MASTER

Investigation into properties of fibre reinforced concrete in extrusion based adaptive manufacturing

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Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Adaptive Manufacturing

Graduation Thesis

W. (Wim) Raedts
Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Adaptive Manufacturing

Graduation Thesis

By Wim Raedts for completion of the Master’s phase of the study of Architecture, Building and Planning at the Department of the Built Environment at the TU/e, unit Structural Design

Title: Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Adaptive Manufacturing


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Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Manufacturing
Preface

The report in front of you is the result of my graduation project “Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Adaptive Manufacturing”. The state of the art of Fibre Reinforced Concrete (FRC) with respect to Extrusion Based Adaptive Manufacturing, or 3D printing, is missing. A start to Fibre Reinforced Concrete Printing (FRCP) has been made in two parts. Experimental and numerical research is conducted. In order to test printed specimens, a device is created to add fibres to the printing setup used by the research group of Three Dimensional Concrete Printing (3DCP) at Eindhoven University of Technology (TUe). The second was, conducting experimental research on the flexural strength of Fibre Reinforced Concrete. Next to the experimental research, a numerical model is created to determine the material behaviour of a beam manufactured of FRC. Each development started with the code used for FRC, and based on these codes, tests were conducted to determine properties of FRCP.

My words of gratitude would go towards many people. Firstly, my supervisors from TUe prof.dr.ir. Theo Salet, dr.ir. Freek Bos and MSc Zeeshan Ahmed. I want to thank them for their support and advice in terms of knowledge and experience during my graduation project. A special thanks goes to the employees of the Structural Lab at TUe. Their accompaniment and practical experience with machinery for the experimental tests was very welcome. Lastly, I want to thank the students involved with concrete printing for their support and criticism during studio meetings. Especially, Evgeniy Jutinov and Casper van der Krift for their support during developing, preparing and testing of specimen and devices.

Wim Raedts

Sevenum, December 2017
Abstract

Three-dimensional concrete printing (3DCP) is a relatively new manufacturing technique but, many studies have revealed that 3DCP can lead to new products. In order to print these products, the material, design, and reinforcement techniques have to be developed. In Eindhoven, a research group of the University of Technology is working hard to get more insight into varying research topics connected to 3DCP.

One of the topics is the implementation of reinforcement into the material used for printing. Nowadays, mostly rebar and fibres are used to reinforce the concrete. In this graduation project, a study on fibres is carried out. Based on the printing setup, an analysis is carried out to find a good solution to entrain fibres in the concrete during printing. By adding fibres, strain hardening material behaviour is desired. A device is designed and created to manage the entrainment of fibres. Due to a pending patent application, details are non-public and are added to this Graduation Thesis in a confidential appendix.

Apart from the device, a CMOD test is executed to verify the contribution of fibres to printed concrete for matters of ductility and flexural tensile strength in comparison with traditionally casted concrete. This is carried out in three steps of which the first is to conduct a test on traditionally cast specimens. The second set of tests is based on a smaller cast specimen in order to correspond with the printing dimensions. The third set of specimens is printed FRC.

The experimental results show an increase of flexural strength and ductility in all the specimens with fibres, despite the difference of casting specimens and printing specimens. The results of all the specimens with the same fibres are in line, regardless the different alignment of fibres due to manufacturing techniques.

A numerical model, based on linear elastic calculations of the multi-layer method and the moment-area method, is created to calculate the deflection of beams designed with FRC. By comparing the deflection of the model with the experimental data, some material parameters can be set for the tested material by means of a trial and error method.

The report concludes with recommendations to further research. More tests could be carried out to create a scientifically report about the classification of the printed FRC. Also, the validation of the test setup chosen to test printed FRC can be studied in further research.

An overall acknowledgement can be given to all the partners of the research into 3DCP at the University of Technology in Eindhoven. Two partners are pointed out which are, Weber Beamix and Bekaert NV. due to the sponsoring of the concrete and steel fibres used in this graduation project.
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Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Manufacturing
1. Introduction

1.1. Three-dimensional concrete printing

3D concrete printing (3DCP) is a relatively new manufacturing method. The traditional way of manufacturing concrete structures is followed by an additive manufacturing method, where the material is added to create the desired shape of an element. In 2015, a research group at the Department of the Built Environment of Eindhoven University of Technology (TUe) started contributing the research on printing concrete. Together with several companies, the research group invested in a concrete printer.

The fundamental part of this printer is a gantry robot. This robot is able to reach each coordinate on a horizontal 2D plane. Next, the robot is also able to move in a vertical direction, to create a 3D shape. The process is based on the placement of filaments of concrete on a horizontal plane. The cross-section of these filaments is determined by the nozzle, and theoretically, any shape could be created with this. By adapting the printer and pump speed, a different flow of concrete can be delivered to the nozzle to create different filament shapes. During the process, layers of concrete filament are stacked on top of each other to create height in the printed element. Because of material properties, it is difficult to create overhang between two layers. Therefore, the stacking procedure leads mostly to an extraction of the first layer. These kinds of structures are called 2.5D structures.

Contour Crafting is a well-known 2.5D manufacturing method which can be compared to the printing method used by the research group at the TUe. Layers of material are stacked onto former layers to build up the desired shapes. In contour crafting, the outline of a shape is printed in order to fill the opening afterwards. This is not necessary with 3DCP at the TUe. The created shape and stacked elements are the end product. Because of the fact that the stacked layers are the element itself, it is possible to create shapes and elements of a much smaller size.

In the graduation thesis of Wolfs, R (2015), the advantages of printing concrete are summed up.

- Framework is not needed. The printed element is stable due to material and shape.
- Freedom in design. Because almost every shape can be printed, the shape will not be the main cost anymore.
- Because the printer places the material in the desired place, the labour taken by the employees and the used material is reduced.
- Through using a shape-stable material, it is possible to manufacture at high speed.

One of the disadvantages is the lack of state of art on the structural performances of printed concrete. This is the main reason for the research group at the TUe to start and develop the research of printed concrete. The research group consists of two PhD students accompanied by graduation and master students. The group is supervised by the chair of Concrete Structures of the Unit Structural Design and is supported by a group of partners.
1.2. Fibre reinforced concrete printed

When developing research on 3DCP, different topics can be addressed. Material aspects are one of these topics, and can be split up into two parts: printed concrete and printed reinforced concrete. Some of the structural properties of printed concrete have already been investigated within the research group. For instance, structural properties as the tensile and compressive strength of the printed concrete are tested by several graduate students. On top of that, the influence of layered manufacturing on the tensile and compressive strength have also been investigated. The properties which are investigated are in line with traditionally casted concrete. This means that the concrete’s tensile strength is almost none. The brittleness which is common with traditionally casted concrete is also seen in tests with printed concrete. In traditionally casted concrete, both these disadvantages are partly solved by reinforcement of the material. In concrete printing, this is a brand new topic, and therefore, it is vital to research in order to create reinforced printed concrete.

The first possibility is reinforcing the currently printed concrete with rebar. This has been conducted for many years with traditionally casted concrete. Apart from reinforcement with rebar, reinforcement with fibres is another option. Fibre Reinforced Concrete (FRC) is used in different structural applications. FRC is known for its ductility. Where concrete is very brittle and breaks, the fibres will take over due to the bond strength of concrete and the fibres. In this case, the fibres will take care of the tensile forces. This leads to a higher peak strength, and much more absorption of energy by FRC according to the concrete itself. Fibre Reinforced Concrete Printed (FRCP) is, therefore, a next step in developing the knowledge of the 3DCP material.

The research to use rebar reinforcement in printed concrete is described in the graduation thesis by Jutinov, E (2017).

1.3. Research Goal and Methodology

“Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Adaptive Manufacturing”

Two goals are set in order to answer the main question in this graduation thesis;

- Set up experimental tests to determine flexural strength of FRCP.
- Develop a numerical tool for determining material behaviour to check print designs.

As it is stated before, the state of the art of FRCP is missing. FRCP can be seen as a new printing technique with a material that has never been printed before. Therefore, the research group needs to find a solution to create FRCP. FRC has advantages in terms of ductility and flexural strength, but disadvantages in terms of workability. When FRC can be printed, it is good to know the behaviour of the new material, so, the comparison between FRC and ‘normal’ concrete can be made.

The approach to achieve the stated goals is given in the experimental part and a numerical part. An experimental test is chosen for the experimental part, which is a CMOD test. This CMOD test is executed in three test cases. First, specimens are tested according to the Dutch code NEN-EN 14651
(2007). These are traditionally cast specimens. After the first CMOD test, a second CMOD test is executed on smaller specimens, comparable to the size of printed concrete. These specimens are also traditionally casted. Finally, printed specimens will be tested with a CMOD test as well. For printing specimens, a way to add fibres to the concrete needs to be determined. The printing process and the setup of the printer are analysed to determine at what stage the fibres can be added to the concrete. From that point on, a device needs to be made to add the fibres to the concrete. The current setup of the printer will be changed in order to print FRC. With the addition of fibres, the aim of creating a strain hardening material is set.

Parallel to the experimental tests, a numerical model will be created. This model is capable of determining the deflection of a beam design based on the dimensions of the beam, the stress-strain diagram of the material, and the load placed on the beam. The model is based on linear elastic calculations in the multi-layer method and the moment-area method.

1.4. Material properties

1.4.1. Concrete

Weber Beamix is the manufacturer of the concrete which is used. The exact composition of the concrete is unknown due to commercial interest. The main ingredients are given and summed up later in this paragraph. Last year’s research has been conducted in order to gain information, mainly, on the strength of the concrete. In a report written by van Alpen and Doomen (2016), pre-knowledge is given about the working of several key ingredients of the concrete used.

- Portland cement (CEM | 52,5 R)
- Siliceous aggregate with an optimised particle size of 1 mm
- Limestone filler and specific additives for ease of pumping
- Rheology modifiers for obtaining thixotropic behaviour of the fresh mortar
- A small amount of polypropylene fibres for reducing crack formation due to early drying

One of the material properties of the used concrete is the thixotropic behaviour. The thixotropic behaviour can be explained best by taking toothpaste as an example. The viscosity of toothpaste is relatively high in rest state, but when motion is applied to toothpaste the viscosity decreases. When the motion stops, the toothpaste will get in rest state very quickly, and therefore the viscosity increases. The concrete’s thixotropic behaviour is not as extreme as toothpaste’s but operates the same. When the concrete is in motion, the viscosity drops. Therefore, the material can move very easy. If the material is printed, it becomes stiff in order to create shape and stability for the layer itself, and a foundation for the layers printed on top of the layer.

In the graduation report of Slager (2017), it is stated that the shrinkage cracks have a great influence on the tensile strength of printed concrete. In traditionally casted concrete, fibres are used to bridge these cracks and generate more bond strength between the concrete parts. The small cracks are bridged by the polypropylene as described above, but longer fibres can bridge bigger cracks to generate more bond strength and therefore more bending strength.
According to Neville (2012), it can be stated that cracks occur while concrete is loaded under compression. Where micro-cracks occur somewhere around 30% of the ultimate theoretical load, they keep developing by increasing load. If the compressive load is increased up until 70 to 90%, the crack pattern has developed in a continuous crack pattern, or fracture zone. This can partly be prevented by using fibres.

**1.4.2. Fibres**

Some of the properties of concrete can be changed by using fibres. FRC can be called homogeneous because of the division of fibres through the concrete. In general, this created FRC has three main advantages in comparison to concrete. First, the flexural strength of the FRC is higher than that of concrete. Second, the use of fibres in concrete will increase the impact resistance of the printed object. And last, used fibres form a 3D reinforcement through the concrete element. One of the most important disadvantages is the reduced workability.

