile strength: \( f_t = 1.04 \, [MPa] \)
Fracture energy: \( G_F = 7.02 \, [J/m^2] \)
Young's modulus: \( E = 11432 \, [Mpa] \)
Displacement at peak: \( \delta_{peak} = 5.6 \, [\mu m] \)

Graphics

Load - deformation 5_4_7d_06

Pre-peak

Post-peak
**General Information**

- **Test name**: 5_4_7d_07
- **Tensile test method**: Non-rotating loading platens
- **Print date**: 2016-dec-07; 2016-dec-14
- **Test date & time**: 2017-jan-10 15:24
- **Deformation rate**: $r = 5 \, [\mu m/min]$

**Specimen**

- **Height**: $z = 40.6 \, [mm]$
- **Width (at crack)**: $x = 27.6 \, [mm]$
- **Thickness (at crack)**: $y = 36.1 \, [mm]$
- **Density**: $\rho = 1986 \, [kg/m^3]$

**Results**

- **Tensile force**: $F_t = 631.2 \, [N]$
- **Tensile strength**: $f_t = 0.64 \, [MPa]$
- **Fracture energy**: $G_F = 3.75 \, [J/m^2]$
- **Young’s modulus**: $E = 10191 \, [MPa]$
- **Displacement at peak**: $\delta_{peak} = 5.0 \, [\mu m]$

**Graphics**

- **Load - deformation 5_4_7d_07**
- **Pre-peak**
- **Post-peak**
General information

Test name: 5_4_7d_08
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-07; 2016-dec-14
Test date & time: 2017-jan-10 16:07
Deformation rate: $r = 5 \text{ [µm/min]}$

Specimen

Height: $z = 40.5 \text{ [mm]}$
Width (at crack): $x = 27.3 \text{ [mm]}$
Thickness (at crack): $y = 35.7 \text{ [mm]}$
Density: $\rho = 1971 \text{ [kg/m}^3]\text{]}$

Results

Tensile force: $F_t = 627.3 \text{ [N]}$
Tensile strength: $f_t = 0.64 \text{ [MPa]}$
Fracture energy: $G_F = 4.09 \text{ [J/m}^2]\text{]}$
Young’s modulus: $E = 10440 \text{ [MPa]}$
Displacement at peak: $\delta_{\text{peak}} = 3.9 \text{ [µm]}$

Graphics

Load - deformation 5_4_7d_08

Pre-peak

Post-peak
General information
Test name 5.4_7d_09
Tensile test method Non-rotating loading platens
Print date 2016-dec-07; 2016-dec-14
Test date & time 2017-jan-10 16:54
Deformation rate \( r \) 5 [\( \mu \text{m/min} \)]

Specimen
Height \( z \) 40.5 [mm]
Width (at crack) \( x \) 28.4 [mm]
Thickness (at crack) \( y \) 37.0 [mm]
Density \( \rho \) 2006 [kg/m\(^3\)]

Results
Tensile force \( F_t \) 1066.1 [N]
Tensile strength \( f_t \) 1.01 [MPa]
Fracture energy \( G_f \) 4.90 [J/m\(^2\)]
Young’s modulus \( E \) 11622 [MPa]
Displacement at peak \( \delta_{\text{peak}} \) 5.8 [\( \mu \text{m} \)]

Graphics

Load - deformation 5.4_7d_09

Pre-peak

Post-peak
General information
Test name 5_4_7d_10
Tensile test method Non-rotating loading platens
Print date 2016-dec-07; 2016-dec-14
Test date & time 2017-jan-10 17:37
Deformation rate $r = 5 \, [\mu m/min]$

Specimen
Height $z = 40.6 \, [mm]$
Width (at crack) $x = 27.9 \, [mm]$
Thickness (at crack) $y = 35.9 \, [mm]$
Density $\rho = 1983 \, [kg/m^3]$

Results
Tensile force $F_t = 700.7 \, [N]$
Tensile strength $f_t = 0.70 \, [MPa]$
Fracture energy $G_F = 3.85 \, [J/m^2]$
Young’s modulus $E = 9713 \, [MPa]$
Displacement at peak $\delta_{peak} = 5.8 \, [\mu m]$

Graphics

Load - deformation 5_4_7d_10

Pre-peak

Post-peak
**General information**
- **Test name**: 5_4_7d_11
- **Tensile test method**: Non-rotating loading platens
- **Print date**: 2016-dec-07; 2016-dec-14
- **Test date & time**: 2017-jan-10 18:18
- **Deformation rate** $r$ 5 [µm/min]

**Specimen**
- **Height** $z$ 40.6 [mm]
- **Width (at crack)** $x$ 28.4 [mm]
- **Thickness (at crack)** $y$ 35.9 [mm]
- **Density** $\rho$ 1989 [kg/m³]

**Results**
- **Tensile force** $F_t$ 918.9 [N]
- **Tensile strength** $f_t$ 0.90 [MPa]
- **Fracture energy** $G_F$ 5.03 [J/m²]
- **Young’s modulus** $E$ 12364 [MPa]
- **Displacement at peak** $\delta_{\text{peak}}$ 4.5 [µm]

