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Crack width estimation

A comparative analysis between ATENA simulation and experimental tests

TU Delft

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By

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Preface

This report contains the bachelor's thesis on Crack width estimation "A comparative analysis between ATENA simulation and experimental tests."

I would like to express my gratitude to my supervisors G. Stamoulis, Dr.ir. P.C.J. Hoogenboom and Dr. Y. Yang for their support during this research. I would also like to express my gratitude to M. Poliotti PhD for assisting in setting up the ATENA software, and to G.I. Zarate Garnica for providing the data from her measurement report of reinforced concrete slabs.

Koen de Rooij
Delft, June 2024

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Summary

Concrete slabs are essential components of modern construction. Concrete slabs are typically made of reinforced concrete and offer stability and support. To determine stresses in concrete slabs a method called finite element method is used. FEM models complex structures by dividing them into smaller and simpler elements. For this report the finite element analysis software called ATENA is used. ATENA is specially designed for reinforced concrete structures. With ATENA you can simulate crushing, concrete cracking and reinforcement yielding. ATENA has limitations, such as singularities at high stress locations. At these locations, the stresses converge to infinite and lead to inaccuracies in the solution. These inaccuracies lead to the main question:

“Is ATENA capable to predict the crack width correctly?”

To answer this question, a model was created in ATENA. Using the measured properties of the concrete led to an inaccurate prediction of the load-deflection diagram. To accurately predict the load-deflection diagram, the Young’s modulus and the tension strength were divided by a factor of three, and the fracture energy was increased to 165 N/m.

To verify the accuracy of the model and its properties, three different scenarios were looked at. In each scenario, the point load was placed at a different location. For each scenario, the element size is respectively half, one-third and one-fourth of the thickness of the slab. For each location, the ultimate load and failure load were predicted accurately.

ATENA uses the Exponential Crack Opening Law as its softening model for concrete. The crack width w is calculated by the following formula:

$$w = \varepsilon_{cr} L_t$$

where: $w\ [mm] = crack\ width$

$\varepsilon_{cr}\ [-] = crack\ opening\ strain$

$L_t\ [mm] = characteristic\ length\ of\ a\ finite\ element$

For the scenario with the element size of one-fifth of the thickness of the slab, ATENA successfully predicted the total crack width over a span of 1800 mm with a margin of error of 0.8%. To conclude, ATENA is able to predict the crack width correctly when the element size is small enough and the load-deflection diagram aligns with the measured data.

Further research should be done to determine whether the usage of smaller element sizes has an impact on the accuracy of the crack width prediction and whether it is worthwhile to use smaller element sizes. Further research should also be done on determine whether the division by a factor of three on the Young’s modulus and the tension strength is only applicable to this model. Or if it holds true for all models in ATENA.

1. Introduction

1.1 Motivation

Concrete slabs are essential components of modern construction. Concrete slabs are typically made of reinforced concrete and offer stability and support. To determine stresses in concrete slabs a method called finite element method is used.
The finite element method (FEM) is a successful approach for modelling complex structures. FEM divides a complex structure into smaller and simpler elements, solving mathematical equations for each element. These equations are combined to estimate the behaviour of the entire structure.
To estimate the stress and crack width in the concrete, the software ATENA is used. ATENA is a finite element analysis software used to simulate the behaviour of reinforced concrete.
Using a finite element analysis software has its limitations. Singularities often occur at locations where high stresses occur or at discontinuities in the model. At these locations, the stresses converge to infinite and lead to inaccuracies in the solution.

1.2 Problem analysis

These inaccuracies give rise to the main research question:

"Is ATENA capable to predict the crack width correctly?"

The main research question will be answered through the examination of three sub-questions and comparing results from both the ATENA model and the test setup.

- *How to set up a model in ATENA?*
- *How to determine the crack width?*
- *What effect does element size have on the crack width?*

1.3 Goal

The purpose of this report is to compare the crack width around a point load between ATENA simulation and experimental tests. This will be done by rebuilding the test setup in ATENA. The test setup is a single loaded reinforced concrete slab. The slab is supported by a simple support and a continuous support. The crack width calculated by ATENA will be compared to the test data. If the data from the model and the test match, another situation is explored. If this is not the case, the model is adjusted where necessary until it does match.

1.4 Reading guide

This bachelor's thesis is divided into seven chapters. **Chapter 2** provides a step-by-step demonstration on the setup of the model. **Chapter 3** presents an analysis of the concrete material properties. This analysis will examine the effect of the material properties on deflection and crack width. From this, the best matching properties will be chosen. In **Chapter 4**, the setup of the model will be verified by changing the location of the point load and the element size. **Chapter 5** will compare the crack widths measured during the SR1M1 test with the crack widths predicted by ATENA. The method how ATENA determines the crack width will be explained. This will be introduced with an explanation of the ATENA crack theory. **Chapter 6** discusses the results and limitations of the research. **Chapter 7** contains the conclusion of the report and recommendations for further research.

2. Creating a model

This chapter explains how the model from the test setup was made in ATENA. Section 2.1 will cover all the data regarding the test setup. Section 2.2 will cover the creation of the ATENA model. In this section, the step-by-step creation of the model is demonstrated.

2.1 Test setup

All the data from the test setup was sourced from the master's thesis draft on the measurement report of reinforced concrete slabs. The ATENA model must be identical to the test setup for a correct comparison between them. The dimensions of the slab and the reinforcement configuration are shown in figure 2.1.

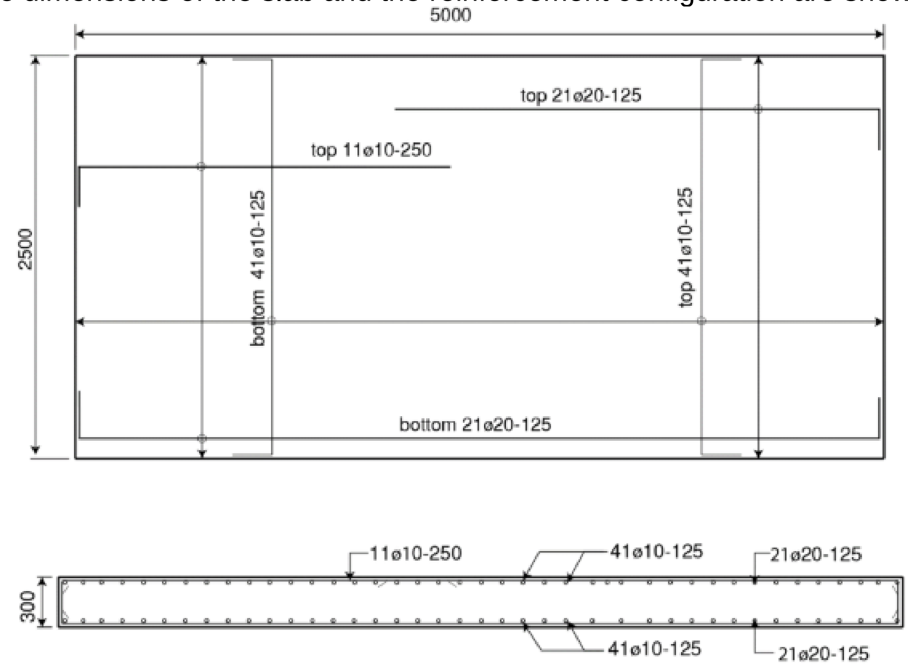

Figure 2.1: Reinforcement layout for slabs with ribbed bars. Dimension in mm. (Zarate Garnica & Lantsoght, 2021).

Figure 2.2 displays the top view of the test setup.

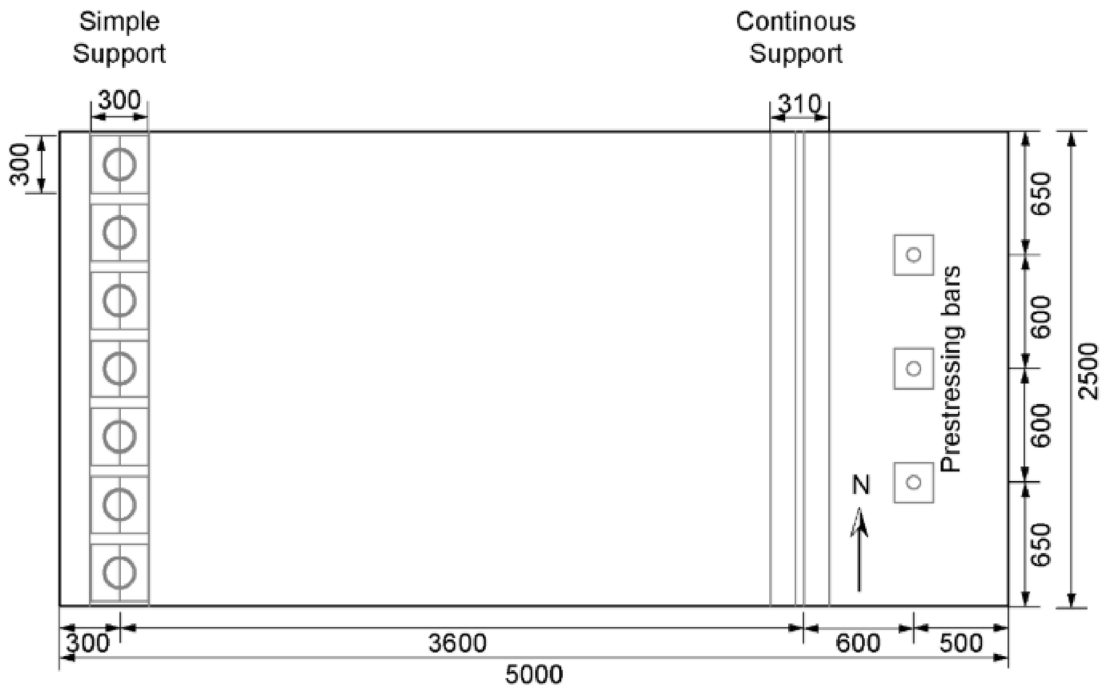

Figure 2.2: Top view of test setup. Units in mm (Zarate Garnica & Lantsoght, 2021).