Many more advantages and disadvantages can be specified when comparing FRC to concrete. Above advantages and disadvantages will contribute the most to printed concrete, and will, therefore, be elucidated.

**Brittleness**

The printed concrete shows shrinkage cracks due to creep during hardening. Chanh (-) describes that fibres can be used to keep a connection with the matrix. Small fibres are able to bridge the small cracks in the matrix. The lost bonding between concrete in a crack will be recreated by fibres which are able to bridge these cracks. This leads to more strength capacity after the failure of the concrete.

**Impact resistance**

As described above micro-cracks develop during hardening of concrete. More cracks occur during loading the structure. In their report, Ulzurrur et al. (2017) wrote, that due to these small cracks the matrix of the concrete is interrupted. With impact loading, the cracks will increase which could lead to failure of a cross-section of a structure. In FRC the cracks are covered by fibres, which take the tensile stress of the impact load.

**Workability**

In different experimental tests, it is shown that the addition of fibres has a negative influence on the flowability of the concrete. Fibres can be seen as aggregates, by adding aggregates the viscosity of the material increases. This influences the flow of material through the hose and the nozzle output. Next to the viscosity of the material, the printability can change too. The length of the fibres influences the workability by the possibility of scratching or blocking the hose or nozzle.

**1.5. Printing setup**

For two years, 3DCP at the TUe has been developing. The principle of concrete printing is similar to contour crafting. The definition of contour crafting is: placing a path of material and building up the object by layered manufacturing. As the name implies, with contour crafting, the material is only placed at the contour of the object. This creates a hollow object. A small difference between contour crafting and concrete printing is that the dimensions of the print nozzle which is used with concrete printing are smaller. This results in smaller layers, and a need for a more accurate placement of the material.
The setup of the printer at TUe is based on a portal frame design. A portal construction supports two combined members. These members are horizontally placed and can move only in one direction, the y-direction. A vertical member is connected between the two horizontal members. This vertical member can move in two directions, horizontally in the x-direction, and vertically in the z-direction. A rotating mechanism is connected to the bottom of the vertical member. The nozzle of the printer is connected to the bottom of this mechanism. The rotating mechanism rotates around the z-axis, which gives the printer a fourth degree of freedom. This fourth degree of freedom is used to turn the nozzle at corners to create smooth corners. A picture of the setup of the portal is shown in Figure 1.1.

![Overview of the printing system](image)

**Figure 1.1. Overview of the printing system**

### 1.5.1. Printing process

The printing process can be split up into seven steps. Each step will be explained in this paragraph. The first three steps are taking place in the mixing machine, called ‘Duomix 2000’. This machine, constructed by M-tec is mostly used in the plaster industry. The range of the delivering of material per hour is around 150 litres. It depends on the viscosity of the material, the speed of the pump and the desired amount of material to work with.

#### Bulk material chamber

The printing process starts with the bulk material. This bulk material is created by Weber Beamix. The bulk material is delivered in bags of 25 kg. These bags are manually dropped into the bulk material chamber of the Duomix 2000. The bulk material chamber is a metal rectangular bucket with an Archimedes screw at the bottom. The bulk material gets scooped out of the chamber automatically by the screw. The chamber is closed with a steel grade, which allows bulk material to get in. Also, the steel grade blocks clumps of material and it prevents workers to stick their hands into the chamber with the screw in movement. The Archimedes screw scoops dry concrete out of the chamber into the mixing chamber. Water is added to the concrete at the mixing device.
Mixing chamber
The mixing chamber is placed directly after the Bulk material chamber. The dry bulk material is added through the centre part of the round chamber, at the outer ring, water is added to the chamber. By turning the blades, the dry concrete is mixed with water. Because the mixing blade has an Archimedes shape, the mixed concrete is pushed in the “wet concrete chamber”.

Wet concrete chamber
To the printing of concrete, the thixotropic behaviour of the concrete is an important material property. Concrete falls into the wet concrete chamber. A mixing blade inside this chamber is turned by a motor above. The rotation of the mixing blade causes the concrete in the chamber to move constantly. Therefore, the material becomes and stays a slump material. The concrete can stay in this part of the process for a while, because the concrete is in motion and therefore, cannot harden. The extrusion pump is attached to the bottom of the wet concrete chamber. Because of the fluidness of the material which is created into the wet concrete chamber, the concrete flows into the pump.

Extrusion pump
The extrusion pump is build up out of two main components. First, the black cylindrical packaging will be described. The outer shell is made of strong plastic. The inside of the shell is made of rubber with a groove in a helix form. The radius of this shell can be adjusted by fastening or loosening three bolts connected to the outside of the packaging. The second component is the worm on the inside of the extrusion pump. This worm is connected to the mixing blade in the wet concrete chamber with a simple locking mechanism and therefore turns with the same speed as the mixing blade above. Because the shape of the worm is not equal to the groove of the outer shell, small openings between the worm and the shell are created. These openings can be filled up with fluid concrete, after which the concrete will be transported into the hose. Because the top of the extrusion pump is constantly filled with fluid concrete, the extrusion pump can build up pressure at the end tip of the pump. This pressure causes the concrete to flow through the hose.

Hose
The extrusion pump is connected to an analogue pressure gauge. The pressure in the hose can be checked constantly. The flow of concrete in the hose is controlled by the pressure and the quantity. The flow of concrete has a lot of influence on the printing product at the end of the hose. At the beginning of a print session, it is needed to obtain a constant pressure and flow before the printer starts the print. The hose is connected in between the pressure gauge and the print nozzle.

Print nozzle
At the end of the hose, a print nozzle is connected. The standardized nozzle is built out of aluminium. This standardized nozzle is used for most of the prints. Because for the research on the printing possibilities it is necessary that different shapes and elements can be printed, it is possible to change the shape of the nozzle. A plastic 3D printer is used to print different nozzles for printing the desired shape for the nozzle. In order to print the desired element shapes, the nozzle is connected to the vertical on the portal frame. This vertical can be placed at any point (X, Y) and the height can also be adjusted (Z). The connection point of the nozzle attached to the vertical can move around the z-axis in order to turn the nozzle. The concrete is printed by the nozzle on a printing table.
Print table
The last step of the printing process is the print table. The print is composed out of different layers, stacked on top of each other. The first layer of the printed element is printed on the print table. A thin layer of plastic foil is placed onto the table in order to prevent the element from sticking to the table. If the print is finished, and the desired element is done, a layer of foil is placed onto the element during the first drying hours. During these hours, small cracks can occur due to shrinkage of the material. These shrinkage cracks can be prevented by keeping the environment moist. After a minimum of one day of drying on the table, most of the elements can be removed and dry at a different location. At that time, the printing space on the table is free to print another element.

1.6. Analysis of addition methods
Different techniques could be used to add fibres to the concrete while the printing process is running. In this chapter, different techniques will be explained and criticized. Because of the fact that FRCP has never been tested, the way of adding fibres is eventually based on assumptions.

Three of the seven steps described in the former subchapter are bound to the machine which is used. These steps, the mixing chamber, the wet concrete chamber and the extrusion pump are too expensive or too hard to modify for the prototype design. This means that in these steps fibres cannot be added. It is possible to add fibres in the other stages of the printing process. It is even possible to change the printing setup if necessary. If we visualize the printing process it can be simplified into the drawing in figure 1.2.

Figure 1.2. Sketch of the printer process.
Numbers 1 to 7 correspond to the numbers of steps taken, which are recapitulated in the following summation;

1. Bulk material chamber
2. Mixing chamber
3. Wet concrete chamber
4. Extrusion pump
5. Hose
6. Print Nozzle
7. Print table
It is stated that fibres cannot be added in step 2, 3, and 4 of the printing process. This means that fibres can be added at the bulk material chamber (1), somewhere over the length of the hose (5), at the nozzle (6) or after printing at the table (7).

In order to select the best option above, some limits are listed and declared. These limits can then be set in a matrix and can be rated for each option.

The addition of fibres will also be limited by the properties of the fibres. As stated in paragraph ‘1.4.2 Fibres’ of the former chapter, the choice of fibre may not lead to a major change in the way of adding fibres.

Table 1.1: Multi-criteria analysis addition method.

<table>
<thead>
<tr>
<th></th>
<th>Value of importance</th>
<th>Mixing Fibres with concrete</th>
<th>Adding fibres in Hose</th>
<th>Adding fibres in Nozzle</th>
<th>Adding Fibres after printing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change of pumps</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Extra container for fibres</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Extra mixer applied</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Fibre length restricted</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Fibre shape restricted</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Transport of fibres and concrete</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Use of different types of fibres</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Interface connection</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Filement connection</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Degrees of Freedom at Nozzle</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Control of fibre direction</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Automatic printing proces</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Development of fibre adding application</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

In table 1.1 a multi-criteria Analysis of the addition process is given. This analysis is based on assessments made by the research group. Possible changes in output due to research is excluded.

According to table 1.1, the addition of fibres will be somewhere in the Hose between the concrete pump and the nozzle. As can be seen in the table, this method has one weak spot, namely a fibre adding device needs to be developed. This weak spot can be relativized because of the great potential advantage to add materials after mixing the concrete.

1.6.1. Cylinder concrete pump

During analysing the way in which to add fibres, it was also concluded that changing pumps could lead to different strategies for adding fibres. The extrusion pump which is used to pump concrete in the hose, will not be satisfactory if FRC is used. It is predicted that the fibres will tear apart the
rubber inner shell of the extrusion pump. This is also the main reason why mixing fibres with the concrete is excluded.

By changing the extrusion pump for a piston pump, the way of creating pressure to transport concrete in the hose changes. The cylindrically shaped piston pump will push the concrete into the hose. This system is used in high-rise buildings and can transport concrete through multistore buildings. Also, FRC is transported with this system in order to create FRC floors in Industrial facilities.

Two cylinders work in opposite direction to create pressure. One cylinder presses the concrete from the cylinder into the hose, the other cylinder sucks the concrete into the cylinder at the same time. If the cylinders are fully extracted, the mechanism changes and the full cylinder is being pushed into the hose where the empty cylinder is sucking new concrete in the cylinder. This system is shown in figure 2.3 below.

![Workflow of a cylinder pump.](image)

This system is able to transport FRC from a mixing device to the nozzle head. It has some disadvantages, though. First, the system is used for the transportation of concrete in high-rise buildings. The smallest system found will deliver more than 200 litres an hour, which is too much for the current printing process.

Not only the amount of concrete per hour is an issue. By creating a system which works the same but transports a lesser amount of concrete there is another problem which shows up. The concrete is not mixed with the fibres in this system. Therefore, a new mixer needs to be combined with the pump. The change of pumps will lead to more necessary developments than desired.

### 1.7. Addition Device

As is stated in the former subchapter, the best place to introduce fibres to the concrete is in the hose. Because of the extrusion pump, it is not possible to mix fibres with concrete before pumping it. This is said, without taking the change of pumps into account. The device is named after the function of the device, namely ‘Fibre Reinforcement Entrainment Device’ (FRED). Due to a pending patent application, this device is described in a separate, confidential appendix.
Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Manufacturing
2. Experimental test

The experimental part of this graduation project is split up into three parts. CMOD1, CMOD2, and CMOD3. Each test part has a different manufacturing method, however, the material used for each test is equal. CMOD1 is manufactured according to the code originally written by Rilem (2002). This code will be explained in the next paragraph. From this start point, the dimensions will change. In CMOD2 the dimensions will be smaller according to the given dimensions in the code. Because printed elements produced by the research group are smaller than the dimensions written in the code, a step is created to go from code to printed material. The last test part, CMOD3, will have the same dimensions as CMOD2 but is different according to the manufacturing technique. Where specimens of CMOD2 are cast traditionally, the specimens of CMOD3 are printed.