**Graphics**

**Load - deformation 5_4_7d_11**

**Pre-peak**

**Post-peak**
### General information

- **Test name**: 5_4_7d_12
- **Tensile test method**: Non-rotating loading platens
- **Print date**: 2016-dec-07; 2016-dec-14
- **Test date & time**: 2017-jan-10 18:57
- **Deformation rate**: \( r = 5 \text{ [µm/min]} \)

### Specimen

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height z</td>
<td>40.7 mm</td>
</tr>
<tr>
<td>Width (at crack) x</td>
<td>28.7 mm</td>
</tr>
<tr>
<td>Thickness (at crack) y</td>
<td>35.8 mm</td>
</tr>
<tr>
<td>Density ( \rho )</td>
<td>1990 kg/m³</td>
</tr>
</tbody>
</table>

### Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile force ( F_t )</td>
<td>568.8 N</td>
</tr>
<tr>
<td>Tensile strength ( f_t )</td>
<td>0.55 MPa</td>
</tr>
<tr>
<td>Fracture energy ( G_F )</td>
<td>5.14 J/m²</td>
</tr>
<tr>
<td>Young’s modulus ( E )</td>
<td>8563 MPa</td>
</tr>
<tr>
<td>Displacement at peak ( \delta_{peak} )</td>
<td>3.9 [µm]</td>
</tr>
</tbody>
</table>

### Graphics

#### Load - deformation 5_4_7d_12

- **Graph**: Load - deformation plot with load \( F \) vs. deformation \( \delta \) [µm].
- **Legend**: LVDT-06, LVDT-07, LVDT-11, LVDT-12, Instron, Average.

#### Stress vs. strain

- **Graph**: Stress vs. strain plot with stress \( \sigma \) [MPa] vs. strain \( \varepsilon \) [%\( \varepsilon \)].

#### Crack opening vs. load

- **Graph**: Crack opening \( w \) [µm] vs. load \( F \) [N].

---

Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
General information
Test name 6_2_0d_01
Tensile test method Non-rotating loading platens
Print date 2016-dec-14
Test date & time 2017-jan-11 10:14
Deformation rate \( r = 5 \, [\mu\text{m/min}] \)

Specimen
Height \( z = 40.3 \, [\text{mm}] \)
Width (at crack) \( x = 28.7 \, [\text{mm}] \)
Thickness (at crack) \( y = 39.7 \, [\text{mm}] \)
Density \( \rho = 1970 \, [\text{kg/m}^3] \)

Results
Tensile force \( F_t = 1722.4 \, [\text{N}] \)
Tensile strength \( f_t = 1.51 \, [\text{MPa}] \)
Fracture energy \( G_F = 27.00 \, [\text{J/m}^2] \)
Young’s modulus \( E = 11508 \, [\text{MPa}] \)
Displacement at peak \( \delta_{\text{peak}} = 7.9 \, [\mu\text{m}] \)

Graphics

Appendix F
Experimental results direct tensile tests
**General information**

- Test name: 6_2_0d_02
- Tensile test method: Non-rotating loading platens
- Print date: 2016-dec-14
- Test date & time: 2017-jan-11 11:01
- Deformation rate: \( r = 5 \, \text{[µm/min]} \)

**Specimen**

- Height: \( z = 40.4 \, \text{[mm]} \)
- Width (at crack): \( x = 26.0 \, \text{[mm]} \)
- Thickness (at crack): \( y = 39.7 \, \text{[mm]} \)
- Density: \( \rho = 1951 \, \text{[kg/m}^3\text{]} \)

**Results**

- Tensile force: \( F_t = 1563.2 \, \text{[N]} \)
- Tensile strength: \( f_t = 1.52 \, \text{[MPa]} \)
- Fracture energy: \( G_F = 32.66 \, \text{[J/m}^2\text{]} \)
- Young’s modulus: \( E = 13326 \, \text{[MPa]} \)
- Displacement at peak: \( \delta_{\text{peak}} = 6.9 \, \text{[µm]} \)

**Graphics**

![Load - deformation graph](image)

- **Load - deformation graph**
  - Pre-peak
    - Stress \( \sigma \) vs. Strain \( \varepsilon \)
    - Load \( F \) vs. Deformation \( \delta \)
  - Post-peak
    - Stress \( \sigma \) vs. Crack opening \( w \)
General information
Test name 6_2_0d_03
Tensile test method Non-rotating loading platens
Print date 2016-dec-14
Test date & time 2017-jan-11 11:43
Deformation rate $r = 5 \text{ [}\mu\text{m/min}]$

Specimen
Height $z = 40.3 \text{ [mm]}$
Width (at crack) $x = 29.2 \text{ [mm]}$
Thickness (at crack) $y = 39.6 \text{ [mm]}$
Density $\rho = 1978 \text{ [kg/m}^3\text{]}$

Results
Tensile force $F_t = 1956.4 \text{ [N]}$
Tensile strength $f_t = 1.69 \text{ [MPa]}$
Fracture energy $G_F = 33.93 \text{ [J/m}^2\text{]}$
Young’s modulus $E = 11455 \text{ [MPa]}$
Displacement at peak $\delta_{\text{peak}} = 9.3 \text{ [}\mu\text{m}]$