As seen in figure 2.2, the test setup consisted of a simple support and a continuous support. The simple support consisted of seven plates of 300 mm x 300 mm. The slab was prestressed by three bars at the beginning of the tests. The bars were prestressed to 15 kN, to compensate for the moment generated by the self-weight of the slab.

G.I. Zarate Garnica conducted multiple tests with the load applied at different points. During the creation of the model, consideration was given to test SR1M1, where the load is applied in the middle between the supports. In chapter 4 a deeper look was taken into the tests where the load is applied at deferent locations.

2.2 Creation of Atena model

2.2.1 Geometry

The first step in Atena was to create the cross section of the concrete slab. This was done by placing points in the corners for the slab and connecting them by line segments. Then the surface was created by using the create surface function and selecting all the lines.

The stirrups were divided into two different layers, one for the 10 mm diameter stirrups and the other for 20 mm diameter stirrups. For the longitude reinforcement point were created. The cross section created in Atena is shown in figure 2.3.

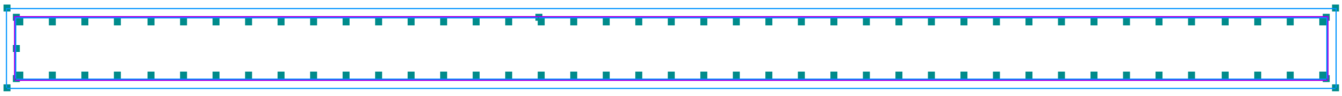

Figure 2.3: Cross section model Atena.

The surface of the concrete slab is extruded to make a to create a solid by using the tool ‘Translate geometry.’ The stirrups and longitude reinforcement were translated into the slab to create the correct cover. The stirrups were copied, and the longitude reinforcement was extruded to create the same dimensions as given in figure 2.1. Figure 2.4 shows from left to right the top view of the 10 mm diameter stirrups, the 20 mm diameter stirrups, and the longitude reinforcement.

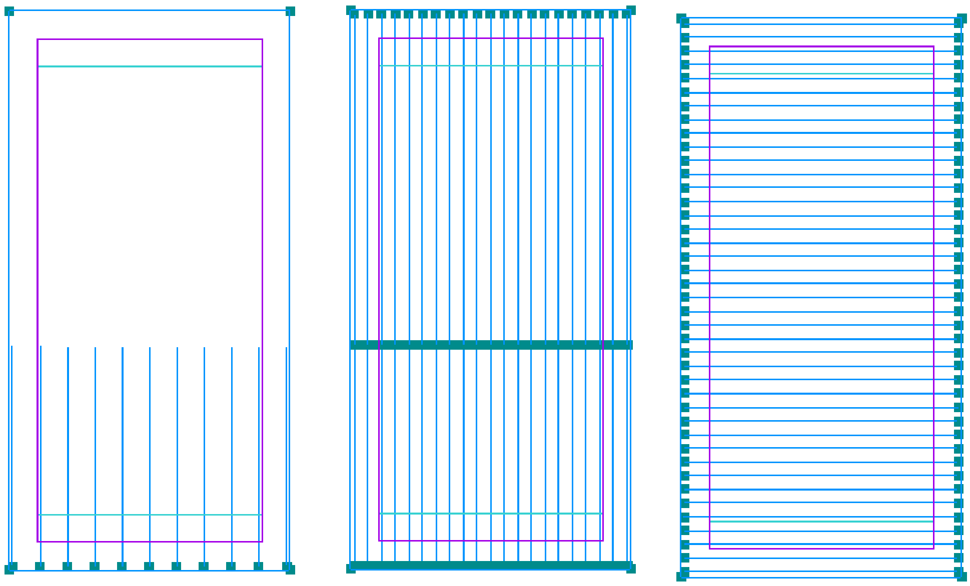

Figure 2.4: Top view of the 10 mm diameter stirrups, the 20 mm diameter stirrups, and the longitude reinforcement.

The supports were added as shown in figure 2.2. The left side consists of seven simple supports connected to the slab by plates of 300 mm x 300 mm x 16 mm. The right side consists of a continuous support connected to the slab by a steel strip with the dimensions of 2600 mm x 300 mm x 10 mm. Loading plates were placed at the location of the live and prestressed loads. Figure 2.5 displays the supports and the loading plates of the model.

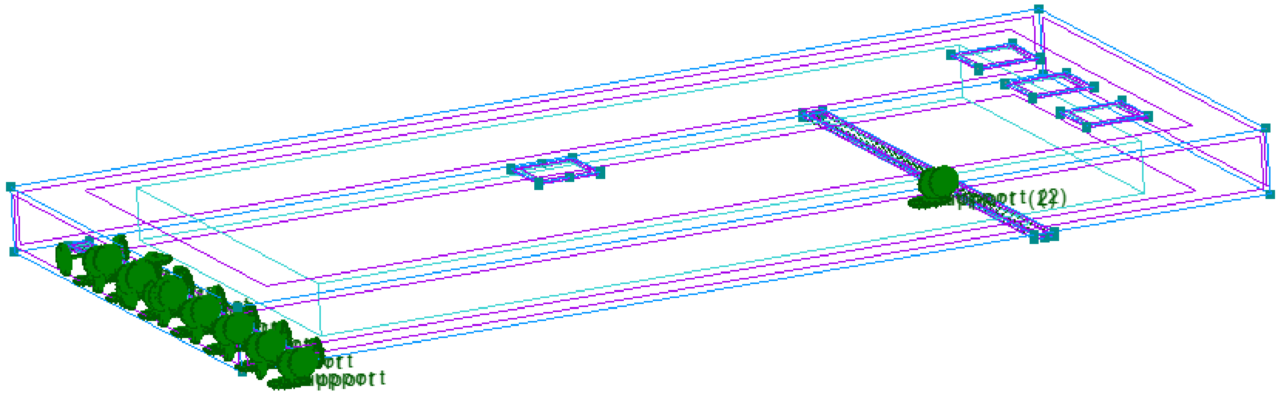

Figure 2.5: Supports and loading plates of the model.

2.2.2 Material defining

Now that all the geometry has been placed correctly, the materials need to be defined. The compressive and splitting tensile strength of the mixture was tested the day before the test. The compressive concrete cube strength at testing was 58.73 MPa. The splitting tensile strength of the mixture was 4.72 MPa.
The yield strength of 585 MPa was measured by the bars with a diameter of 20 mm. For the bars with a diameter of 10 mm, the yield strength of 415 MPa was measured. To correctly model the supports and loading plates an elastic material was used. Figure 2.6 displays the slab with the defined materials.