2.1. NEN-EN 14651

Rilem Technical Committees (2002) wrote a report about testing FRC and called it the CMOD test. In 2005 a European Standard was written to accept the CMOD test, and the Dutch national index was written in 2007. The CMOD test is a three-point bending test through which the Crack Mouth Opening Displacement (CMOD) can be determined. Three strengths can be obtained by conducting the CMOD test. Firstly, the limit of proportionality can be calculated. Secondly, the equivalent flexural tensile strength can be determined by means of deflection and load capacity. Lastly, the residual flexural tensile strength can be determined by means of CMOD and load capacity.

In Figure 2.1 the arrangement of the notch, and the load and supporting points is shown.

![Figure 2.1. Setup CMOD test.](image)

In Figure 2.1 three rollers are drawn. The rollers with number 1 are supporting rollers, the roller number 2 is the loading roller. The rollers support or load the specimen over the whole width of the specimen. It is necessary that one of the supporting roller and the loading roller can move freely. The specimen wants to move during the test. First in bending, but this will lead to horizontal movement.
in the load and support points as well. The rollers are not allowed to create friction because friction in the supports can lead to a distortion of the desired stress pattern.

In the CMOD test, two formulas are given to determine the flexural strength. These formulae are given as;

\[ f_{ct,L}^f = \frac{3F_L l}{2b h s^2} \quad \text{and} \quad f_{R,j}^f = \frac{3F_j l}{2b h s^2} \]

- \( f_{ct,L}^f \) Limit of Proportionality in Newton per square millimetre.
- \( f_{R,j}^f \) Residual Flexural Strength at point j in Newton per square millimetre.
- \( F_L \) Maximum load \( F \) at \( 0 < \text{CMOD} < 0.05 \text{ mm} \) in Newton
- \( F_j \) Corresponding load with \( \text{CMOD} = \text{CMOD}_j = 0.5; 1.5; 2.5; 3.5 \) in Newton.
- \( l \) is the span length, in millimetres
- \( b \) is the width of the specimen, in millimetres
- \( h \) is the height of the specimen, in millimetres

According to di Prisco (2013), the calculated Flexural Strength values above can be used to characterise the FRC. This characterisation is always based on two post-cracking residual strengths which characterize the material on the SLS (CMOD \(_1 ; f_{R,1}^f \)) and the ULS (CMOD \(_3 ; f_{R,3}^f \)). The FRC is classified by a number and a letter. The number denotes the \( f_{R,1}^f \) class, followed by a letter denoting the ratio \( f_{R,3}^f / f_{R,1}^f \).

The \( f_{R,1}^f \) strength values for classification are given;

1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0 [N/mm\(^2\)]

The letter which represents the ratio between the SLS and the ULS is given by the following equations;

- \( a \rightarrow 0.5 \leq \frac{f_{R,3}^f}{f_{R,1}^f} < 0.7 \)
- \( b \rightarrow 0.7 \leq \frac{f_{R,3}^f}{f_{R,1}^f} < 0.9 \)
- \( c \rightarrow 0.9 \leq \frac{f_{R,3}^f}{f_{R,1}^f} < 1.1 \)
- \( d \rightarrow 1.1 \leq \frac{f_{R,3}^f}{f_{R,1}^f} < 1.3 \)
- \( e \rightarrow 1.3 \leq \frac{f_{R,3}^f}{f_{R,1}^f} \)

Concluding; For instance Material 4C has a flexural strength between 3.5 and 4.5 N/mm\(^2\) at \( f_{R,1}^f \) and a \( f_{R,3}^f / f_{R,1}^f \) ratio between 0.9 and 1.1.
2.2. Test specimen

2.2.1. Material
The concrete which is used is the same as the concrete used in 3DCP. For each test part, concrete is mixed with water according to the 0.2 water-concrete ratio. According to the fibres, two types of fibres are used. First, the workability and the design of FRED are based on these types of fibres. Secondly, by testing FRC and FRPC it is shown if and what the addition of fibres to the concrete adds up to the bending strength of the concrete. The first fibre which is used is 6 mm long and has a thickness of 0.16 mm, the second fibre is 13 mm long and has a thickness of 0.20 mm. The quantity of fibres which are added to the concrete is prescribed by the manufacturer of the fibres. For the specimens with 6 mm fibres, the fibre amount is 150 kg/m³. For 13 mm fibres, the amount is 60 kg/m³. The fibre prescription is given in Appendix A.

2.2.2. Dimensions and manufacturing

CMOD1
The dimensions of the specimen are 150 x 150 mm cross-section with a length of 600 mm. In the code, it is stated that the specimens are not intended for FRC with fibres longer than 60 mm. A minimal length of fibre is not written in the code.

The material described above are mixed in a 40-litre concrete mixer. Concrete, water and fibres are added stepwise to create a smooth mixed material. The specimens are cast in a given order to create a homogeneous distribution of material in the formwork. The formwork is filled 90% and compacted. After compaction, the formwork is filled and compacted again, now for 100%. After casting the formwork is levelled off. The conditions and procedures for demoulding and hardening of the FRC specimens are comparable with traditionally concrete specimens.

After 28 days, a notch of 25 mm depth is made in the specimen to determine the initiation point of the crack during testing. The cross-section of the specimen decreases at the notch. Because the notch has a depth of 25 ± 1 mm, the reduced height of the cross-section is around 125 mm. The notch is created in the middle of the beam. The specimen is turned for 90 degrees in order to exclude the feasible advantage of the unequal distribution of fibres due to vibrating the specimen during compacting.

In figure 2.2 the specimen is shown. Three lines are drawn on the specimen to set the support and loading points. These lines are used to define the support points, load point and connection points for measuring devices, which is further explained in the test setup in paragraph 2.3.
In the first CMOD test, nine specimens are tested in three series. Three specimens without fibres, three specimens with 6 mm fibres, and three specimens with 13 mm fibres. More specifications of the manufacturing of test specimens are added in appendix B.

**CMOD2**
The manufacturing procedure of the CMOD2 specimens is almost equal to the manufacturing procedure of the specimens in CMOD1. Because the width of the printed layers is mostly 40 mm, the specimen is scaled down to a cross section of 40 x 40 mm. The length of the specimen is scaled down with the same scale factor (40/150) and will be 160 mm. Because of the low amount of FRC needed for these tests, the FRC used in this test setup is mixed by hand, with a motorised mixing device.

The casting procedure and hardening procedure are equal to CMOD1. Because of the scaled-down dimensions, the notch is set on 7 mm ± 1 mm. This standard deviation cannot be minimalized because of the limits of the blade.

In figure 2.3 the series with 13 mm fibres cast is shown before and after demoulding. After demoulding, the specimens are stored in water to create the same hardening condition as CMOD1.
**CMOD3**
The specimens tested for CMOD3 manufactured with a new printing mechanism. Due to the patent application of the addition device, the production of the specimens is stated in the confidential appendix. Because the specimens are printed, the dimensions need to be adapted to the test dimensions described for CMOD2. After sawing, the test specimens are photographed in Figure 2.4.

![Printed specimens without fibres.](image1)

![Printed specimens with 6mm fibres.](image2)

Figure 2.4a Printed specimens without fibres.  

Figure 2.4b Printed specimens with 6mm fibres.

As can be concluded from the photographs in figure 2.4a/b, the series 3 of CMOD3 is not manufactured. The reason for this can be found in the confidential appendix. As described in chapter 2.1, in CMOD3, the specimens are titled 90 degrees parallel to the printing direction in order to eliminate the feasible advantage that could be gained due to vibrating when compacting the specimens. In printed specimens, this advantage is excluded. It is assumed that the contribution of fibres to withstand in-plane bending (perpendicular to the longitudinal section of the filament), is more convenient than the bending of the staples filaments.

**2.3. Test setup.**

**2.3.1. Bench setup**

The test setup is built according to the description in NEN-EN 14651. The beams are placed in an Instron test bench. A sub construction is made in order to test the beams as described. An overview of the test setup is shown in figure 2.3.

![Test setup in test bench](image3)
Two steel rolls are placed on a steel plate. These rolls have a span-width of 500 mm centre-to-centre. The roll on the left side of the figure cannot rotate. It can only buckle to the front or to the back, which makes it a hinge support. The roll on the right side can buckle to the front or to the back and allows displacements in the length of the beam. These degrees of freedom makes it a roller support. Another roll is attached to the top of the test bench and is used to apply a load to the beam. The two bricks between the roller supports are placed to prevent the blocks from falling and wrecking the measurement devices at the bottom of the beam.

### 2.3.2. Measuring devices

**CMOD**

During the test, several displacements and other parameters are measured. The most important measurement is the value of CMOD. The CMOD is measured by a clip below the specimen. In NEN-EN 14651 a sketch shows how this clip needs to be mounted to the specimen. This sketch and a picture made during the test is shown in figure 2.4 below.

![Figure 2.4. a. Sketch of the CMOD clip. b. picture of CMOD measure clip mounted on the specimen.](image)

The amount of force acting on the specimen is determined by the displacement of the CMOD. The working force acting on the specimen is determined according to a CMOD-time ratio. First, this ratio is set to 0.05 mm/min. after a CMOD of 0.1 mm is reached, the ratio is raised to 0.2 mm/min.

For CMOD2 and CMOD3 the test setup changes due to different dimensions of the specimens. The small setup is based on the large CMOD setup, as is shown above, but is scaled down to deal with the smaller specimens.

**LVDT**

The LVDT (Linear Variable Differential Transformer) is able to measure variations in length. The tip of the LVDT can be pressed 10 mm in total. In this setup, one LVDT is used to determine the deflection in the middle of the specimen. Figure 2.5 shows the LVDT mounted on the specimens of CMOD1.
The method of measuring the deflection is changed for CMOD2 and CMOD3. Because the setup for the test bank changes, the point of measuring the LVDT is replaced to the bottom of the specimen. Here the deflection of the specimen is measured by 2 LVDT units, one on each side of the specimen. The setup for CMOD2 and CMOD3 is shown in figure 2.6.

As is shown in figure 2.6, aluminium plates are glued onto the bottom of the specimen. To determine the most accurate deflection in the middle of the specimen, it is necessary to determine the deflection on both sides of the specimen. In Figure 2.7 the hatched areas show where the aluminium is glued to the specimen.
Load
The load which is needed to achieve the CMOD described before is measured by a load cell connected to the test bench. The load cell is connected to a computer, in order to show real-time graphs to control the test. This is shown in figure 2.8.

Figure 2.8. Overview test setup

2.3.3. Labelling test specimen
Each test specimen is labelled by a code in order to store the data after testing. For each test, the specimens are labelled differently. Because they are combined in this report, the decision was made to give the test specimen new labels, in order to prevent possible confusion. The new label is given;

For instance CM1.0.3

CM1: executed test (CMOD1; could vary in CM1, CM2, CM3)
0: length of the fibre (could vary in 0, 6, 13)
3: specimen number in the series (could vary in 1,2,3)
3. Experimental Results and discussion

3.1. FRED
During this process, different designs passed along the way, and the final design of FRED is given and explained in a confidential appendix due to patent applications. It can be stated that FRED is being developed. Some parts are developed and can be used, where other parts are still under construction.

3.2. Printed FRC
Different shapes and filaments are printed with the use of FRED and some of these created elements are tested during CMOD3. Rest pieces of these elements and other elements are sawn to determine the alignment of the fibres in the printed FRC. The specimens tested in CMOD3 are printed with a nozzle. After the specimens are printed, the nozzle is detached from the system. Round shaped filaments are printed to determine the alignment of the fibres in the hose.

First, the alignment in the hose will be discussed in more detail. Two filaments are printed directly next to each other without a nozzle attached to the hose. On top of these two layers, two new layers are printed. The created element is sawn after 28 days of hardening. In figure 3.1 a cross-section of the element is shown.