Graphics

Appendix F Experimental results direct tensile tests
**General information**

Test name: 6_2_0d_04  
Tensile test method: Non-rotating loading platens  
Print date: 2016-dec-14  
Test date & time: 2017-jan-11 12:30  
Deformation rate: \( r = 5 \text{ [\mu m/min]} \)

**Specimen**

Height: \( z = 40.4 \text{ [mm]} \)  
Width (at crack): \( x = 28.2 \text{ [mm]} \)  
Thickness (at crack): \( y = 39.8 \text{ [mm]} \)  
Density: \( \rho = 1951 \text{ [kg/m}^3]\)

**Results**

Tensile force: \( F_t = 1965.2 \text{ [N]} \)  
Tensile strength: \( f_t = 1.75 \text{ [MPa]} \)  
Fracture energy: \( G_F = 21.31 \text{ [J/m}^2]\)  
Young’s modulus: \( E = 12587 \text{ [MPa]} \)  
Displacement at peak: \( \delta_{peak} = 8.6 \text{ [\mu m]} \)

**Graphics**

Load - deformation 6_2_0d_04

Pre-peak

Post-peak

Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
**General information**

Test name: 6.2_0d_05

Tensile test method: Non-rotating loading platens

Print date: 2016-dec-14

Test date & time: 2017-jan-11 13:14

Deformation rate: \( r = 5 \, \text{[µm/min]} \)

**Specimen**

Height: \( z = 40.4 \, \text{[mm]} \)

Width (at crack): \( x = 29.4 \, \text{[mm]} \)

Thickness (at crack): \( y = 39.3 \, \text{[mm]} \)

Density: \( \rho = 1953 \, \text{[kg/m}^3\text{]} \)

**Results**

Tensile force: \( F_t = 1813.7 \, \text{[N]} \)

Tensile strength: \( f_t = 1.57 \, \text{[MPa]} \)

Fracture energy: \( G_F = 48.96 \, \text{[J/m}^2\text{]} \)

Young's modulus: \( E = 11159 \, \text{[MPa]} \)

Displacement at peak: \( \delta_{\text{peak}} = 8.0 \, \text{[µm]} \)

**Graphics**

![Load - deformation graph](image)

![Pre-peak and Post-peak graphs](image)
General information
Test name 6_2_0d_06
Tensile test method Non-rotating loading platens
Print date 2016-dec-14
Test date & time 2017-jan-11 14:03
Deformation rate \( r \) [\( 5\, \mu \text{m/min} \)]

Specimen
Height \( z \) [40.2 mm]
Width (at crack) \( x \) [27.8 mm]
Thickness (at crack) \( y \) [40.3 mm]
Density \( \rho \) [1961 kg/m\(^3\)]

Results
Tensile force \( F_t \) [1703.3 N]
Tensile strength \( f_t \) [1.52 MPa]
Fracture energy \( G_F \) [24.52 J/m\(^2\)]
Young’s modulus \( E \) [11052 MPa]
Displacement at peak \( \delta_{\text{peak}} \) [8.6 \( \mu \text{m} \)]

Graphics

Load - deformation 6_2_0d_06

Pre-peak

Post-peak
General information
Test name: 6_2_0d_07
Tensile test method: Non-rotating loading platens
Print date: 2016-Dec-14
Test date & time: 2017-Jan-11 14:50
Deformation rate: \( r = 5 \, \text{[\mu m/min]} \)

Specimen
Height: \( z = 40.2 \, \text{[mm]} \)
Width (at crack): \( x = 28.3 \, \text{[mm]} \)
Thickness (at crack): \( y = 39.1 \, \text{[mm]} \)
Density: \( \rho = 1966 \, \text{[kg/m}^3\text{]} \)

Results
Tensile force: \( F_t = 1741.1 \, \text{[N]} \)
Tensile strength: \( f_t = 1.57 \, \text{[MPa]} \)
Fracture energy: \( G_F = 42.31 \, \text{[J/m}^2\text{]} \)
Young’s modulus: \( E = 11794 \, \text{[MPa]} \)
Displacement at peak: \( \delta_{\text{peak}} = 7.4 \, \text{[\mu m]} \)

Graphics

Load - deformation 6_2_0d_07

Pre-peak

Post-peak
General information

Test name 6_2_0d_08
Tensile test method Non-rotating loading platens
Print date 2016-dec-14
Test date & time 2017-jan-11 15:39
Deformation rate \( r = 5 \) [µm/min]

Specimen

Height \( z = 40.3 \) [mm]
Width (at crack) \( x = 28.4 \) [mm]
Thickness (at crack) \( y = 39.4 \) [mm]
Density \( \rho = 1974 \) [kg/m³]

Results

Tensile force \( F_t = 1597.2 \) [N]
Tensile strength \( f_t = 1.43 \) [MPa]
Fracture energy \( G_F = 22.68 \) [J/m²]
Young’s modulus \( E = 12013 \) [Mpa]
Displacement at peak \( \delta_{\text{peak}} = 6.8 \) [µm]

Graphics

Load - deformation 6_2_0d_08

Pre-peak

Post-peak

Influence of the interface between layers on the tensile properties of 3D printed concrete | Appendices
**General information**