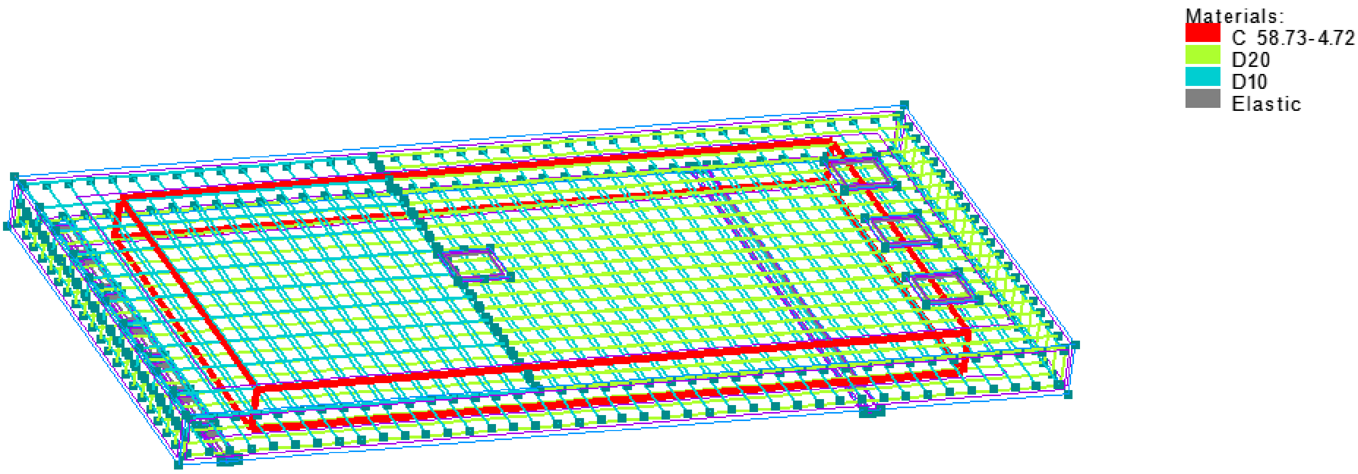

Figure 2.6: Slab with defined materials.

2.2.3 Finite element mesh

At this point, the geometry of the model and materials models have been set up. Therefore, the FEM mesh can be prepared. The default FEM mesh was generated by the FE mesh generator. The mesh size was changed to 0.15 m, half the size of the thickness of the slab. In chapter 4 the mesh size has been adjusted. The mesh type has been changed to structured. The slab must be connected to the loading plates by the fixed contact function because its mesh size differs from that one of the loading plates. Figure 2.7 displays the FEM mesh.

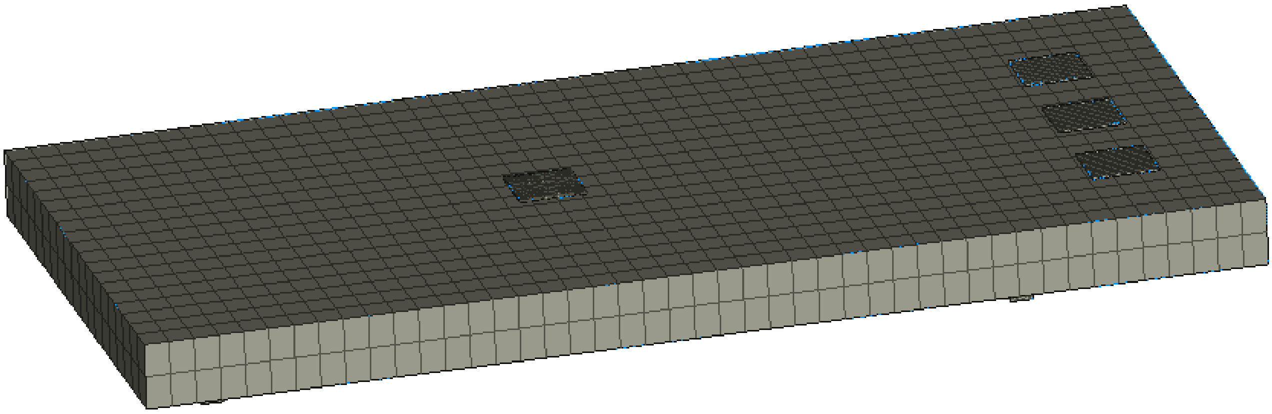

Figure 2.7: FEM mesh.

2.2.4 Analysis

Before the model can be analysed, load cases and boundary conditions need to be added. A distributed load of 166.67 kN/m^2 was added to each prestressed loading plate. This leads to a prestressed load of 15 kN to each plate. A distributed load of 12500 kN/m^2 was added to the main loading plate. This leads to a load of 1125 kN, which equals the load under which the crack width was measured. The self-weight, with a value of 25 kN/m^3, was added.

A task was set up in which the slab was loaded with the self-weight and prestress loads over the course of ten steps. One-tenth of the load is added with each step. In the second interval, the slab was loaded with a point load over the course of fifty steps. Figure 2.8 illustrates how the task is classified, demonstrating the setup of the first interval.

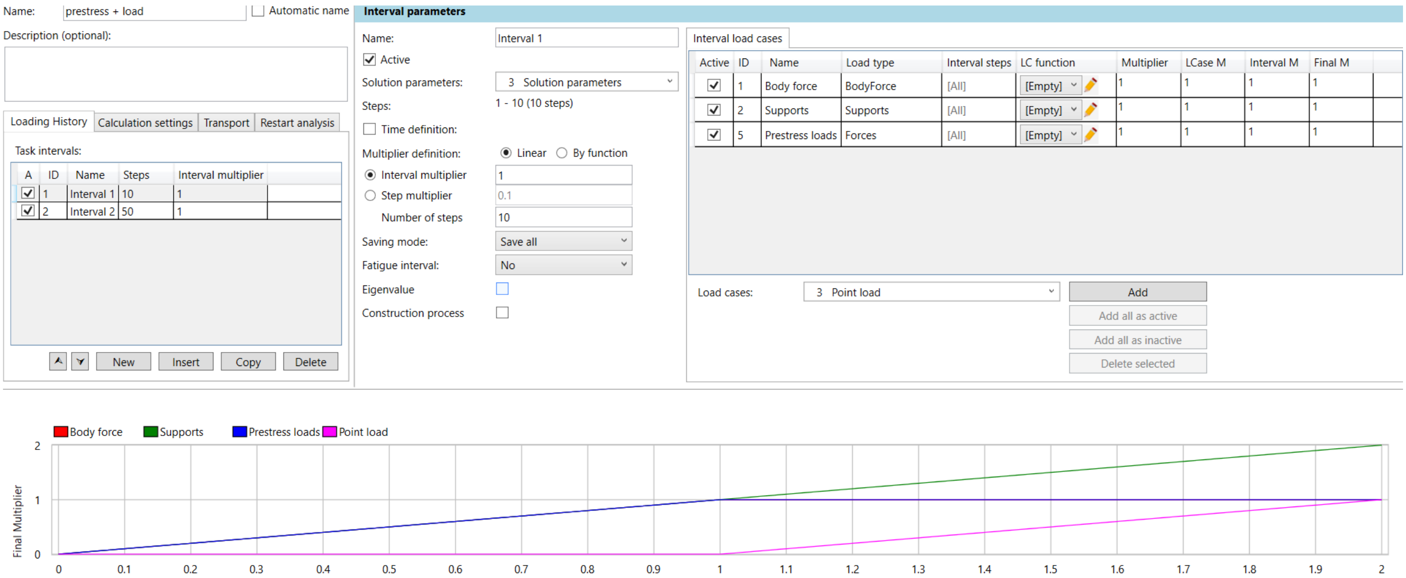

Figure 2.8: Classification of the task, demonstrating the setup of the first interval.

3. Material properties concrete

In this chapter, the material properties of the concrete will be analysed. The effect of the material properties on deflection and crack width will be explained. The correct material properties of the concrete will be chosen based on the load-deflection diagrams.

3.1 Comparison deflection of model and test

The properties used for the first analysis are the properties measured by the SR1M1 test and the standard values provided by ATENA for the respective concrete strength. The used values that were measured or provided by ATENA that are dependent on the concrete strength are:

- Young's modulus: $E_c = 34000\ \mathrm{MPa}$
- Tension strength: $f_t = 4.72\ \mathrm{MPa}$
- Compressive strength: $f_c = -58.73\ \mathrm{MPa}$
- Fracture energy: $G_F = 100\ \mathrm{N/m}$
- Plastic strain: $\varepsilon_{cp} = -0.0014$
- Onset of nonlinearity $f_{c0} = -31.77\ \mathrm{MPa}$

Figure 3.1 shows the load-deflection diagram corresponding to these properties. Figure 3.2 shows the load deflection diagram measured during the SR1M1 test.

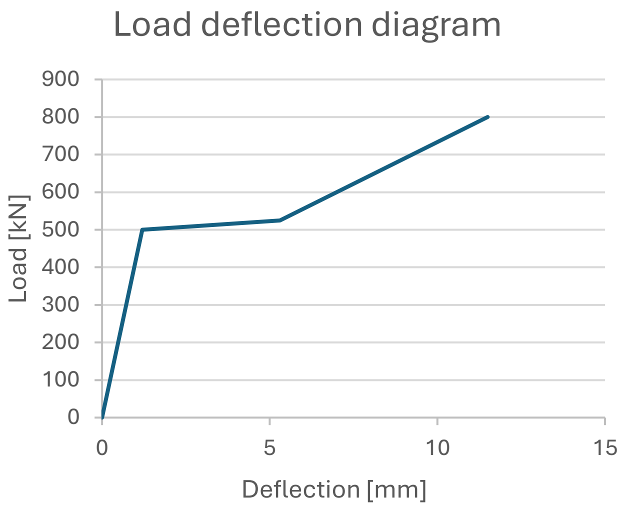

Figure 3.1: Load-deflection diagram starting values.