![Figure 3.1. Cross-section of an element with FRC 13 mm fibres without a nozzle.](image)

The cross-section in figure 3.1 above contains 13 mm fibres. These fibres are visualized as dots, which persuades that most of the fibres are aligned perpendicular to the plane of the cross-section. In the bottom half of the cross-section, it can be seen that some of the fibres are pulled out the specimen by the blade while sawing the specimen. Figure 3.2 shows a section of the same filament parallel to the print direction.
Figure 3.2. Section of an element with 13 mm fibres parallel to the print direction.

In figure 3.2 the fibres are mostly visualized as lines, wherein figure 3.1 the fibres are shown in dots. This intensifies the assumption made before, that the fibres are aligned in the printing direction. In the bottom half of the section shown in figure 3.2, more dots are visible. This means that the fibres in the bottom half could be aligned differently to the ones in the top half of the specimen.

After sawing the specimens of CMOD3, the rest pieces are used to determine the alignment of the fibres in elements printed with a nozzle. In figure 3.3a a cross-section of a rest piece is shown.

Figure 3.3a. Cross-section of CM3.6.2.

b. Longitudinal Section of CM3.6.2.

The samples shown in figure 3.3a/b are printed. It can be stated that the cross-section does not show any signs of a layered technique. The figure suggests that most of the fibres are pulled out of the specimen and bent while sawing the specimen. Parallel to the printing direction another section is made which is shown in figure 3.3b. In this section, the fibres show a distinctive line pattern. After testing CMOD 3, the small block with 6 mm fibres is opened in the crack, which is visualised in figure 3.4.
Almost all of the fibres in the specimen shown in figure 3.4 are aligned in the same direction after testing. The fibres could have been in this direction before the test started, but the alignment of the fibres could also be a result of the test. The alignment shown in figure 3.4 implies that most of the fibres have contributed to the flexural strength during the CMOD test.

After testing CMOD2, a photograph (figure 3.5) is made of the crack in specimen CM2.6.2.

The alignment of the fibres shown in figure 3.5 is more divided than the alignment shown in the printed specimen before. In figure 3.6a and 3.6b, a cross-section and a longitudinal section of specimen CM2.6.2 are shown.
There is a difference in colour appearance between figures 3.1-3.3 and 3.6 because the photographs are made on a different day and time. In figure 3.6 there is no visual difference between the cross-section of a casted specimen and the longitudinal section of a casted element. Therefore, a controlled alignment due to the manufacturing techniques can be excluded.

### 3.3. CMOD 1

The results of the test are split up into the three series explained in chapter 2. The result of each specimen is combined with the specimens in the same series. Series 1 contains specimens without fibres, series 2 contains specimens with 6 mm fibres, and series 3 contains specimens with 13 mm fibres. The load-CMOD curve, a limit of proportionality and also the residual flexural strength is calculated. With the results of previous tests, we are able to calculate the stress-strain relationship of the beam. The flexural tensile strength can be used to characterize the FRC.

#### 3.3.1. Series 1

*Specimens without fibres*

![Image of Load-CMOD diagram Series 1](image-url)
The diagram above (figure 3.7) shows some remarkable points. First, the CMOD test has not reached the minimum CMOD value. Because concrete is a brittle material, the material cracked, and the beam broke into two pieces. At a CMOD of approximately 0.45 mm the concrete broke, and the test setup automatically stopped the test. Secondly, there is a jump in all the curves at a CMOD of 0.1 mm. As explained in the paragraph ‘Test setup’ in chapter 2, the speed of the test setup changes at a CMOD of 0.1 mm. Because of the increase of displacement per minute, the test setup increases the load on the specimen, this can be seen in each of the following load-CMOD diagrams in this chapter.

Because series 1 contains no fibres, there are no further results to be discussed.

### 3.3.2. Series 2

**Specimens consisting of concrete with OL 6/.16 steel fibres 150 kg/m³.**

![Figure 3.8. Load-CMOD diagram series 2.](image)

The load-CMOD diagram of series 2 above in figure 3.8 shows a clean diagram. In the explanation of the CMOD test in chapter 2, two equations are expressed to calculate the Limit of Proportionality (LOP) and residual flexural strengths. The equations are repeated and solved for CMOD1 series 2;

\[
 f_{ct, L}^f = \frac{3F_L l}{2bh^2_p} \quad \text{and} \quad f_{R, L}^f = \frac{3F_j l}{2bh^2_p}
\]

The Load input for the given formula’s is stated in table 3.1. Other parameters can be derived out of table ‘Series Properties’, Listed in Appendix B.
Table 3.1. Load input in kN and corresponding stress in N/mm² of series 2.

<table>
<thead>
<tr>
<th>Load [kN]</th>
<th>CM_2.1</th>
<th>CM_2.2</th>
<th>CM_2.3</th>
<th>CM_2.1</th>
<th>CM_2.2</th>
<th>CM_2.3</th>
<th>Mean Series 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15.25</td>
<td>15.32</td>
<td>14.2</td>
<td>4.8</td>
<td>4.9</td>
<td>4.6</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>15.11</td>
<td>13.35</td>
<td>13.59</td>
<td>4.8</td>
<td>4.2</td>
<td>4.4</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>7.73</td>
<td>6.82</td>
<td>7.02</td>
<td>2.5</td>
<td>2.2</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>4.39</td>
<td>3.80</td>
<td>3.93</td>
<td>1.4</td>
<td>1.2</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>2.49</td>
<td>2.13</td>
<td>2.24</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The flexural residual stress can be determined for all the measurement points in the datasheet. The strain can be determined by dividing the extension of the specimen by the span of the specimen. The CMOD is measured at the bottom of each specimen. The specimen initiates to crack at the bottom of the notched section. At the place where crack initiates, the strain is determined. This means that the CMOD value needs to be translated to the top of the notch. Because the notch ends at 125mm from the top, the value will be translated with the following formula:

$$\Delta l = CMOD \cdot \frac{125}{150}$$

This leads to the following definition of the strain calculation;

$$\varepsilon = \frac{\Delta l}{l_{sp}} \cdot 10^3 = \frac{125 \cdot CMOD}{150 \cdot l_{sp}} \cdot 10^3 \ [\%]$$

Where $l_{sp}$ is equal to the span length of 150 mm according to di Prisco et al. (2013)

Combining the formula with the residual stresses and the strain formulation with corresponding CMOD values, a stress-strain diagram can be obtained in figure 3.9.
Figure 3.9. Stress-Strain diagram series 2.

This stress-strain curve can be used to calculate the displacement. First, it is necessary to determine the modulus of Elasticity. This can be calculated by dividing the stress value by the corresponding strain value. Because this equation is based on the linear state of the structure, the LOP is determined as value for calculating the modulus of Elasticity.

With the strength listed in table 3.1, it is possible to characterize the FRC according to the CMOD test in chapter 2. Because the mean strength value is 3.8, the number can be rounded off to 5. By calculating the ratio of $\frac{f_{R,3}}{f_{R,1}} = 0.3$. This means that the inclination of the diagram between SLS and ULS is too large to characterize the material.
3.3.3. Series 3

The same process can be applied in order to characterize specimens tested in Series 3.

Specimens consisting of concrete with OL 13/20 steel fibres 60 kg/m³.

Table 3.2. Load input in kN and corresponding stress of Series 3

<table>
<thead>
<tr>
<th>Load [kN]</th>
<th>CM_3.1</th>
<th>CM_3.2</th>
<th>CM_3.3</th>
<th>CM_3.1</th>
<th>CM_3.2</th>
<th>CM_3.3</th>
<th>Mean Series 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$</td>
<td>11.08</td>
<td>8.58</td>
<td>12.46</td>
<td>3.5</td>
<td>2.7</td>
<td>3.9</td>
<td>3.4</td>
</tr>
<tr>
<td>$F_2$</td>
<td>10.73</td>
<td>11.16</td>
<td>11.04</td>
<td>3.4</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>$F_3$</td>
<td>6.85</td>
<td>6.97</td>
<td>7.23</td>
<td>2.2</td>
<td>2.2</td>
<td>2.3</td>
<td>2.2</td>
</tr>
<tr>
<td>$F_4$</td>
<td>5.33</td>
<td>5.31</td>
<td>5.64</td>
<td>1.7</td>
<td>1.7</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>$F_5$</td>
<td>4.29</td>
<td>4.16</td>
<td>4.50</td>
<td>1.4</td>
<td>1.3</td>
<td>1.4</td>
<td>1.4</td>
</tr>
</tbody>
</table>

After computing the stress, a stress-strain diagram of the test results can be computed according to the steps in series 2. By calculating the correct values, the stress-strain diagram of series 3 can be made as is shown in figure 3.11.
The same steps as mentioned in series 2 can be taken in order to characterize the material of series 3.

According to $f_{R,1}$ the number of characterization will be “3”. The formula’s below can again be used in order to determine the letter for characterization. Calculating $f_{R,3}$ gives 0.5. This means that the letter which can be given to the material is “a”. By combining both results, it can be stated that the material can be characterized by “3a”.

### 3.3.4. Comparison of series in CMOD1.

The Load-CMOD results of the three series can be combined into one diagram. This diagram is shown in figure 3.12.
In separate load-CMOD curves, it is shown that the results are very close. This is also visible in the diagram in Figure 3.12. In figure 3.12 it is clear that series 2 is strong initially. After the peak strength is reached, the fibres cannot contribute a lot to the strength of the beam, and the opening of the crack will increase with a decreasing load. It can be concluded that series 3 does not have the same initial strength as series 2, although it lasts longer. The result was to be expected because of the length of the fibres. Short fibres can contribute to small microcracks. After the microcracks are derived, the small fibres cannot bridge the cracks anymore. Besides the length of the fibre, the quantity of fibres is also of importance. The amount of steel in series 2 is 150 kg/m³ which will deliver a high initial strength. The fibres in Series 3 are longer, and the amount of steel is 60 kg/m³. This leads to a smaller initial strength and will bridge the crack for a longer displacement because of its length.

The same conclusion can be drawn out of the diagram in which the stress-strain curve of series 2 and series 3 is shown. This diagram is shown in the next figure, figure 3.13.

![Figure 3.13. Combined Stress-Strain diagram CMOD1.](image)
3.4. CMOD 2
In CMOD2 the results will be shown of the experimental test on the small casted beams.

3.4.1. Series 1
Specimens without fibres.

![Load-CMOD diagram Series 1 of CMOD2](image1)

As can be seen in figure 3.14 the load-CMOD diagram is given. One of the specimens was not correctly tested according to the setup described in chapter 2. The CMOD was not measured during the test. Because of that, the specimen broke immediately. The result of this test is therefore excluded from this experiment.

3.4.2. Series 2
Specimens consisting of concrete with OL 6/16 steel fibres 150 kg/m³.

![Load-CMOD diagram Series 2 of CMOD2](image2)

Figure 3.15. Load-CMOD diagram Series 2 of CMOD2.
In figure 3.15 the load-CMOD diagram of the specimens with 6mm fibres is shown. It is shown that the peak load of CM2.6.1 is 0.5 kN smaller than the other specimens. As can be seen in the diagram, the after peak slope of specimen CM2.6.1 is equal to the other specimens. Therefore it can be concluded that the after peak strain softening behaviour is equal to the other specimens.