Test name: 6_2_0d_09  
Tensile test method: Non-rotating loading platens  
Print date: 2016-dec-14  
Test date & time: 2017-jan-11 16:39  
Deformation rate: \( r \equiv 5 \text{ [µm/min]} \)

**Specimen**

Height: \( z \equiv 40.2 \text{ [mm]} \)  
Width (at crack): \( x \equiv 36.9 \text{ [mm]} \)  
Thickness (at crack): \( y \equiv 39.8 \text{ [mm]} \)  
Density: \( \rho \equiv 1961 \text{ [kg/m}^3\text{]} \)

**Results**

Tensile force: \( F_t \equiv 1766.1 \text{ [N]} \)  
Tensile strength: \( f_t \equiv 1.21 \text{ [MPa]} \)  
Fracture energy: \( G_F \equiv 36.48 \text{ [J/m}^2\text{]} \)  
Young’s modulus: \( E \equiv 8362 \text{ [MPa]} \)  
Displacement at peak: \( \delta_{peak} \equiv 8.8 \text{ [µm]} \)

**Graphics**

*Load - deformation 6_2_0d_09*

*Pre-peak*

*Post-peak*

Appendix F Experimental results direct tensile tests 141
**General information**

Test name: 6_2_0d_10  
Tensile test method: Non-rotating loading platens  
Print date: 2016-dec-14  
Test date & time: 2017-jan-11 17:24  
Deformation rate: \( r = 5 \, \mu \text{m/min} \)

**Specimen**

Height: \( z = 40.4 \, \text{mm} \)  
Width (at crack): \( x = 28.8 \, \text{mm} \)  
Thickness (at crack): \( y = 39.7 \, \text{mm} \)  
Density: \( \rho = 1956 \, \text{kg/m}^3 \)

**Results**

Tensile force: \( F_t = 1508.4 \, \text{N} \)  
Tensile strength: \( f_t = 1.32 \, \text{MPa} \)  
Fracture energy: \( G_F = 45.95 \, \text{J/m}^2 \)  
Young's modulus: \( E = 10340 \, \text{MPa} \)  
Displacement at peak: \( \delta_{\text{peak}} = 9.0 \, \mu \text{m} \)

**Graphics**

*Load - deformation 6_2_0d_10*

- Load - deformation graph showing the relationship between load \( F \) and deformation \( \delta \) for different LVDTs (LVDT-06, LVDT-07, LVDT-11, LVDT-12) and Instron average.

*Pre-peak*

- Stress \( \sigma \) vs. strain \( \varepsilon \) graph in the pre-peak phase.

*Post-peak*

- Stress \( \sigma \) vs. crack opening \( w \) graph in the post-peak phase.
General information

Test name: 6_2_0d_11
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-14
Test date & time: 2017-jan-11 18:10
Deformation rate: \( r = 5 \text{ [\mu m/min]} \)

Specimen

Height: \( z = 40.4 \text{ [mm]} \)
Width (at crack): \( x = 29.5 \text{ [mm]} \)
Thickness (at crack): \( y = 39.8 \text{ [mm]} \)
Density: \( \rho = 1968 \text{ [kg/m}^3] \)

Results

Tensile force: \( F_t = 1571.4 \text{ [N]} \)
Tensile strength: \( f_t = 1.34 \text{ [MPa]} \)
Fracture energy: \( G_F = 39.70 \text{ [J/m}^2] \)
Young's modulus: \( E = 10403 \text{ [MPa]} \)
Displacement at peak: \( \delta_{\text{peak}} = 8.8 \text{ [\mu m]} \)

Graphics

Load - deformation 6_2_0d_11

Pre-peak

Post-peak

Appendix F Experimental results direct tensile tests
**General information**

Test name: 6_2_0d_12  
Tensile test method: Non-rotating loading platens  
Print date: 2016-dec-14  
Test date & time: 2017-jan-11 18:52  
Deformation rate: \( r = 5 \text{ [\mu m/min]} \)

**Specimen**

Height: \( z = 40.4 \text{ [mm]} \)  
Width (at crack): \( x = 29.7 \text{ [mm]} \)  
Thickness (at crack): \( y = 39.7 \text{ [mm]} \)  
Density: \( \rho = 1961 \text{ [kg/m}^3\text{]} \)

**Results**

Tensile force: \( F_t = 1473.8 \text{ [N]} \)  
Tensile strength: \( f_t = 1.25 \text{ [MPa]} \)  
Fracture energy: \( G_F = 20.22 \text{ [J/m}^2\text{]} \)  
Young’s modulus: \( E = 9242 \text{ [MPa]} \)  
Displacement at peak: \( \delta_{\text{peak}} = 10.5 \text{ [\mu m]} \)

**Graphics**

**Load - deformation 6_2_0d_12**

[Graph showing load vs. deformation]

**Pre-peak**

[Stress vs. strain graph]

**Post-peak**

[Stress vs. crack opening graph]
**General information**

Test name 7_1_0d_01
Tensile test method Non-rotating loading platens
Print date 2016-dec-14
Test date & time 2017-jan-12 10:22
Deformation rate $r = 5 \text{ [µm/min]}$