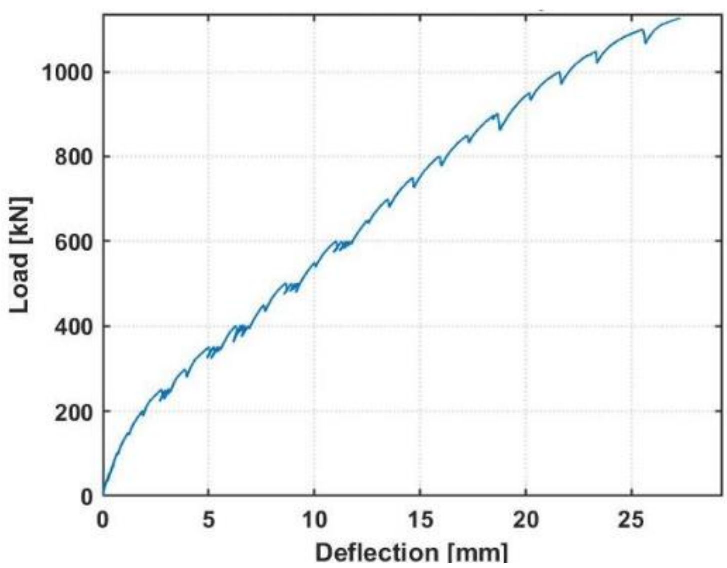

Figure 3.2: Load-deflection diagram SR1M1 test (Zarate Garnica & Lantsoght, 2021).

When comparing these two diagrams, it is showcased that the deflection and the failure load of the model are both too low. The properties must be adjusted to align the model's load-deflection diagram with the test. This was done by running the same model multiple times with a different Young's modulus, tension strength or fracture energy. For each of the three properties, the model has been run three times with a different value. This allows the determination of the influence of each property on the ultimate load and deflection.

Young's modulus
The Young's modulus influences the stiffness and elasticity of a concrete slab. A higher Young's modulus points to an increase in stiffness, resulting in a lower deflection at a certain load. On the contrary, a lower Young's modulus points to a decrease in stiffness, resulting in a higher deflection at a certain load. Figure 3.3 shows the displacement at different Young's modulus. It was observed that the ultimate load was minimally affected by the Young's modulus. The model with the lowest Young's modulus was found to have a failure load of 25 kN higher than the other two models.

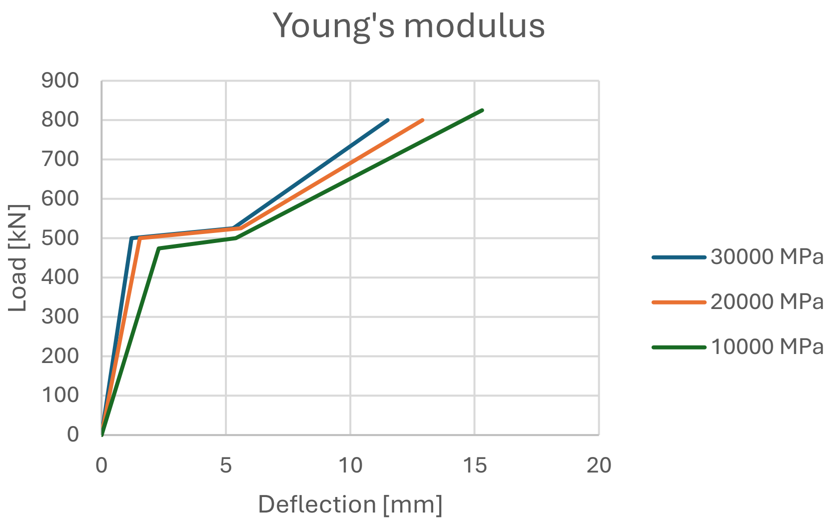

Figure 3.3: Load-deflection diagram for multiple Young's modulus.

Tension strength
The tension strength of concrete influences the ability to withstand tensile stresses and therefore the deflection. A higher tension strength generally leads to a lower deflection since the material can withstand greater tensile stresses before yielding. On the contrary, a lower tension strength results in a higher deflection at a certain load.

But contrary to reason, as shown in Figure 3.4 a lower tension strength results in a higher failure load. It was observed that at a lower load, the tension strength has effect on the deflection. While at a load of 550 kN or higher, the deflection of the three runs remains virtually the same.

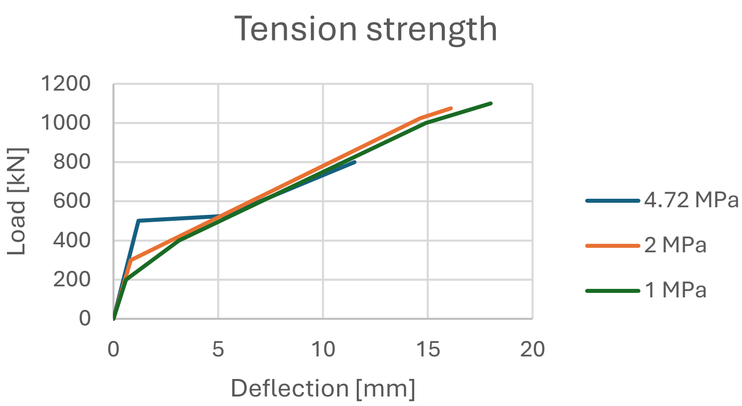

Figure 3.4: Load-deflection diagram for multiple tension strengths.

Fracture energy
Fracture energy G_F [kJ/m^2], defined as the amount of energy absorbed to create a unit area of a crack (Ding & Yu, 2022). As shown in Figure 3.5, a higher fracture energy results in a higher failure load and a lower deflection at a given load.

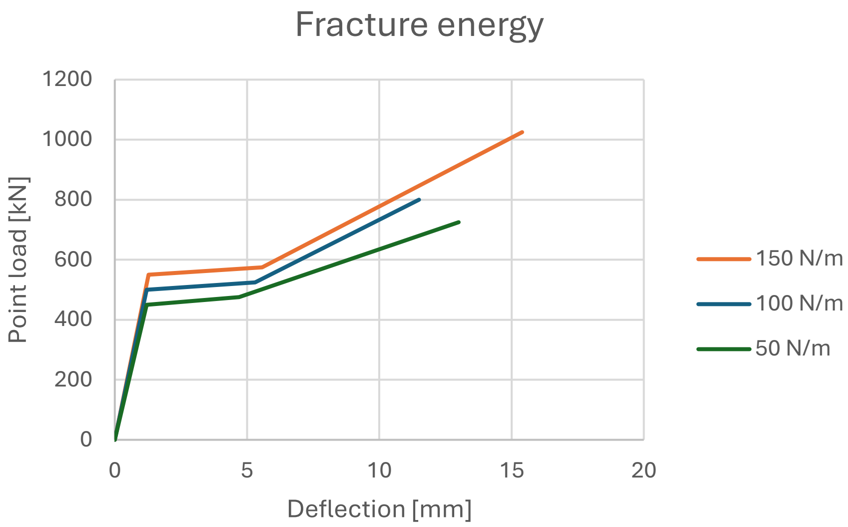

Figure 3.5: Load-deflection diagram for multiple fracture energies.

3.2 Chosen concrete properties
To get the model as close to the measured results, the Young's modulus and tension strength were lowered. Lowering these two properties brought the model closer to the measurements. Multiple iterations were done. The closest iteration came after using the following properties:

- Young's modulus: $E_c = 11333 \text{ MPa}$
- Tension strength: $f_t = 1.6 \text{ MPa}$
- Compressive strength: $f_c = -58.73 \text{ MPa}$
- Fracture energy: $G_F = 165 \text{ N/m}$
- Plastic strain: $\varepsilon_{cp} = -0.0014$
- Onset of nonlinearity $f_{c0} = -31.77 \text{ MPa}$

The only properties that are changed are the Young's modulus, the tension strength and the fracture energy. The Young's modulus and the tension strength are both divided by a factor of three. The fracture energy is changed from 100 N/m to 165 N/m. The load-deflection diagram corresponding to these properties is given in figure 3.6.