In CMOD1, a classification can be given to the material. This can be executed by using the following equations to determine the LOP and the residual strength of the material.

\[ f_{ct,I} = \frac{3F_I l_I}{2bh^2p} \quad \text{and} \quad f_{R,I} = \frac{3F_I l_I}{2bh^2p} \]

**Stress-Strain relationship**

As can be seen in the results of CMOD1, the stress-strain relationship can be made by using the datasheet of the load-CMOD diagram. At the place where crack initiates, the strain is determined. This means that the CMOD value needs to be translated to the top of the notch. In CMOD1, a standard ratio is used to translate the CMOD value. Because the dimension of the specimens is over three times smaller, the difference in ratio is more governing. Therefore the standard equation is given in the CMOD code;

\[ \Delta l = CMOD \cdot \frac{125}{150} \]

Where 125 is the standardized height of the cross-section at the notch, and 150 is the standardized height of the specimen, it changed to;

\[ \Delta l = CMOD \cdot \frac{\text{height}_\text{notch}}{\text{height}_\text{specimen}} \]

The real values of each specimen are taken into account. This leads to the following definition of the strain calculation;

\[ \varepsilon = \frac{\Delta l}{l_{sp}} \times 10^3 = \frac{\text{height}_\text{notchCMOD}}{\text{height}_\text{specimen} l_{sp}} \times 10^3 \text{ [%]} \]

Where \( l_{sp} \) is equal to the height of the specimen according to di Prisco et al. (2013) which leads to;

\[ \varepsilon = \frac{\text{height}_\text{notchCMOD}}{\text{height}_\text{specimen}^2} \times 10^3 \text{ [%]} \]

Although the equation for the residual strength cannot be used for classification, it is still useable to determine the stresses which can be used in the stress-strain diagram. Combined with the equation to derive the strain in the specimen, the stress-strain diagram can be composed and is shown in figure 3.16.
Because the datasheet of the load-CMOD diagram is used to determine the stress-strain diagram, it is logically the CM2.6.1 shows a different result than the two other specimens.

Because of the fact that the dimensions of the specimens used in CMOD2 are not corresponding with the dimensions of CMOD1, a classification for this material cannot be given. This is explained further in the comparison between the three tests.

3.4.3. Series 3
For series 3, the same results can be shown as for series 2.

Specimens consisting of concrete with OL 13/.20 steel fibres 60 kg/m$^3$. 

Figure 3.17. Load-CMOD diagram Series 3
It can be concluded that the specimens tested in series 3 are more eccentric compared to the specimens tested in series 2. The results have a higher distribution compared to the results shown thus far.

**Stress-strain relationship**
The stress-strain relationship of series 3 can be concluded as in series 2, shown in figure 3.18.

![Stress-Strain diagram series 3](image)

Figure 3.18. Stress-Strain diagram series 3

**3.4.4. Comparison of series 1, series 2 and series 3.**
The Load-CMOD results of the three series can be combined into one diagram. This diagram is shown in figure 3.19.

![Combined load-CMOD diagram of CMOD2](image)

Figure 3.19. Combined load-CMOD diagram of CMOD2.
In separate load-CMOD diagrams, the results are better visual than in the diagram above. The blue curves shown are from series 1, The purple results are from series 2, and the green results are the results of series 3. As can be seen in the diagram, the specimens without fibres of series 1 are not capable of resisting the bending forces. The specimens of series 2, excluded CM2.6.1, have a high initial flexural strength, but after the peak strength is reached, not much load is needed to increase the CMOD value during the test. The specimens tested with 13 mm fibres have a lower initial flexural strength, but keep more resistance during the increase of the CMOD distance.

The same conclusion can be drawn out of the diagram in which the stress-strain curves of series 2 and series 3 are shown. This diagram is shown in the next figure, figure 3.20.

![Stress-Strain Curve Diagram](image)

**Figure 3.20. Combined Stress-Strain curve diagram of CMOD2**

According to the used fibres, this result is logical. The principal; “shorter fibre, more initial strength” and “longer fibre, more residual strength” is also applicable to the combination of fibres with concrete used in the printing.
3.5. CMOD 3

3.5.1. Series 1

Figure 3.21. Load – CMOD diagram Series 1 of CMOD 3.

Figure 3.21 shows the load-CMOD diagram of CMOD3 series 1. There is a large difference between the results as CM3.0.1 and CM3.0.3 have a 30% difference in peak strength. Although the peak strength is different, the specimens show the same after peak behaviour.

3.5.2. Series 2

Specimens consisting of concrete with OL 6/.16 steel fibres 150 kg/m³.

Figure 4.22. Load-CMOD diagram series 2 of CMOD3.
The specimens tested in series 2 are shown in figure 3.22. Specimen CM3.6.3 was loaded with a maximum point load of 1.2 kN before the test actually started. The clip which measures the CMOD opening was out of range during the first test. After resetting the test, the specimen is tested again. This is the main explanation for the specimen being weaker at the peak strength. The three specimens are equally strong after a CMOD of 2.25 mm. A stress-strain diagram can be made as well.

![Stress-Strain diagram series 2 of CMOD3.](image)

3.5.3 Comparison of Series 1 and Series 2.

The results of series 1 and series 2 can be compared by viewing the stress-CMOD diagrams in figure 3.24.

![Stress-CMOD diagram CMOD3 series 1 and 2.](image)

It is shown in the diagram of figure 3.24 that the addition of fibres to the printed concrete increases the ductility and the tensile strength of the specimens.
3.6. Comparison between CMOD1, CMOD2 and CMOD3

The link between the different tests is described in chapter 3. It is stated that the test specimens only vary in one variable. This variation can be summarized by the following statements.

- CMOD1 is based on the code for the CMOD test; NEN-EN-14651.
- CMOD2 varies from CMOD1 in dimensions. CMOD1 is 150*150*500 and CMOD 2 is 40*40*130.
- CMOD 3 varies from CMOD 2 in terms of the manufacturing method. CMOD2 is traditionally cast and CMOD 3 is printed.

3.6.1. CMOD1 vs. CMOD2

The Stress-CMOD results of each series, containing the same fibre, can be compared.

![Stress-CMOD diagram CMOD1 and CMOD2 series 1.](image)

In figure 3.25 the stress-CMOD diagrams of CMOD1 and CMOD2 regarding series 1 are shown. The behaviour of the after peak strength is comparable in both test series because the peak strength of CMOD 2 is lower than the peak strength of CMOD1. Firstly, it needs to be mentioned that the width of the notch, created in both samples is the same because it could not be scaled down. Secondly, it is possible that the zone where the maximum axial forces are reached was not scaled down either. This could lead to a different stress in the cross-section of the beams. If the support points could not rotate freely, as they should, it is possible that the difference in self-weight of the beam has an influence on the test results.
Figure 3.26. Stress-CMOD diagram CMOD1 and CMOD2 series 2.

Figure 3.26 above shows the combined stress-CMOD diagram of series 2. These results imply that the variation in dimensions of the specimens does not influence the stress-CMOD diagram. The green curves in the diagram are results of the smaller blocks of CMOD2. It can be seen that the lines are less smooth. The reason for this is that because of a smaller cross-section, fewer fibres bridged the crack when the specimen was tested. If one of the fibres is gone, fewer fibres can take over the stresses, which leads to the drops in the curves.

Figure 3.27. Stress-CMOD diagram CMOD1 and CMOD2 series 3.

The specimens tested with 13 mm fibres show the same results as described for the specimens of series 2. Although the lines of the smaller specimens have a bigger distortion.
3.6.2. CMOD2 vs. CMOD3

In figure 3.28 the series 1 results of CMOD2 and CMOD 3 are shown. The two graphs of CMOD2 have a higher peak and after peak strength. Although, the behaviour between both pieces is nearly the same. The weaker specimens tested in CMOD3 are manufactured with a printing technique. Which means that the specimens are not compacted. This is the main reason for a smaller result.

Figure 3.29. Stress-CMOD diagram CMOD2 and CMOD3 series 2.

Figure 3.29 above shows the results of series 2. According to these results, it can be stated that the bending stress derived at CMOD2 is comparable with the bending stress derived at CMOD3. It was expected that CMOD3 would show different results because CMOD3 is printed, but in this case, the results do not show a difference in bending stress. The alignment of the fibre in CMOD3 due to
printing may be the reason for the overall higher strength because almost every fibre collaborates while bridging the crack.
Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Manufacturing
4. Numerical test

A numerical model is created to calculate the strain hardening material. The calculations are based on linear elastic theories, in which the material properties can be adapted in order to determine the deflection of a loaded beam. After comparing the experimental results with the deflection of the beam in the model, the material behaviour can be validated and used to predict designs in numerical programs.

4.1. MLMA model

A numerical model has been developed which is based on the MultiLayer method and the Moment-Area method. This model is able to predict the deflection of beams with a varying cross-section, length and force. The stress-strain behaviour of FRC-material can be determined by changing this behaviour and comparing the output of the model with the experimental test results.

4.1.1. Multi-Layer Method Calculation

Linear Elastic Moment calculation

In order to create a numerical model to determine the deflection of a beam, a couple of values need to be known. One of these values is a moment-curvature (M-κ) diagram. This diagram shows the comparison between the curvature of the beam and the resistant moment capacity of the beam.

The following calculation is called a model calculation. The values are chosen for matters of simplicity and, therefore, non-realistic values. If tests are done and more values can be determined, they can give a more accurate result of the calculation. The values are chosen to check the calculations while building the numerical model.

As a starting point, a stress-strain diagram is computed which can be seen in figure 4.1. The strains and corresponding stress values are an educated guess in order to set up a numerical model.

![Stress-strain diagram example](image)

Figure 4.1. Stress-strain diagram example
The moment-curvature diagram which will be the end conclusion of this calculation is based on certain values. One of these values can be determined by taking the point where the crack starts. This is the point where the material reaches the maximum tensile stress. As can be seen in the diagram above this point is reached at a tensile strain of 1.0, corresponding to a maximum tensile stress of 4.0 N/mm².

Next to this stress-strain diagram, a cross-section needs to be determined by choosing values for the width and the height of the beam. A number of layers are chosen to reflect the corresponding stress diagram. The strain is determined at the centre of gravity of the layer. Before the maximum tensile stress is reached, the moment-curvature diagram increases linearly. A strain diagram can be made at the point where the crack starts, followed by a stress diagram. This diagram can be used to calculate the axial compression and tension force followed by the moment capacity. The diagrams are shown in figure 4.2.

![Diagram](image)

**Figure 4.2 Strain, stress and normal force diagram at maximum tensile stress.**

The diagrams lead to the following calculations which can be used to come up with the curvature. This curvature corresponds to the strain at maximum stress in the bottom region of the beam. A height of the cross-section is chosen. All values which are determined can be summed up;

Dimensions of the beam:

- Height (h): 120 mm
- Number of layers per zone: 6
- Max tensile stress: 4.0 N/mm²
- Unit reduced tensile stress: 1.0 N/mm²
- Unit compressive stress: 4.0 N/mm²

With above values the curvature can be calculated by the next formula;

$$\kappa = \frac{\varepsilon}{\frac{1}{2} \cdot h} = \frac{1.0}{60} = 0.016667$$
The cross-section is split between a compression and a tension part. The height of both parts is therefore 60 mm. Each layer has a height of 60/6=10 mm, with a centre distance of z= 5, 15, 25, 35, 45 and 55 mm.

With a curvature of 0.016667 at a distance of 60 mm from the neutral axis, the strain is 1.0. For each centre distance the strain can be obtained by ratio;

$$\varepsilon_i = \frac{1.0}{60} \ast z_i$$

According to the diagram given in figure 5.1 the corresponding stress per strain can be derived by using the next formula;

$$\sigma_i = 4 \ast \varepsilon_i$$

For each layer ‘i’, the stress can be determined. After multiplying the stress with the surface (A) of the layer, a Force (Fi) is derived.