**Specimen**

Height $z = 40.7 \text{ [mm]}$
Width (at crack) $x = 29.3 \text{ [mm]}$
Thickness (at crack) $y = 40.3 \text{ [mm]}$
Density $\rho = 1957 \text{ [kg/m}^3\text{]}$

**Results**

Tensile force $F_t = 1670.2 \text{ [N]}$
Tensile strength $f_t = 1.42 \text{ [MPa]}$
Fracture energy $G_F = 34.88 \text{ [J/m}^2\text{]}$
Young’s modulus $E = 11450 \text{ [Mpa]}$
Displacement at peak $\delta_{\text{peak}} = 9.5 \text{ [µm]}$

**Graphics**

![Load - deformation 7_1_0d_01](image)

![Pre-peak](image)

![Post-peak](image)
**General information**

Test name: 7_1_0d_02  
Tensile test method: Non-rotating loading platens  
Print date: 2016-dec-14  
Test date & time: 2017-jan-12 11:07  
Deformation rate: \( r = 5 \text{ [\( \mu \text{m/min} \)]} \)

**Specimen**

Height: \( z = 40.7 \text{ [mm]} \)  
Width (at crack): \( x = 28.5 \text{ [mm]} \)  
Thickness (at crack): \( y = 40.6 \text{ [mm]} \)  
Density: \( \rho = 1986 \text{ [kg/m}^3\text{]} \)

**Results**

Tensile force: \( F_t = 1710.6 \text{ [N]} \)  
Tensile strength: \( f_t = 1.48 \text{ [MPa]} \)  
Fracture energy: \( G_F = 38.99 \text{ [J/m}^2\text{]} \)  
Young’s modulus: \( E = 11791 \text{ [MPa]} \)  
Displacement at peak: \( \delta_{\text{peak}} = 8.3 \text{ [\( \mu \text{m} \)]} \)

**Graphics**

---

**Load - deformation 7_1_0d_02**

- **Pre-peak**
  - Stress \( \sigma \) vs. strain \( \varepsilon \)
  - Crack opening \( w \) vs. load \( F \)

- **Post-peak**
  - Stress \( \sigma \) vs. deformation \( \delta \)
General information
Test name 7_1_0d_03
Tensile test method Non-rotating loading platens
Print date 2016-dec-14
Test date & time 2017-jan-12 11:55
Deformation rate $r = 5 \text{ [µm/min]}$

Specimen
Height $z = 40.6 \text{ [mm]}$
Width (at crack) $x = 29.3 \text{ [mm]}$
Thickness (at crack) $y = 40.3 \text{ [mm]}$
Density $\rho = 1961 \text{ [kg/m}^3\text{]}$

Results
Tensile force $F_t = 1577.6 \text{ [N]}$
Tensile strength $f_t = 1.34 \text{ [MPa]}$
Fracture energy $G_F = 33.67 \text{ [J/m}^2\text{]}$
Young’s modulus $E = 10654 \text{ [Mpa]}$
Displacement at peak $\delta_{\text{peak}} = 10.3 \text{ [µm]}$

Graphics

Load - deformation 7_1_0d_03

Pre-peak

Post-peak
General information
Test name: 7_1_0d_04
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-14
Test date & time: 2017-jan-12 12:48
Deformation rate: \( r = 5 \, [\mu m/min] \)

Specimen
Height: \( z = 40.4 \, [mm] \)
Width (at crack): \( x = 29.2 \, [mm] \)
Thickness (at crack): \( y = 39.9 \, [mm] \)
Density: \( \rho = 1970 \, [kg/m^3] \)

Results
Tensile force: \( F_t = 1552.6 \, [N] \)
Tensile strength: \( f_t = 1.33 \, [MPa] \)
Fracture energy: \( G_F = 42.90 \, [J/m^2] \)
Young’s modulus: \( E = 11367 \, [Mpa] \)
Displacement at peak: \( \delta_{peak} = 7.7 \, [\mu m] \)

Graphics

Load - deformation 7_1_0d_04

Pre-peak

Post-peak
General information
Test name 7_1_0d_05
Tensile test method Non-rotating loading platens
Print date 2016-dec-14
Test date & time 2017-jan-12 13:30
Deformation rate \( r = 5 \) [\( \mu \text{m/min} \)]

Specimen
Height \( z = 40.6 \) [mm]
Width (at crack) \( x = 29.4 \) [mm]
Thickness (at crack) \( y = 40.2 \) [mm]
Density \( \rho = 1948 \) [kg/m\(^3\)]

Results
Tensile force \( F_t = 1826.0 \) [N]
Tensile strength \( f_t = 1.55 \) [MPa]
Fracture energy \( G_F = 27.12 \) [J/m\(^2\)]
Young's modulus \( E = 11076 \) [Mpa]
Displacement at peak \( \delta_{\text{peak}} = 8.2 \) [\( \mu \text{m} \)]

Graphics
General information
Test name 7_1_0d_06
Tensile test method Non-rotating loading platens
Print date 2016-dec-14
Test date & time 2017-jan-12 14:54
Deformation rate \( \tau \) 5 [\mu m/min]