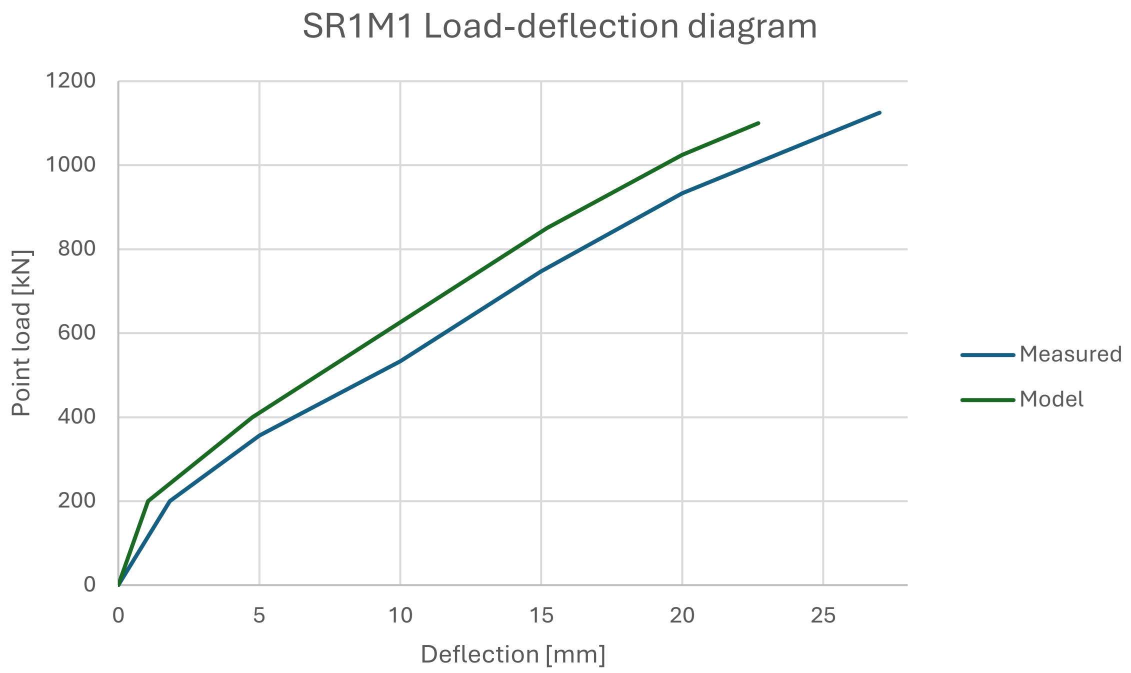

Figure 3.6: Load-deflection diagram for chosen concrete properties

To check if the model is correct, three different scenarios were looked at. For each scenario, the point load was placed at a different location. For each scenario, the element size is respectively half, one-third and one-fourth of the thickness of the slab. These three scenarios will be discussed in the next chapter, Chapter 4: Changing boundary conditions.

4. Changing boundary conditions

This chapter examines three scenarios where the load is applied at various locations. For each scenario, the element size is respectively half, one-third and one-fourth of the thickness of the slab. For the SR1M1 test, the 60 mm element size was also used. The model will be checked by the load-deflection diagram and if the failure mode corresponds to one that was measured during the tests.

4.1 Scenarios

The scenarios that were looked at are shown in figure 4.1. The SR1E1 and SR1E2 tests were done under the same conditions as the SR1M1 test. The only difference between these tests was the location of the point load. The load of the SR1M1 test was in the middle of the two supports. The load of the SR1E1 test was 815 mm to the north and 600 mm to the west in comparison to the SR1M1 test. The load of the SR1E2 test was 815 mm to the south and 1000 mm to the west in comparison to the SR1M1 test. The location of the point loads can be seen in figure 4.1 and figure 4.2.

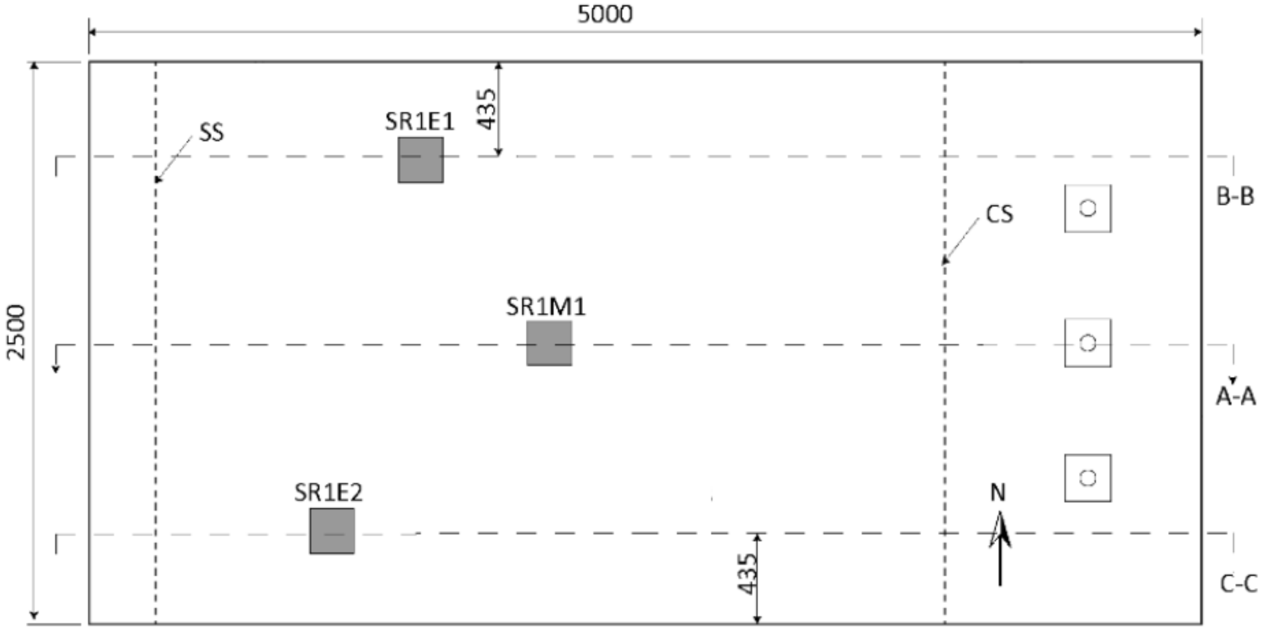

Figure 4.1: Load locations top view. Units in mm (Zarate Garnica & Lantsoght, 2021).

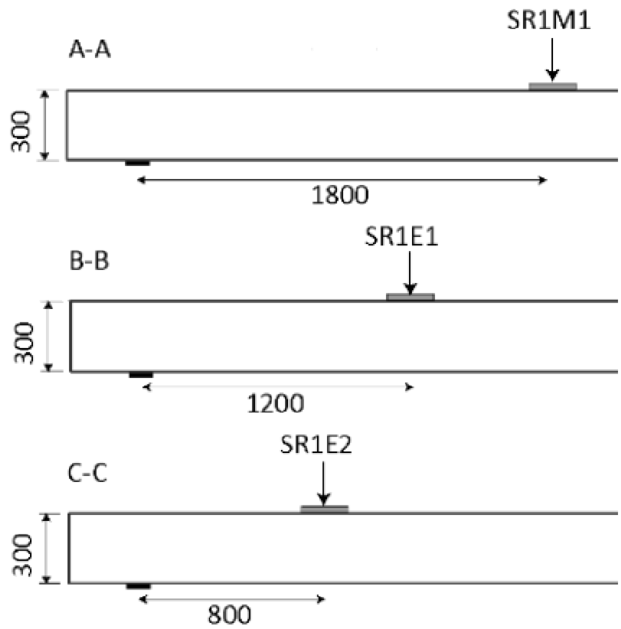

Figure 4.2: : Load locations side view. Units in mm (Zarate Garnica & Lantsoght, 2021).

4.2 SR1M1

The load-deflection diagram for the SR1M1 test was measured for the element sizes of 150 mm, 100 mm, 75 mm and 60 mm. The load-deflection diagram corresponding to these element sizes and the measured values is shown in figure 4.3. From the load-deflection diagram it can be concluded that the model with the smallest element size gives the closest values to the measured values. The estimated deflection at a lower force is nearly equal to the measured values. As the force increases, the estimations diverge slightly.