Total amount of force applied to the compression and tension part of the section can be calculated by taking the sum of the forces per layer;

$$F_{compr.} = \sum F_{i_{compr.}}$$

$$F_{tens.} = \sum F_{i_{tens.}}$$

The total compressive force and the total tensile force need to be equal because of the sum of horizontal force are equal to zero. The surfaces under the diagrams are equal because the strain in tension and compression do not exceed the maximum. As can be seen in the stress-strain diagram, the compressive and tensile stress have the same modulus of Elasticity and are both linear elastic.

The centre of gravity of each layer can be determined and the distance to the neutral line can be calculated. With these values, the bending moment of the compression and the tension zone can be calculated. The sum of the bending moments in each zone leads to the bending moment resistance of the beam.

$$M = M_{compr.} + M_{tens}$$

$$M_{tens.} = \sum (z_i \ast F_{i_{tens.}})$$

$$M_{compr.} = \sum (z_i \ast F_{i_{compr.}})$$

This moment resistance corresponds to the curvature which is determined before.

**After Crack moment.**

If the strain increases at the bottom of the cross-section, the maximum stress of the linear elastic diagram exceeds. This means that the concrete failed at this stage. The fibres will take over tensile
stress at this point. The stress-strain curve in tension can be extended by taking the strength of the fibres into account. Figure 4.3 shows the new stress-strain diagram.

Figure 4.3. Stress-strain diagram example with tensile stress extended.

As discussed before, the tension stress increases linearly until a strain, $\varepsilon_{t, \text{max}}$, has been reached. In this case $\varepsilon_{t, \text{max}}$ is chosen to be 1.0. After the maximum stress, $\sigma_{t, \text{max}}$, has been reached, the stress decreases linearly with 1.0 N/mm² per unit strain. For this part of the Moment-curvature calculation, a higher curvature needs to be chosen. A newly educated guess leads to a curvature which is twice the curvature calculated at the cracking moment. This leads to the following curvature:

$$\kappa_2 = 2 \times \kappa_1 = 2 \times 0.016667 = 0.033334$$

Figure 4.4. Strain, stress and normal force diagram after the maximum tensile stress of concrete is reached.

As can be seen in the stress diagram in figure 4.4, the angle of the stress line changes at the point where the maximum stress is reached. The inclination of the stress curve decreases and another shape in the tension zone covers the total tensile stress. The same layer theory is used in the ‘linear Elastic Moment Calculation’, where the strain is determined for each layer, and according to a formula, the stress for the layer can be obtained.

The equation which is used to determine the stress, for strains higher than 1.0, can be formulated as follows;
\( \sigma_i = \varepsilon_i + 3.0 \)

The force which can be dealt with by the layer can again be obtained by multiplying the stress with the surface of the layer.

Now it can be stated that the axial tension force is lower than the axial compression force.

Because of equilibrium, the compression and tension forces need to be equal. This can be obtained by shifting the neutral axis to increase the tension zone and decrease the compression zone. In figure 4.5, a comparison can be made between the stress diagram of the linear elastic moment calculation and the diagram with the shifted neutral axis.

![Figure 4.5. Comparison of Stress diagrams](image)

If the compression force and the tension force are in equilibrium, the moment resistance of the beam can be obtained by multiplying the force of each layer with the new lever arm according to the shifting of the neutral axis. This moment resistance corresponds to the curvature stated in the beginning of this paragraph.

With the method above, moments can be calculated for each curvature. The equations which represent the material properties can be changed according to the change of material. More linear equations can be used to describe the material behaviour better.

After having a list of curvatures with the corresponding calculated moments, a moment-curvature diagram can be made. This material depending diagram is the input for the moment-area method.

### 4.1.2. Moment-Area method

The moment-area method is based on a simple beam theory, with a beam supported by two supports. By applying a force in the middle of the beam, a bending moment originates. By dividing the beam into a certain amount of slices, the moment per slice can be calculated by;

\[
M_i = \frac{1}{2} F \cdot l_i
\]

Where \( l_i \) is the distance between the closest support point and the center of the selected slice. The calculated moment can be used to determine the curvature in the beam. The moment-curvature...
diagram derived with the Multi-Layer method can be used. Now, each slice of the beam has a certain curvature. By calculating the second derivative of the curvature, the deflection of each slide is known.

\[
\delta_i = \kappa \ast l_i
\]

Every slice on one side of the midpoint of the beam contributes to the deflection of the midspan of the beam in total. This can be calculated by taking the sum of each slice of the beam and dividing this by two.

\[
\delta_{\text{tot.}} = \frac{\sum \delta_i}{2}
\]

This is only possible by using a simply supported structure with a point-load on mid-span. The force, which is applied on the beam, corresponds with the deflection of the beam and leads to a force-deflection diagram.

The force-deflection diagram is depending on the moment-curvature diagram obtained by the Multi-Layer method, and the moment-curvature diagram is depending on the stress-strain diagram. The force-deflection diagram of the experimental test could be matched by changing the stress-strain diagram in the model. The implementation of the model in Grasshopper is described in Appendix D.

4.2 Numerical results.

The first part of the model is based on the Multi-Layer method. The output of this part is a moment-curvature diagram. The output of the model is depending on material factors which can change. The material factors are presented in a stress-strain diagram and, to create the model, a simple stress-strain diagram is used. The values of stress and strain are not of importance when creating the model and are, therefore, chosen values for matters of simplicity. In figure 4.6a a sketched stress-strain diagram is shown which describes the plain concrete. The maximum tensile strain is 1.0 if a layer is loaded with more strain, that layer fails. The moment-curvature diagram which is derived from the model is shown in figure 4.6b.

![Figure 4.6a. Sketch stress-strain behaviour plain concrete. b. Moment-curvature diagram derived.](image)

As is shown in the moment-curvature diagram in figure 4.6b, a moment can be determined for a set curvature. The peak, which is reached in point ‘A’, shows the maximum moment derived with the
material properties inserted in the model. After the peak, the bottom layer in the tension zone exceeds the maximum tensile stress of 4.0 N/mm² and the layer fails. After the first layer failed, the second layer failed immediately after the first one because of the redistribution of the tension zone. If fibres are added, the tensile part of the stress-strain diagram could be extended. The new stress-strain diagram is given in figure 4.7a. Figure 4.7b shows the corresponding moment-curvature diagram.

![Figure 4.7a. Sketch stress-strain behaviour with fibres. b. Moment-curvature diagram derived.]

By adding fibres to the plain concrete, the maximum moment is increased. Point A is derived from plain concrete, point B is the maximum moment capacity of the material which is described in figure 4.7a. After the maximum moment is obtained, the failing of layers as described for plain concrete is shown in figure 4.7b. The material behaviour of fibres is dependent on the various properties of fibres. Ideally, the material keeps on increasing in tensile strength but, this is not realistic material behaviour. It would be exciting if point B is reached in the first attempt at creating FRC.

![Figure 4.8a. Sketch stress-strain behaviour endless behaviour. b. Moment-curvature diagram derived.]

Figure 4.9. Load-deflection diagram by Moment Area method.

After the model is running correctly, the results of the experimental tests can be inserted. The experimental test results show a strain softening material. The experimental test results cannot be compared with the numerical test results because the moment-area method is a force depending calculation method and the experimental test is a displacement depending test method.

Because the model built in Grasshopper is not able to calculate the force-displacement diagram, two options can be computed. The first option is to create a new composition of the material. This composition must be strain softening. After testing the material with the CMOD test as described in chapter 2, a force-displacement diagram would be obtained which has the same regression as the diagram in figure 4.33. Then, by using a trial and error method, the correct values for the stress-strain material could be obtained to derive the same load-deflection diagram. If this loop is closed, the stress-strain diagram will be known for the new material.

Another way to derive the stress-strain diagram of the material which is tested during the experimental tests in this graduation project is to create a new, or use an already existing FEM-model to predict the material behaviour. The FEM-model can be created in Abaqus, and a smeared-crack material behaviour can be used. Van der Krift (2017) has made a model in which de correct material behaviour and mesh can be inserted and the test setup needs to be translated into the model correctly. Because of time limitations, creating the new material and the implementation of the experimental test in Abaqus is recommended for further research.
5. Conclusion

In the introduction, the goal of this project is stated, namely; “Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Adaptive Manufacturing.” The statement is followed by three steps which are addressed in this report. These steps will be repeated and concluded in this chapter.

Experimental conclusions

The manufacturing of 3D Fibre Reinforced Printed Concrete is achieved by the manufacturing of FRED. FRED is still under construction, and parts have been built and connected separately. Each part is tested before it is attached to FRED. When testing one of the prototypes (figure CA.3 of the confidential appendix), decent specimens were created. Based on rest parts of the specimens and other small printed elements it can be concluded that the fibres in the printed specimens are aligned in the print direction. The opening of the nozzle which is used to print FRC was 50*10 mm, which turned out to be too small for the 13 mm fibres.

Three different test setups are executed to compare the print material to normal FRC. Based on the test results it can be concluded that fibres contribute to the ductility of the material and the flexural strength of the casted specimens and the printed specimens. The specimens with the 6 mm fibres were equally strong in CMOD1, CMOD2 and CMOD3 and reached a flexural peak stress of 6.2 N/mm². The after peak behaviour of the specimens with 6 mm fibres in line as well, although the fibres of the printed specimens are more aligned with the printing, and therefore testing, direction.

Numerical conclusions

A numerical tool was developed in which different linear stress-strain diagrams can be inserted and lead to different force-displacement diagrams. Through the comparison of the force-displacement diagram of the model to experimental tests, the stress-strain behaviour of the experimental test could be linked to the inserted stress-strain behaviour of the model. This model is only applicable for strain-hardening material and therefore not usable for the created FRC.
6. Recommendations

Because FRED is still under construction, it is important to finish FRED before new experimental tests can be carried out. In this report, it is concluded that, with 3DCP as a manufacturing technique, fibres contribute to the bending strength of the specimens. Mainly the connection between the printing system and FRED needs to be developed further. As can be concluded out of the first tests, it is very important to create the same output speed compared to the input speed of the concrete. When the possibility exists to control these speeds, then FRED can be developed further to insert other fibres or supplements.

Parallel to the development of FRED a study on different types of fibres could be executed. This study is excluded from this project because of time limitations. Before new tests are executed to determine the bending strength of the FRC, it is recommended to see which fibre can contribute most to the printing environment. Simple casted CMOD tests can be used to determine the bending strength of the different fibres, and eventually, printed specimens can be manufactured and tested.

While printing the test specimens of CMOD3, it is concluded that the 13 mm fibres will eventually block the 50*10 mm nozzle. It is therefore recommended if steel fibres are used to check which dimensions are minimal for the size of the nozzle. It can be checked by a trial and error method with the system after FRED is ready to print, or parallel to the development of FRED by using the prototype for the printed specimens (figure CA.3 in the confidential appendix).

If the control speed of FRED is known, and prints with FRC material can be made continuously, it is possible to create elements. Out of these elements, specimens can be created which can be used to determine different properties of the manufactured FRC. One of these properties could be the in-plane bending stress which is determined in this graduation project. Other properties could be the axial compression strength and the axial tensile strength.

If the stress-strain material which is created is strain-hardening, this could be inserted directly into the MLMA model created in this graduation project. The stress-strain material properties are also significant for further numerical research. Difficult 3D shaped constructions could numerically and experimentally be tested in order to verify the new models. These models can predict the capacity of 3D printed structures.

A numerical model based on non-linear calculations can be created in order to compare the behaviour of the experimental material. In the model, a smeared crack formulation can be used as the material behaviour of the FRC in the numerical model. Van der Krift created a model based on the experimental FRC material. It is recommended to use this model as inspiration.
7. Acknowledgements

This research is conducted with sponsored material from two partners. First the manufacturer of the concrete, Weber Beamix. They sponsored the concrete to conduct research on 3DCP. Secondly, the manufacturer of the fibres, Bekaert NV. They sponsored the steel fibres. Both the partners are widely acknowledged.
8. References

Documents


Figures

Figure 2.1: Printing setup at the University of Technology Eindhoven, by Rien Meulman (2015)

Figure 2.3: Workflow of a cylindrical pump. Website: http://www.schwing-stetter.co.uk/Images/Animation/Pumpkit.gif (retracted 2017-08-29)

Figure 3.1: Setup CMOD test (NEN-EN 14651)
Appendix

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A. Fibre Prescription Bekaert NV.