Specimen
Height \( z \) 40.6 [mm]
Width (at crack) \( x \) 28.1 [mm]
Thickness (at crack) \( y \) 40.2 [mm]
Density \( \rho \) 1959 [kg/m\(^3\)]

Results
Tensile force \( F_t \) 1646.3 [N]
Tensile strength \( f_t \) 1.46 [MPa]
Fracture energy \( G_F \) 31.97 [J/m\(^2\)]
Young’s modulus \( E \) 10566 [MPa]
Displacement at peak \( \delta_{\text{peak}} \) 8.3 [\mu m]

Graphics

Load - deformation 7_1_0d_06

Pre-peak

Post-peak
### General Information

<table>
<thead>
<tr>
<th>Test name</th>
<th>7_1_0d_07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile test method</td>
<td>Rotating loading platens</td>
</tr>
<tr>
<td>Print date</td>
<td>2016-dec-14</td>
</tr>
<tr>
<td>Test date &amp; time</td>
<td>2017-jan-12 15:49</td>
</tr>
<tr>
<td>Deformation rate r</td>
<td>2.5 [µm/min]</td>
</tr>
</tbody>
</table>

### Specimen

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height z</td>
<td>40.6 [mm]</td>
</tr>
<tr>
<td>Width x (at crack)</td>
<td>28.4 [mm]</td>
</tr>
<tr>
<td>Thickness y (at crack)</td>
<td>40.0 [mm]</td>
</tr>
<tr>
<td>Density ρ</td>
<td>1956 [kg/m³]</td>
</tr>
</tbody>
</table>

### Results

<table>
<thead>
<tr>
<th>Result</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile force $F_t$</td>
<td>1205.4 [N]</td>
</tr>
<tr>
<td>Tensile strength $f_t$</td>
<td>1.06 [MPa]</td>
</tr>
<tr>
<td>Fracture energy $G_F$</td>
<td>21.96 [J/m²]</td>
</tr>
<tr>
<td>Young’s modulus $E$</td>
<td>31558 [MPa]</td>
</tr>
<tr>
<td>Displacement at peak $δ_{peak}$</td>
<td>4.0 [µm]</td>
</tr>
</tbody>
</table>

### Graphics

---

**Load - deformation 7_1_0d_07**

- Pre-peak
- Post-peak

---

Appendix F Experimental results direct tensile tests
General information

Test name: 7_1_0d_08
Tensile test method: Rotating loading platens
Print date: 2016-dec-14
Test date & time: 2017-jan-12 17:01
Deformation rate: \( r = 2.5 \, [\mu m/min] \)

Specimen

Height: \( z = 40.6 \, [mm] \)
Width (at crack): \( x = 28.3 \, [mm] \)
Thickness (at crack): \( y = 40.2 \, [mm] \)
Density: \( \rho = 1980 \, [kg/m^3] \)

Results

Tensile force: \( F_t = 1442.0 \, [N] \)
Tensile strength: \( f_t = 1.27 \, [MPa] \)
Fracture energy: \( G_F = 27.62 \, [J/m^2] \)
Young’s modulus: \( E = 24521 \, [MPa] \)
Displacement at peak: \( \delta_{peak} = 3.5 \, [\mu m] \)

Graphics

Load - deformation 7_1_0d_08

Pre-peak

Post-peak
**General information**

- **Test name**: 7_1_0d_09
- **Tensile test method**: Rotating loading platens
- **Print date**: 2016-Dec-14
- **Test date & time**: 2017-Jan-12 17:28
- **Deformation rate**: \( r = 2.5 \) [µm/min]

**Specimen**

- **Height**: \( z = 40.6 \) [mm]
- **Width (at crack)**: \( x = 30.2 \) [mm]
- **Thickness (at crack)**: \( y = 39.9 \) [mm]
- **Density**: \( \rho = 1967 \) [kg/m³]

**Results**

- **Tensile force**: \( F_t = 1559.4 \) [N]
- **Tensile strength**: \( f_t = 1.30 \) [MPa]
- **Fracture energy**: \( G_F = 34.43 \) [J/m²]
- **Young’s modulus**: \( E = 30343 \) [MPa]
- **Displacement at peak**: \( \delta_{\text{peak}} = 3.7 \) [µm]

**Graphics**

- **Load - deformation 7_1_0d_09**
- **Pre-peak**
  - Stress \( \sigma \) vs. strain \( \epsilon \)
  - Crack opening \( w \) vs. deformation \( \delta \)
- **Post-peak**
  - Load \( F \) vs. deformation \( \delta \)
  - Stress \( \sigma \) vs. crack opening \( w \)
General information
Test name 7_1_0d_10
Tensile test method Rotating loading platens
Print date 2016-dec-14
Test date & time 2017-jan-12 17:48
Deformation rate $r = 2.5 \, [\mu m/min]$

Specimen
Height $z = 40.4 \, [mm]$
Width (at crack) $x = 26.5 \, [mm]$
Thickness (at crack) $y = 40.0 \, [mm]$
Density $\rho = 1973 \, [kg/m^3]$