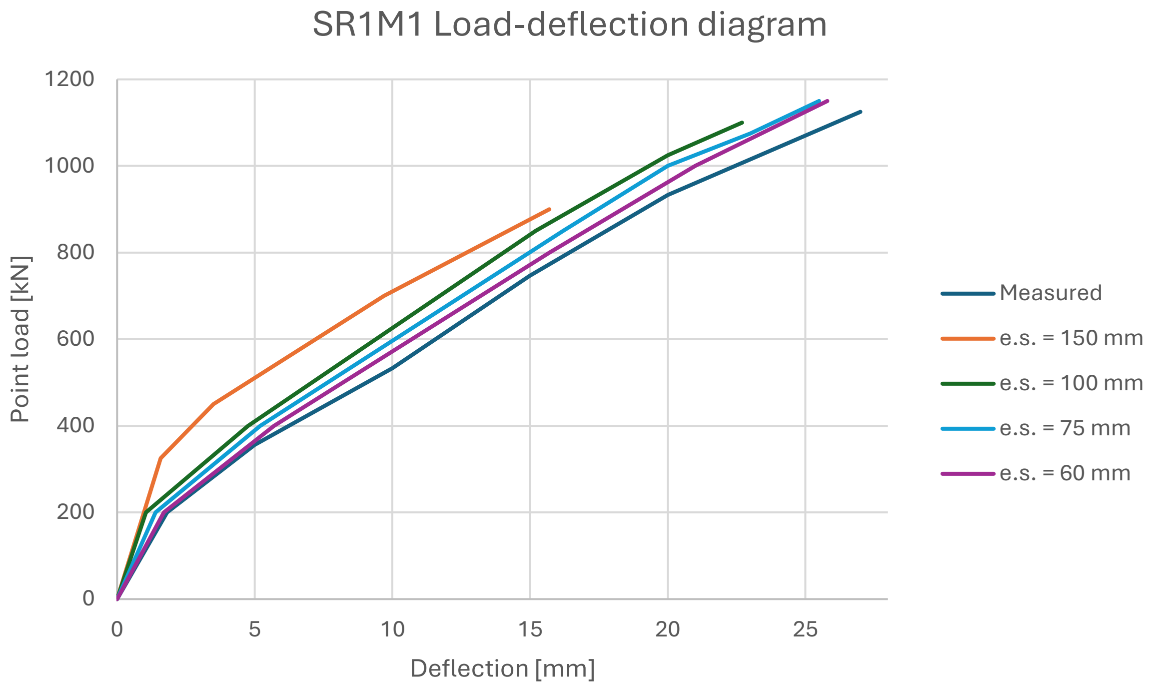

Figure 4.3: SR1M1 Load-deflection diagram.

The experiment failed due to flexure-induced punching. Figure 4.4. displays the top view after failure. Figure 4.5 displays the bottom view after failure where large crack openings up to 20 mm can be seen.

Figure 4.4: Top view after failure (Zarate Garnica & Lantsoght, 2021).

Figure 4.5: Bottom view after failure (Zarate Garnica & Lantsoght, 2021).

Running the ATENA model until failure visualises the failure mode by deformation and/or cracks. Running the model until failure visualises the following cracks as shown in figure 4.6 and figure 4.7. Figure 4.6 displays the cracks from the top view. In this figure it is visible that around the loading plate the biggest cracks form. From the loading plate cracks are formed diagonally. Figure 4.7 shows the cracks from the bottom view. Significantly large cracks form underneath the loading plate. From these pictures it can be concluded that the model predicts the failure mode correctly.

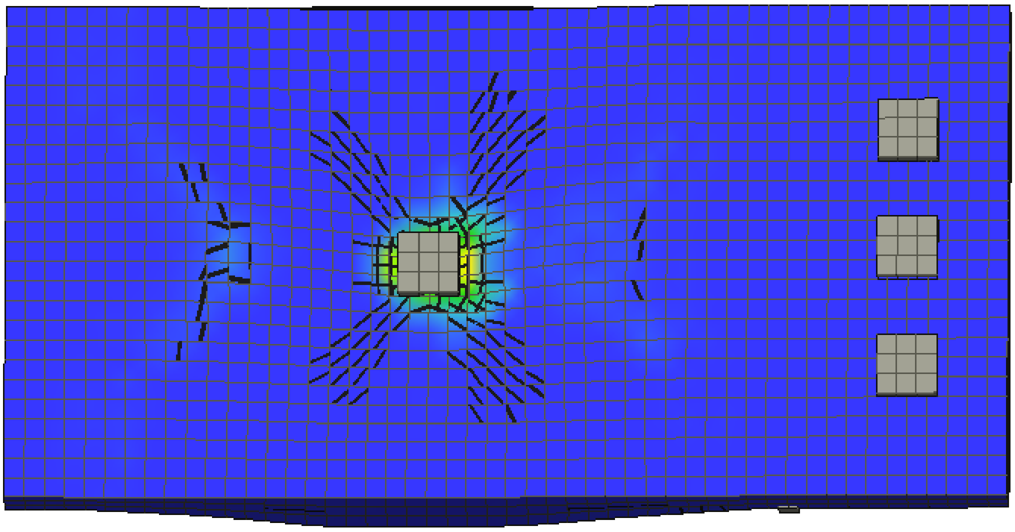

Figure 4.6: Top view of crack forming after failure.

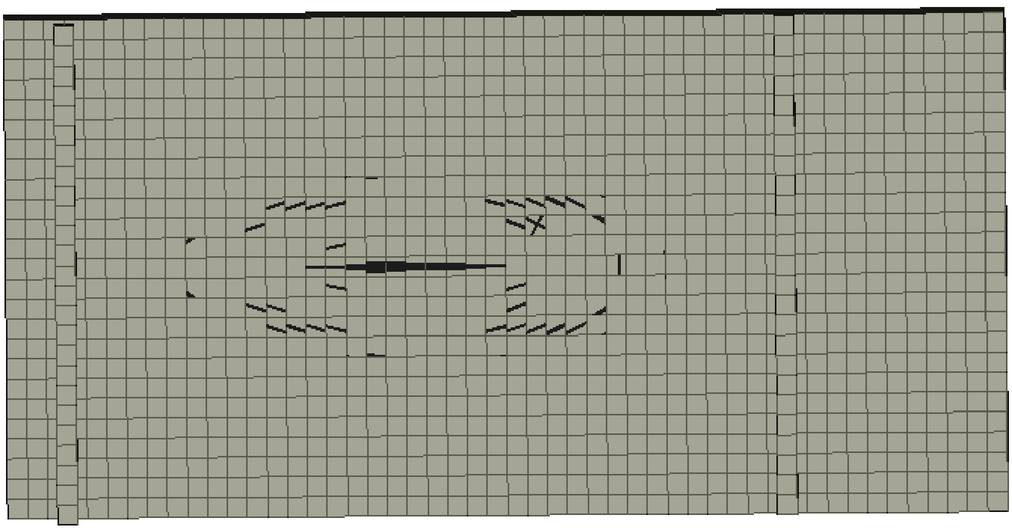

Figure 4.7: Bottom view of crack forming after failure.

4.3 SR1E1

The load-deflection diagram for the SR1E1 test was measured for the element sizes of 150 mm, 100 mm and 75 mm. The load-deflection diagram corresponding to these element sizes and the measured values is shown in figure 4.8. From the load-deflection diagram it can be concluded that the model with the smallest element size gives the closest values to the measured values. The estimation of the deflection at lower forces deviates significantly from the measured values. The higher the forces, the better the estimations become.

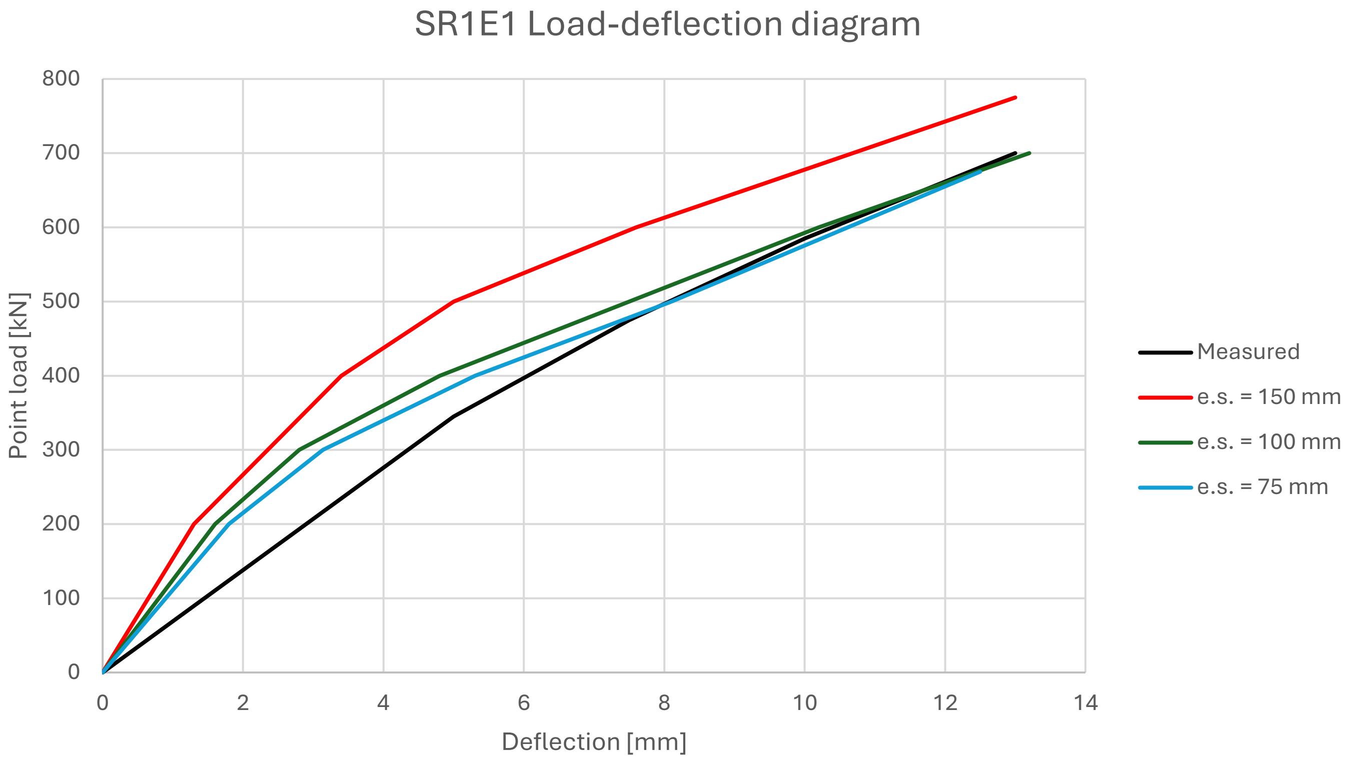

Figure 4.8: SR1E1 Load-deflection diagram.