**EC Declaration of Performance**

**DRAMIX® OL 6/16**

1. Unique identification code of the product: DRAMIX® OL 6/16
2. Type- and traceability info, allowing identification of the construction product as required pursuant to Article 11(4): is provided on the product packaging and product label.
3. Intended use of the construction product in accordance with EN 14889-1: 2006. DRAMIX® OL 6/16 are steel fibres, made of cold-drawn wire, for STRUCTURAL USE in concrete, mortar and grout.
4. Name, registered trade name and contact address of the manufacturer as required pursuant to Article 11(5): NV BEKAERT SA, Bekaertstraat 2, B-8550 Zwevegem, Belgium.
5. Not applicable.
6. System of assessment and verification of constancy of performance of the construction product; System n°1
7. Notified Certification Body:
   - BCNA - registration nr: 0749 / B-1040 Brussel, Rue d’Arlon, 53 has performed under System n°1
   - determination of the product-type on the basis of Type Testing,
   - initial inspection of the manufacturing plant and of Factory Production Control
   - continuous surveillance, assessment and evaluation of Factory Production Control
   - issued: a certificate of constancy of performance per product - see table 1.

   Notified Labs:
   - TSUS - registration nr: 1301 / SK-821 04 Bratislava, Studená 3 performed: Initial Type Testing and issued ITT reports – see table 2.
8. Not applicable.
9. Declared performance; the essential characteristics per product type are listed in table 1.
10. The performance of the products identified in points 1 and 2 and listed in table 1, are in conformity with the declared performance in point 9.

Signed for and on behalf of the manufacturer by:
Paul De Geyter, senior Quality manager NV Bekaert SA

Approved by:
Sr. CQA manager Bekaert
P. De Geyter

---

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**Creation date 19/06/2015 - Language EN**

**Electronically approved**

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### Addendum to pt 9. Declared Performance on essential characteristics – see table 1 in accordance with EN 14686-1: 2008.

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### Addendum to pt 7. Reports issued under surveillance of Notified body – see table 2

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EC Declaration of Performance
DRAMIX® OL 13/20

1. Unique identification code of the product: DRAMIX® OL 13/20
2. Type- and traceability info., allowing identification of the construction product as required pursuant to Article 11(4): is provided on the product packaging and product label.
3. Intended use of the construction product in accordance with EN 14889-1:2006. DRAMIX® OL 13/20 are steel fibres, made of cold-drawn wire, for STRUCTURAL USE in concrete, mortar and grout.
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   has performed under System n°1
   - determination of the product-type on the basis of Type Testing,
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   - continuous surveillance, assessment and evaluation of Factory Production Control
   issued: a `certificate of constancy of performance` per product - see table 1.
   Notified Labs:
   TSUS - registration nr: 1301 / SK-821 04 Bratislava, Studená 3
   performed: Initial Type Testing and issued ITT reports – see table 2.
8. Not applicable.
9. Declared performance: the essential characteristics per product type are listed in table 1.
10. The performance of the products identified in points 1 and 2 and listed in table 1, are in conformity with the declared performance in point 9.
    This declaration of performance is issued under the sole responsibility of the manufacturer identified in point 4.

Signed for and on behalf of the manufacturer by:
Paul De Geyter, senior Quality manager NV Bekaert SA

Approved by:
Sr. CQA manager Bekaert
P. De Geyter
### Table 1: Declaration on essential characteristics

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### Table 2: related ITT reports

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### B. CMOD Specimen description

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| **Time Casted**   | min Printed after mixing | Printed after mixing | Printed after mixing |
| **Temperature after casted** | 22.8 | 22.9 | 0 |
| **Water input**   | kg 0.6 | 0.6 | 0.6 |
| **Time input**    | 0 min | 0 min | 0 min |

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**Remarks**

- Printed with 50*10 nozzle
- Sawn in test dimensions
- Printing was not able, nozzle got blocked due to length fibres
C. Grasshopper

The goal of the model is to determine the deflection at mid-span of a simply supported beam. The model is divided into two methods, which are described in chapter 4. The model runs on a C# script. C# or “C-sharp” is a widely used scripting language, which is applied in all sorts of fields. The numerical model is created in Grasshopper. Grasshopper is used as input for Rhinoceros, which is a 3D modelling program. Grasshopper uses blocks. Each block has input and output slots, and a code to convert the input to the output. Grasshopper has a block which is based on C#, where code can be written by the user. In this paragraph, the implementation of the theory in the C# code is explained.

C.1. Multi-layer method

The C# block “Multilayer” with the input variables are shown below in figure C.1.

![Figure C.1. C# block “Multilayer” with input variables.](image)

**Specimen type:** The selection of reference material can be chosen.

**Htotaal:** Total height of the cross-section of the beam.

**Ni:** Number of layers in which each zone is divided.

**Btotaal:** Width of the beam

By using the multi-layer theory, the moment resistance of the cross-section can be obtained as described in chapter c.1 of the appendix. The advantage of scripting the calculation by the C# code, it is possible to repeat calculations in a loop statement. Therefore, each layer is calculated separately one by one. The calculation starts with layer number 1, and after the axial force and the moment resistance is calculated, these values are stored in a list. Now, the loop adds +1 to the number statement. This means that the axial force and moment resistance of layer number 2 is calculated by the same calculation. This loop continues until all the layers are calculated. Then, all the separate values can be summed up to obtain the axial force and the moment resistance of the total cross-section.
For compression, the script is written in figure C.2. For tension, the script is written in figure C.3. The summation of all the values of $F_{druk}$ and $F_{trek}$ is given in figure C.4.

```csharp
// compression
double Hdl = Hdruk / n;
int ni = 1;
while (ni <= n)
{
    double zi = (ni - 0.5) * Hdl;
    double Ed = ((curvature * zi) / Lcs) * 1000;
    double druk = 0;
    if (Ed == 0)
    {
        druk = 0;
    }
    else
    if (Ed <= Ec)
    {
        druk = 4 * Ed; // formula compressive stress
    }
    else
    {
        druk = 4 * Ec;
    }
    double Fi = Hdl * width * druk;
    double Mi = Fi * zi;
    Fdruk.Add(Fi);
    Mdruk.Add(Mi);
    ni++;
}

Figure C.2. Script compression zone.

// tension
double Htrek = Htotaal - Hdruk;
double Htl = Htrek / n;
int nj = 1;
while (nj <= n)
{
    double zj = (nj - 0.5) * Htl;
    double Et = ((curvature * zj) / Lcs) * 1000;
    double trek = 0;
    if (Et > E1)
    {
        trek = 9; // formula tensile stress part 3
        resultaat5.Add("part 3");
        string stringEt = System.Convert.ToString(Et);
        resultaat5.Add(stringEt);
    }
    else
    if (Et > EL)
    {
        trek = 1 * Et + 3; // formula tensile stress part 2
        resultaat5.Add("part 2");
        string stringEt = System.Convert.ToString(Et);
        resultaat5.Add(stringEt);
    }
    else
    if (Et > 0 && Et <= EL)
    {
        trek = 4 * Et; // formula tensile stress part 1
        resultaat5.Add("part 1");
        string stringEt = System.Convert.ToString(Et);
        resultaat5.Add(stringEt);
    }
    else
    if (Et == 0)
    {
        trek = 0;
```
double Fj = Htl * width * trek;
double Mj = Fj * zj;
Ftrek.Add(Fj);
Mtrek.Add(Mj);
nj++;

Figure C.3. Script tension zone.

double M = Mdruk.Sum() + Mtrek.Sum();
double Fd = Fdruk.Sum();
double Ft = Ftrek.Sum();
Mdruk.Clear();
Mtrek.Clear();
Fdruk.Clear();
Ftrek.Clear();

Figure C.4. Computing total forces and clear lists.

To obtain horizontal equilibrium, the normal forces in the compression and tension zone need to be equal. The neutral axis can shift upwards or downwards to change the height of both zones. New calculations lead to a different normal force under compression and tension. These can be compared and the neutral axis can be shifted again if needed. By following this loop, the model can give the most accurate value in between a certain range. This range is determined and set by the variables ‘limitmax’ and ‘limitmin’ at the top of the script. The control mechanism checks the value of the variable ‘control’. The variable ‘control’ is based on the force in the compression zone and the force under tension as can be seen in figure C.5.

control = Fd / Ft;
if (control < limitmin)
{
    Hdruk = Hdruk + 0.5;
}
else if (control > limitmax)
{
    Hdruk = Hdruk - 0.5;
}
else
{
    resultaat.Add(curvature);
    resultaat2.Add(M);
    resultaat3.Add(Fd);
    resultaat3.Add(Ft);
    resultaat4.Add(control);
    resultaat4.Add(Hdruk);
}

Figure C.5. Control mechanism for Fd/Ft=1.

For any value for control smaller then ‘limitmin’, or larger than ‘limitmax’, the Hdruk value is changed, and the calculation is restarted. If the value for control ends in between the values ‘limitmin’ and ‘limitmax’, the values of ‘curvature, M, Fd, Ft, control and Hdruk’ are added to different lists to save the data.
It is desired to compute a moment-curvature diagram. With only one value known, it is not possible to create a diagram. Therefore more curvature points will be calculated with the corresponding moments. This loop is created at the top of the script by a value of curvature which is set. This value will be increased after values are saved. Figure D.8 shows the combination of the start and the end of the loop.

```csharp
while (curvature <= CurveMax) // loop curvature
{
    ...
    // calculation script
}
if (curvature <= 0.0015)
{
    curvature = curvature + 0.0001;
}
else
{
    curvature = curvature + 0.0004;
}
```

**Figure C.6. Loop curvature.**

The curvature value changes with different values according to the value of ‘curvature’. Because of the punctuality for the first values of ‘curvature’.

After the curvature loop has been ended, all the saved data can be displayed in panels in Grasshopper. The moments and the curvatures are listed separately. In figure C.7 and C.8, an overview of the Multi-layer block with the output panels is given.

**Figure C.7. C# block with variables and output panels for Moment and Curvature**
Figure C.8. Output panels to check the calculated output.

The multi-layer method is elaborated in one C# block. The complete script is shown in chapter D.2.3 Scripts.

The last step is creating a moment-curvature diagram. Grasshopper is able to export data to Microsoft Excel. By creating a file in excel where the data can be sent to, it is possible to create a moment-curvature diagram of the data obtained by the C# block. The export connection is made by a combination of Grasshopper blocks shown in figure C.9.
Figure C.9. Overview export data to Excel.

The data is stored and written to a file saved on the computer of the user. Three data trees are used as input data for Excel. By selecting the row of Excel where the data can be stored, a graph is automatically made by Excel. This graph is shown in figure C.10.

Figure C.10. Moment Curvature diagram Grasshopper data.
C.2. Moment Area method

The second C# block which is used in Grasshopper is based on the Moment-Area method. In figure C.11 the block is shown with its input variables.