Results
Tensile force $F_t = 1159.1 \, [N]$
Tensile strength $f_t = 1.10 \, [MPa]$
Fracture energy $G_F = 20.70 \, [J/m^2]$
Young’s modulus $E = 27664 \, [Mpa]$
Displacement at peak $\delta_{peak} = 3.8 \, [\mu m]$

Graphics
**General information**

- **Test name**: 7_1_0d_11
- **Tensile test method**: Rotating loading platens
- **Print date**: 2016-Dec-14
- **Test date & time**: 2017-Jan-12 18:08
- **Deformation rate**: \( r = 2.5 \, [\mu m/min] \)

**Specimen**

<table>
<thead>
<tr>
<th>Height</th>
<th>( z )</th>
<th>40.6 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (at crack)</td>
<td>( x )</td>
<td>30.8 [mm]</td>
</tr>
<tr>
<td>Thickness (at crack)</td>
<td>( y )</td>
<td>40.0 [mm]</td>
</tr>
<tr>
<td>Density</td>
<td>( \rho )</td>
<td>1955 [kg/m(^3)]</td>
</tr>
</tbody>
</table>

**Results**

- **Tensile force**: \( F_t = 1204.7 \, [N] \)
- **Tensile strength**: \( f_t = 0.98 \, [MPa] \)
- **Fracture energy**: \( G_f = 29.48 \, [J/m^2] \)
- **Young’s modulus**: \( E = 30568 \, [MPa] \)
- **Displacement at peak**: \( \delta_{peak} = 4.5 \, [\mu m] \)

**Graphics**

- **Load - deformation 7_1_0d_11**
- **Pre-peak**
  - **stress** \( \sigma \) [MPa] vs **strain** \( \varepsilon \) [%]
  - **Post-peak**
  - **stress** \( \sigma \) [MPa] vs **crack opening** \( w \) [\mu m]
**General information**

Test name: 7_1_0d_12  
Tensile test method: Rotating loading platens  
Print date: 2016-dec-14  
Test date & time: 2017-jan-12 18:24  
Deformation rate: $r = 2.5$ [μm/min]

**Specimen**

Height: $z = 40.7$ [mm]  
Width (at crack): $x = 28.0$ [mm]  
Thickness (at crack): $y = 40.0$ [mm]  
Density: $\rho = 1969$ [kg/m$^3$]

**Results**

Tensile force: $F_t = 1634.7$ [N]  
Tensile strength: $f_t = 1.46$ [MPa]  
Fracture energy: $G_F = 28.23$ [J/m$^2$]  
Young’s modulus: $E = 23762$ [Mpa]  
Displacement at peak: $\delta_{\text{peak}} = 5.5$ [μm]

**Graphics**

---

**Load - deformation 7_1_0d_12**

---

**Pre-peak**

---

**Post-peak**

---
General information
Test name: 8_4_0d_01
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-7
Test date & time: 2017-jan-26 14:21
Deformation rate: $r = 5 \text{ [µm/min]}$

Specimen
Height: $z = 40.4 \text{ [mm]}$
Width (at crack): $x = 27.2 \text{ [mm]}$
Thickness (at crack): $y = 38.5 \text{ [mm]}$
Density: $\rho = 1941 \text{ [kg/m}^3\text{]}$

Results
Tensile force: $F_t = 1094.5 \text{ [N]}$
Tensile strength: $f_t = 1.05 \text{ [Mpa]}$
Fracture energy: $G_F = 20.08 \text{ [J/m}^2\text{]}$
Young's modulus: $E = 10927; 14084 \text{ [Mpa]}$
Displacement at peak: $\delta_{peak} = 7.5 \text{ [µm]}$

Graphics

Load - deformation 8_4_0d_01

Pre-peak

LVDT's 6,7

Post-peak

LVDT's

Appendix F Experimental results direct tensile tests
**General information**

Test name: 8_4_0d_02
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-7
Test date & time: 2017-jan-26 15:16
Deformation rate: $r = 5 \text{ [μm/min]}$

**Specimen**
Height: $z = 40.5 \text{ [mm]}$
Width (at crack): $x = 29.2 \text{ [mm]}$
Thickness (at crack): $y = 38.1 \text{ [mm]}$
Density: $\rho = 1943 \text{ [kg/m}^3]\text{]}

**Results**
Tensile force: $F_t = 1292.3 \text{ [N]}$
Tensile strength: $f_t = 1.17 \text{ [MPa]}$
Fracture energy: $G_f = 26.60 \text{ [J/m}^2]\text{]}
Young's modulus: $E = 12084; 15202 \text{ [MPa]}$
Displacement at peak: $\delta_{peak} = 8.9 \text{ [μm]}$

**Graphics**

Load - deformation 8_4_0d_02

Pre-peak

Post-peak
**General information**

Test name: 8.4_0d_03

Tensile test method: Non-rotating loading platens

Print date: 2016-dec-7

Test date & time: 2017-jan-26 16:19

Deformation rate: \( r = 5 \ \mu \text{m/min} \)

**Specimen**

Height: \( z = 40.5 \ \text{mm} \)

Width (at crack): \( x = 28.0 \ \text{mm} \)

Thickness (at crack): \( y = 38.2 \ \text{mm} \)

Density: \( \rho = 1946 \ \text{kg/m}^3 \)