The experiment failed due to yielding. At a load of 700 kN the maximum strain in the reinforcement was approximately 0.0033, as visible from figure 4.9. The strain was measured underneath the concentrated load. Figure 4.10 illustrates the strain in the steel rebars as predicted by the model in ATENA. ATENA accurately predicts the strain for the given load.

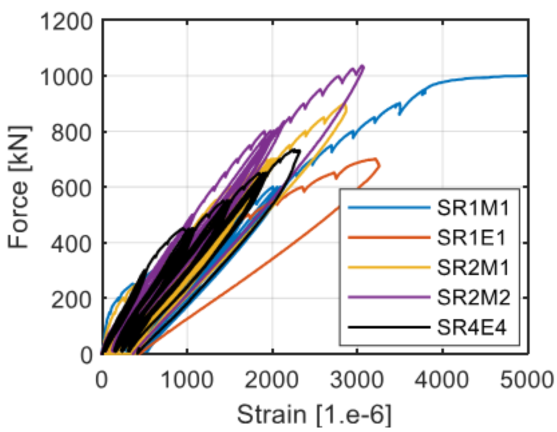

Figure 4.9: Load-strain diagram (Zarate Garnica & Lantsoght, 2021).

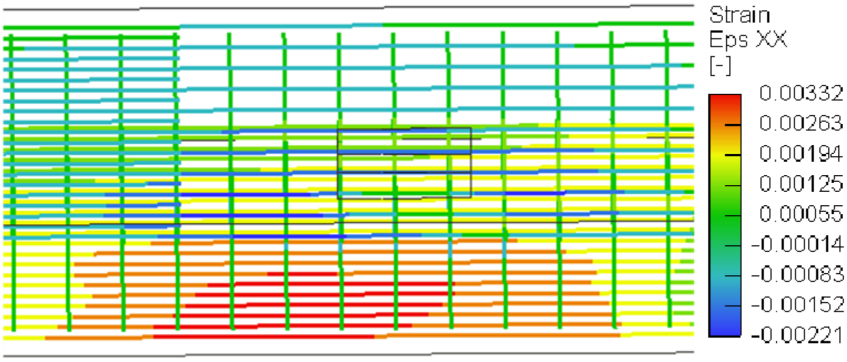

Figure 4.10: Reinforcement strain at a load of 700kN ATENA.

4.4 SR1E2

The load-deflection diagram for the SR1E2 test was measured for the element sizes of 150 mm, 100 mm and 75 mm. The load-deflection diagram corresponding to these element sizes and the measured values is shown in figure 4.11. Just like the other load-deflection diagrams it can be concluded that the model with the smallest element size gives the closest values to the measured values. Similar to the SR1E1 test, the estimated deflection at a lower force deviates significantly from the measured values. As the force increases, the estimations become more accurate.

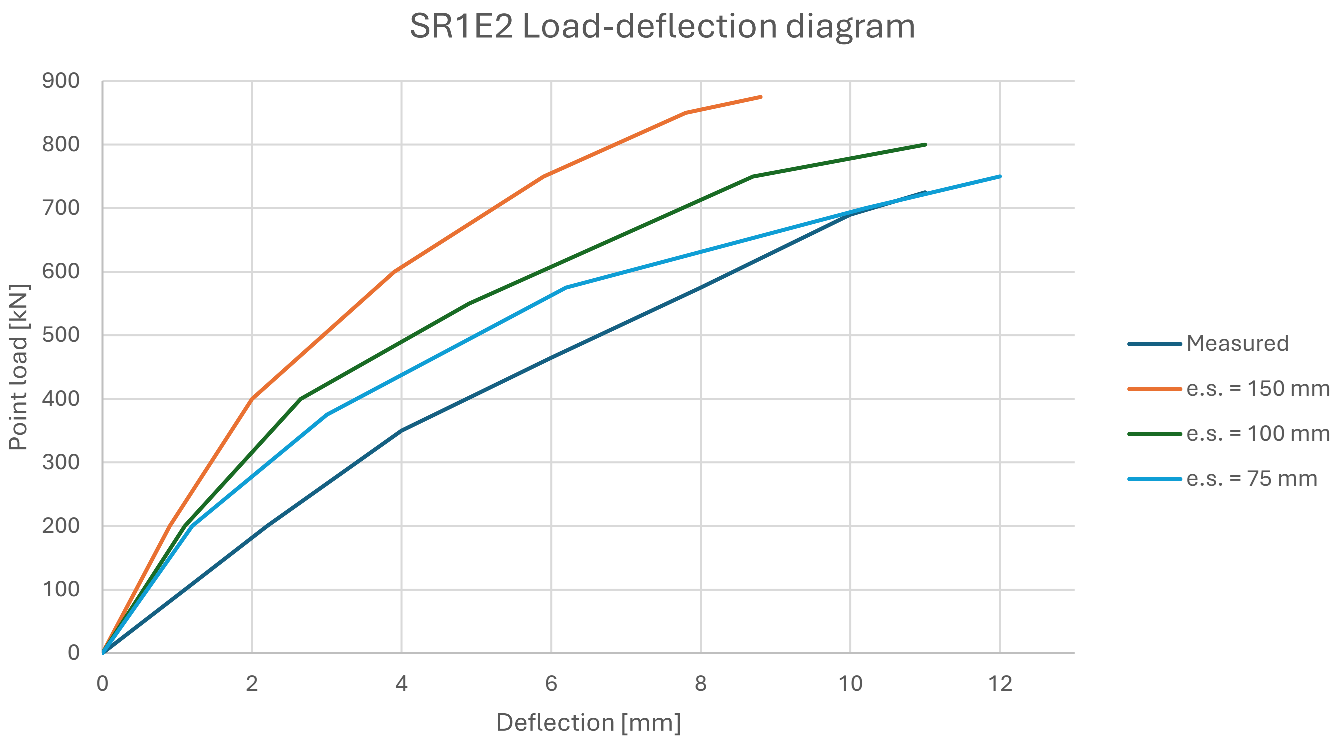

Figure 4.11: SR1E2 Load-deflection diagram.

The experiment failed due to shear crack. Figure 4.12. displays the crack pattern at failure load. In this figure it is visible, despite the pole in front of it, that the failure mode is shear crack.

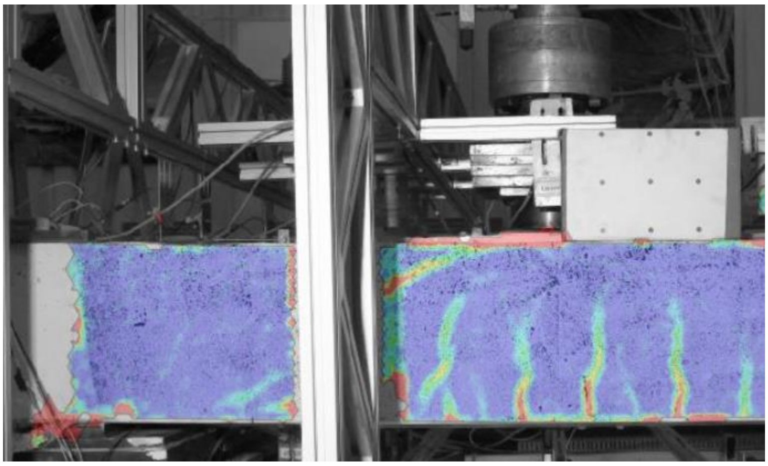

Figure 4.12: Crack pattern at failure load SR1E2 (Zarate Garnica & Lantsoght, 2021).

Running the ATENA model until failure visualises the failure mode by deformation and/or cracks. Running the model until failure visualises the following cracks as shown in figure 4.13. From this figure it can be concluded that the failure mode predicted by ATENA is also shear crack.