![Figure C.11. Moment-area C# block with variables.](image)

**Slices:** Number of slices in which the beam is split up.

**Length specimen:** Length of the beam.

**x:** Input Moment (Moment-Curvature diagram)

**y:** Input Curvature (Moment-Curvature diagram)

**Max Force:** Maximum vertical force applied to the beam at midspan.

First, the beam is split up into a number of slices. For each slice, the Moment is calculated in terms of the length of the beam and the applied force. The curvature per slice can be found by interpolating this moment with the data obtained by the multi-layer method. This is done with the script written in figure C.12, where ‘a’ stands for the first moment of the list, and ‘a1’ stands for the moment after the first moment. By adding these values, the interpolation can be executed.

```csharp
for (int a = 0; a < max; a++) // Search for the corresponding curvature (interpolation)
{
    int a1 = a + 1;
    double Y0 = y[a];
    double Y1 = y[a1];
    double X0 = x[a];
    double X1 = x[a1];

    // boundaries
    if (Mi == Y0)
    {
        curvature = X0;
        break;
    }
    if (Mi == Y1)
    {
        curvature = X1;
        break;
    }
    if (Mi < Y1)
    {
        curvature = X0 + (Mi - Y0) * (X1 - X0) / (Y1 - Y0)); // interpolation formule
        break;
    }
}
```
Figure C.12. The script for the interpolation of moments to obtain the curvature per slice.

The deflection per slice can be calculated by calculating the second derivative of the curvature as is executed in the script in figure C.13.

```csharp
double Hi = curvature;
double Ai = Hi * ls;
double end = Ai * zi;
Deflection.Add(end);
Moments.Add(Mi);
Curvature.Add(curvature);
i++;
}
```

Figure C.13. Script for the interpolation of moments to obtain the curvature per slice.

After the deflection is known, the values for the deflection and the corresponding moment and curvature are stored in separate lists. These values are depending on the force applied to the beam. By using a loop system, explained in chapter C.2.1, where the number of the slice is increased by 1 after the calculated values are listed, the deflection can be obtained for each slice. This same loop is used to increase the Force after the deflection is listed. An overview of the control panels used to check the output of the C# block of the Moment-Area method is given in figure C.14 below.

Figure C.14. Output panels of the C# block moment-area method.
C.3. Scripts

Two C# blocks are used in Grasshopper. By making use of a C# block in Grasshopper, Grasshopper automatically writes down codes to compute C# with Grasshopper’s variables. This script is shown first, followed by the scripts written to implement the multi-layer theory and the moment-area theory.

Grasshopper automatic script C# block

using Rhino;
using Rhino.Geometry;
using Rhino.DocObjects;
using Rhino.Collections;
using GH_IO;
using GH_IO.Serialization;
using Grasshopper;
using Grasshopper.Kernel;
using Grasshopper.Kernel.Data;
using Grasshopper.Kernel.Types;

using System;
using System.IO;
using System.Xml;
using System.Xml.Linq;
using System.Linq;
using System.Data;
using System.Drawing;
using System.Reflection;
using System.Collections;
using System.Windows.Forms;
using System.Collections.Generic;
using System.Runtime.InteropServices;

/// <summary>
/// This class will be instantiated on demand by the Script component.
/// </summary>
public class Script_Instance : GH_ScriptInstance
{
    #region Utility functions
    /// <summary>Print a String to the [Out] Parameter of the Script component.</summary>
    /// <param name="text">String to print.</param>
    private void Print(string text) { /* Implementation hidden. */ }
    
    /// <summary>Print a formatted String to the [Out] Parameter of the Script component.</summary>
    /// <param name="format">String format.</param>
    /// <param name="args">Formatting parameters.</param>
    private void Print(string format, params object[] args) { /* Implementation hidden. */ }
    
    /// <summary>Print useful information about an object instance to the [Out] Parameter of the Script component.</summary>
    /// <param name="obj">Object instance to parse.</param>
    private void Reflect(object obj) { /* Implementation hidden. */ }
    
    /// <summary>Print the signatures of all the overloads of a specific method to the [Out] Parameter of the Script component.</summary>
    /// <param name="obj">Object instance to parse.</param>
    /// <param name="method_name">Object instance to parse.</param>
    private void Print(object obj, string method_name) { /* Implementation hidden. */ }
    #endregion
    
    #region Members
    /// <summary>Gets the current Rhino document.</summary>
    private readonly RhinoDoc RhinoDocument;
    
    /// <summary>Gets the Grasshopper document that owns this script.</summary>
    private readonly GrasshopperDocument GrasshopperDocument;
    
    /// <summary>Gets the Grasshopper script component that owns this script.</summary>
    private readonly IGH_Component Component;
    
    /// <summary>Gets the current iteration count. The first call to RunScript() is associated with Iteration=0.
    /// Any subsequent call within the same solution will increment the Iteration count.
    /// </summary>
    public int Iteration { get; private set; }
    #endregion
}
/// <summary>
private readonly int Iteration;
#endregion

/// <summary>
/// This procedure contains the user code. Input parameters are provided as regular arguments,
/// Output parameters as ref arguments. You don’t have to assign output parameters,
/// they will have a default value.
/// </summary>
private void RunScript(int v, int u, int x, double z, ref object A, ref object B, ref object C, ref object D, ref object E)
{

Multi-layer method script C# strain hardening material behaviour

/// Multi-Layer Model Script
/// Strain softening material behaviour

// set lists
List<double> resultaat = new List<double>(); //Output list A
List<double> resultaat2 = new List<double>(); //Output list B
List<double> resultaat3 = new List<double>(); //Output list C
List<double> resultaat4 = new List<double>(); //Output list D
List<string> resultaat5 = new List<string>();  //Output list E
List<double> Fdruk = new List<double>();  //Temporary list Force Compression Zone
List<double> Ftrek = new List<double>();  //Temporary list Force Tension Zone
List<double> Mdruk = new List<double>();  //Temporary list Moment Compression Zone
List<double> Mtrek = new List<double>();  //Temporary list Moment Tension Zone

// set variables
int n = x;     //Number of layers per zone
double limitmin = 0.9;    //Control range minimum
double limitmax = 1.1;    //Control range maximum
double curvature = 0;    //Curvature
double width = z;    //Width of the cross-section
double Htotaal = u;    //Height of the cross-section
double compres = v;    //sort fibre (not used in script)
double Lcs = u;
double CurveMax = 4.1 / (u / 2);  //max curvature according to opening CMOD

while(curvature <= CurveMax)   // loop curvature
{
  double control = 0;   //control equilibrium compression and tension force
  double Hdruk = Htotaal / 2;    //Height compression zone
  while(control < limitmin || control > limitmax)  //loop Fd/Ft
  {
    // compression
    double Hd1 = Hdruk / n;    //Height layers compression zone
    int ni = 1;
    while(ni <= n)     //loop layer calculation
    {
      double zi = (ni - 0.5) * Hd1;  //lever arm layer
      double Ed = ((curvature * zi) / Lcs) * 1000;  //strain layer
      double druk = 0;
      if (Ed == 0)
      {
        druk = 0;
      }
      else
      {
        if (Ed <= Ec)
        {
          druk = 4 * Ed;       // formula compressive stress
        }
      }
    }
  }
}
else
{
    druk = 4 * Ec; // formula compressive stress
}

double Fi = Hdl * width * druk; //force layer
double Mi = Fi * zi; //moment layer
Fdruk.Add(Fi); //save layer force in list
Mdruk.Add(Mi); //save layer moment in list
ni++;

//tension
double Htrek = Htotaal - Hdruk; //height tension zone
double Htl = Htrek / n; //height layers tension zone
int nj = 1;

while (nj <= n)
{
    double zj = (nj - 0.5) * Htl; //lever arm layer
double Et = ((curvature * zj) / Lcs) * 1000; //strain layer
double trek = 0; //tensile stress
    if (Et > E1)
    {
        trek = 9; // formula tensile stress part 3
        resultaat5.Add("part 3");
        string stringEt = System.Convert.ToString(Et);
        resultaat5.Add(stringEt);
    }
    else
    {
        if (Et > EL)
        {
            trek = 1 * Et + 3; // formula tensile stress part 2
            resultaat5.Add("part 2");
            string stringEt = System.Convert.ToString(Et);
            resultaat5.Add(stringEt);
        }
        else
        {
            if (Et > 0 && Et <= EL)
            {
                trek = 4 * Et; // formula tensile stress part 1
                resultaat5.Add("part 1");
                string stringEt = System.Convert.ToString(Et);
                resultaat5.Add(stringEt);
            }
            else
            {
                if (Et == 0)
                {
                    trek = 0;
                    resultaat5.Add("part 0");
                }
                else
                {
                    resultaat5.Add("part 6");
                    string stringEt = System.Convert.ToString(Et);
                    resultaat5.Add(stringEt);
                }
            }
        }
    }
    double Fj = Htl * width * trek;
double Mj = Fj * zj;
Ftrek.Add(Fj);
Mtrek.Add(Mj);
nj++;
}

double M = Mdruk.Sum() + Mtrek.Sum(); //Moment cross-section
double Fd = Fdruk.Sum(); //total compression force
double Ft = Ftrek.Sum(); //total tension force

//clear temporary lists
Mdruk.Clear();
Mtrek.Clear();
Fdruk.Clear();
Ftrek.Clear();
Investigation into Properties of Fibre Reinforced Concrete in Extrusion Based Manufacturing

Appendix

```csharp
// control equilibrium
if (Fd == 0 || Ft == 0)
{
    resultaat.Add(curvature);
    resultaat2.Add(M);
    resultaat3.Add(Fd);
    resultaat3.Add(Ft);
    resultaat4.Add(control);
    resultaat4.Add(Hdruk);
    break;
}

control = Fd / Ft;

if (control < limitmin)
{
    Hdruk = Hdruk + 0.5;
}
else if (control > limitmax)
{
    Hdruk = Hdruk - 0.5;
}
else
{
    resultaat.Add(curvature);
    resultaat2.Add(M);
    resultaat3.Add(Fd);
    resultaat3.Add(Ft);
    resultaat4.Add(control);
    resultaat4.Add(Hdruk);
}

// increase curvature
if (curvature <= 0.0015)
{
    curvature = curvature + 0.0001;
}
else
{
    curvature = curvature + 0.0004;
}

// show results
A = resultaat;
B = resultaat2;
C = resultaat3;
D = resultaat4;
E = resultaat5;

// <Custom additional code>
// </Custom additional code>

Moment-area method script C#

// Moment Area Method
List<double> Deflection = new List<double>();
List<double> Moments = new List<double>();
List<double> Curvature = new List<double>();
List<double> Force = new List<double>();
List<double> slidechange = new List<double>();
double L = u;
double s = v;
double ls = (L / 2) / s;

int maxforce = z;
int force = 0;
while (force <= maxforce)
{
```
int i = 1;
while (i <= s) {
    double zi = (i - 0.5) * ls;
    double Mi = 0.5 * force * L * zi; //moment per slice
    int max = x.Count();
    int min = 0;
    double curvature = 12.34565;
    // Search for the corresponding curvature (interpolation)
    for (int a = min; a < max; a++) {
        int a1 = a + 1;
        double Y0 = y[a];
        double Y1 = y[a1];
        double X0 = x[a];
        double X1 = x[a1];
        // boundaries
        if (Mi == Y0) {
            curvature = X0;
            break;
        }
        if (Mi == Y1) {
            curvature = X1;
            break;
        }
        if (Mi < Y1) {
            curvature = X0 + (Mi - Y0) * ((X1 - X0) / (Y1 - Y0)); // interpolation formula
            break;
        }
        else {
            //...
        }
    }
    double Hi = curvature;
    double Ai = Hi * ls;
    double end = Ai * zi;
    slidechange.Add(end);
    Moments.Add(Mi);
    Curvature.Add(curvature);
    i++;
    double deflection = slidechange.Sum();
    Deflection.Add(deflection);
    slidechange.Clear();
    Moments.Clear();
    Curvature.Clear();
    i++;
}
A = Deflection;
F = Moments;
G = Curvature;
B = Force;