**Results**

Tensile force: \( F_t = 1440.4 \ \text{N} \)

Tensile strength: \( f_t = 1.35 \ \text{Mpa} \)

Fracture energy: \( G_f = 29.04 \ \text{J/m}^2 \)

Young’s modulus: \( E = 11455; 16219 \ \text{Mpa} \)

Displacement at peak: \( \delta_{\text{peak}} = 8.4 \ \mu \text{m} \)

**Graphics**

![Load - deformation 8.4_0d_03](image)

**Appendix F**

Experimental results direct tensile tests
General information
Test name 8_4_0d_04
Tensile test method Non-rotating loading platens
Print date 2016-dec-7
Test date & time 2017-jan-26 18:49
Deformation rate \( r = 5 \, \mu\text{m/\text{min}} \)

Specimen
Height \( z = 40.5 \, \text{mm} \)
Width (at crack) \( x = 28.3 \, \text{mm} \)
Thickness (at crack) \( y = 38.2 \, \text{mm} \)
Density \( \rho = 1964 \, \text{kg/m}^3 \)

Results
Tensile force \( F_t = 1477.4 \, \text{N} \)
Tensile strength \( f_t = 1.37 \, \text{Mpa} \)
Fracture energy \( G_F = 31.80 \, \text{J/m}^2 \)
Young’s modulus \( E = 11968; \, 16636 \, \text{Mpa} \)
Displacement at peak \( \delta_{\text{peak}} = 7.7 \, \mu\text{m} \)

Graphics

Load - deformation 8_4_0d_04

Pre-peak

Post-peak
General information

Test name: 8_4_0d_05
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-7
Test date & time: 2017-jan-31 12:14
Deformation rate: $r \, 2.5 \, [\mu m/min]$

Specimen

Height: $z \, 40.4 \, [mm]$
Width (at crack): $x \, 28.6 \, [mm]$
Thickness (at crack): $y \, 38.7 \, [mm]$
Density: $\rho \, 1945 \, [kg/m^3]$

Results

Tensile force: $F_t \, 1497.4 \, [N]$
Tensile strength: $f_t \, 1.36 \, [MPa]$
Fracture energy: $G_F \, 27.66 \, [J/m^2]$
Young’s modulus: $E \, 15958 \, [Mpa]$
Displacement at peak: $\delta_{peak} \, 4.5 \, [\mu m]$

Graphics

Load - deformation 8_4_0d_05

Pre-peak

Post-peak
**General information**

Test name: 8.4.0d.06  
Tensile test method: Non-rotating loading platens  
Print date: 2016-dec-7  
Test date & time: 2017-jan-31 13:49  
Deformation rate: $r = 2.5 \, [\mu \text{m/min}]$

**Specimen**

- Height: $z = 40.5 \, [\text{mm}]$
- Width (at crack): $x = 28.5 \, [\text{mm}]$
- Thickness (at crack): $y = 38.0 \, [\text{mm}]$
- Density: $\rho = 1951 \, [\text{kg/m}^3]$

**Results**

- Tensile force: $F_t = 1675.8 \, [\text{N}]$
- Tensile strength: $f_t = 1.55 \, [\text{MPa}]$
- Fracture energy: $G_F = 30.33 \, [\text{J/m}^2]$
- Young’s modulus: $E = 16097 \, [\text{MPa}]$
- Displacement at peak: $\delta_{\text{peak}} = 8.4 \, [\mu \text{m}]$

**Graphics**

Load - deformation 8.4.0d.06
General information
Test name: 8.4_0d_07
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-7
Test date & time: 2017-jan-31 15:02
Deformation rate: $r = 2.5 \, [\mu m/min]$

Specimen
Height: $z = 40.4 \, [mm]$
Width (at crack): $x = 28.0 \, [mm]$
Thickness (at crack): $y = 38.5 \, [mm]$
Density: $\rho = 1956 \, [kg/m^3]$

Results
Tensile force: $F_t = 1917.4 \, [N]$
Tensile strength: $f_t = 1.78 \, [MPa]$
Fracture energy: $G_F = 36.15 \, [J/m^2]$
Young’s modulus: $E = 13935 \, [MPa]$
Displacement at peak: $\delta_{peak} = 7.7 \, [\mu m]$

Graphics

Appendix F
Experimental results direct tensile tests
General information

Test name: 8_4_0d_08
Tensile test method: Non-rotating loading platens
Print date: 2016-dec-7
Test date & time: 2017-jan-31 16:42
Deformation rate: $r = 2.5 \, [\mu m/min]$

Specimen

Height: $z = 40.5 \, [mm]$
Width (at crack): $x = 27.5 \, [mm]$
Thickness (at crack): $y = 38.5 \, [mm]$
Density: $\rho = 1959 \, [kg/m^3]$

Results

Tensile force: $F_t = 1415.3 \, [N]$
Tensile strength: $f_t = 1.34 \, [MPa]$
Fracture energy: $G_F = 18.59 \, [J/m^2]$
Young’s modulus: $E = 15962 \, [MPa]$
Displacement at peak: $\delta_{peak} = 7.2 \, [\mu m]$

Graphics

Load - deformation 8_4_0d_08

Pre-peak

Post-peak