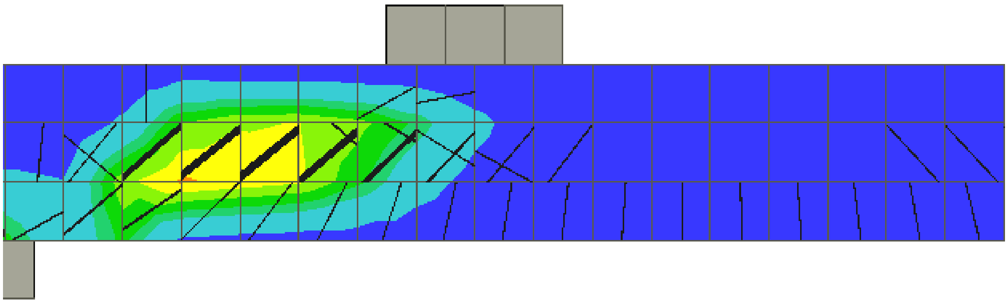

Figure 4.13: Crack pattern at failure load SR1E2 ATENA

5. Comparing crack width

This chapter will compare the crack widths measured during the SR1M1 test with the crack widths predicted by ATENA. The method how ATENA determines the crack width will be explained. Then, the crack width will be determined for the element sizes of a half, one-third, one-fourth and one-fifth of the slab thickness. The sum of the crack widths over a length of 1800 mm will be calculated and compared to the sum of the crack widths measured during the test.

5.1 ATENA crack theory

ATENA can simulate the cracking of concrete when its tensile strength is exceeded. "The behavior of concrete in tension without cracks is assumed linear elastic. E_c is the initial elastic modulus of concrete, $f_t^{\prime ef}$ is the effective tensile strength" (Červenka et al., 2021).

The strain softening law proposed by Hordijk captures the behaviour of materials that become weaker when they undergo deformation. This law is expressed through a stress-strain diagram show in the upper left of figure 5.1. The area underneath this curve is equal to the fracture energy. "The behaviour of concrete under tensile loading can be split into a stress-strain relation for the concrete outside a crack (process zone), and a stress-crack opening relation for the crack itself" (Hordijk, 1991).

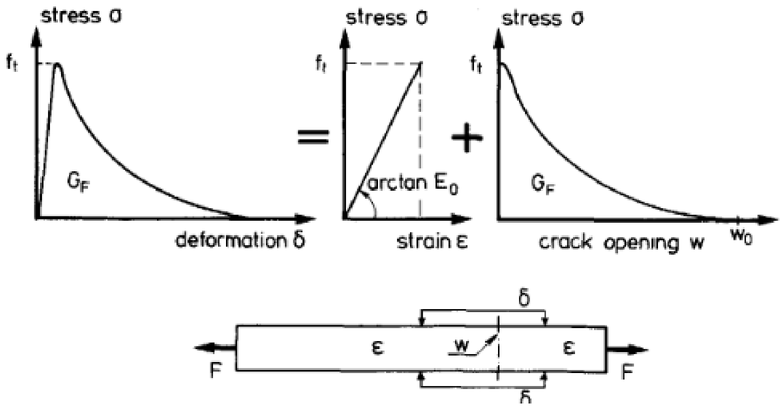

Figure 5.1: Stress-strain diagram Hordijk (Hordijk, 1991).

ATENA uses the Exponential Crack Opening Law as its softening model for concrete. ATENA determines the crack opening at the complete release of stress by using the following function derived by Hordijk (1991).

$$w_c = 5.14 \frac{G_f}{f_t^{\prime ef}}$$

Where w_c is the crack opening at the complete release of stress, G_f is fracture energy and $f_t^{\prime ef}$ is the effective tensile strength.

ATENA divides the crack formation into three stages. The first stage is the uncracked stage, this is before the tensile strength is reached. The second stage is the process zone, here the crack form and the tensile strength decreases. The last stage is the cracked stage, here the crack opening continues without the stress (Červenka et al., 2021). The three stages of crack opening are shown in figure 5.2.

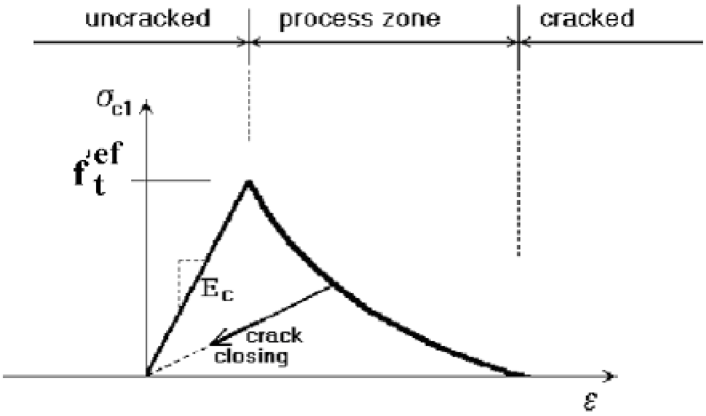

Figure 5.2: Stages of crack opening (Červenka et al., 2021).

The crack width w is calculated by the following formula:

$$w = \varepsilon_{cr} L_t$$

where: $w\ [mm] = crack\ width$
$\varepsilon_{cr}\ [-] = crack\ opening\ strain$
$L_t\ [mm] = characteristic\ length\ of\ a\ finite\ element$

The characteristic length L_t of a finite element is shown in figure 5.3.

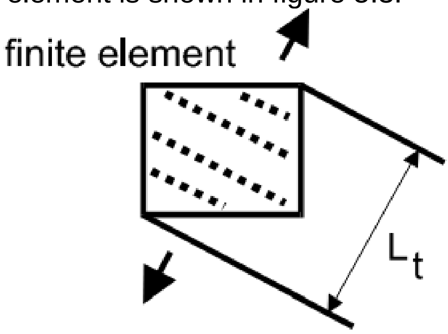

Figure 5.3: Characteristic length L_t of a finite element (Červenka et al., 2021).

5.2 Crack width comparison

The crack width measured during the SR1M1 test at a load of 1100 kN is show in figure 5.4. The cracks were measured over a length of 1800 mm. A total of 16 cracks formed over this length. All the cracks combined formed a total width of 4.521 mm.

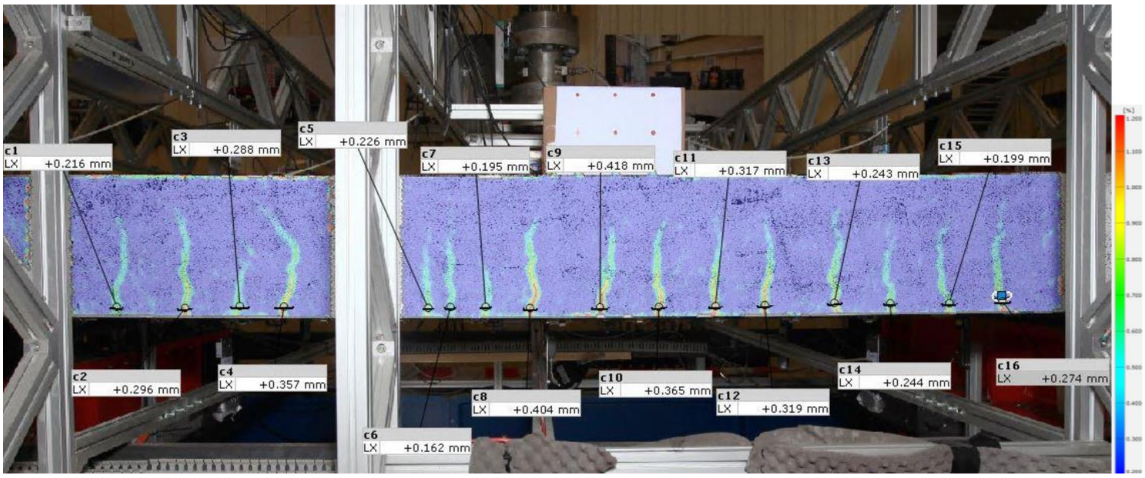

Figure 5.3: Crack width at 1100 kN (Zarate Garnica & Lantsoght, 2021).

A comparative analysis between ATENA simulation and experimental tests was made. This comparison was done by summing the cracks in the elements and comparing this value to the previously obtained value in the experimental test with a value of 4.521 mm. This was done for the element sizes of a half, one-third, one-fourth and one-fifth of the slab thickness, corresponding to the respective sizes of 150 mm, 100 mm, 75 mm, and 60 mm.

5.2.1 Element size of 150 mm

The model with the element size of 150 mm only reached a point load of 900 kN before failing. This model is not suitable for comparison since the crack width was measured during the experimental test only at a load of 1100 kN. As seen in figure 4.3 the model failed at a load of 900 kN with a deflection of 15.7 mm. The measured deflection of the test was 26 mm at a load of 1100 kN. The crack width of each element was multiplied with a factor of $\frac{26}{15.7}$ to make the results usable for comparison. Figure 5.4 displays the 12 elements used to calculate the total crack width over a length of 1800 mm.

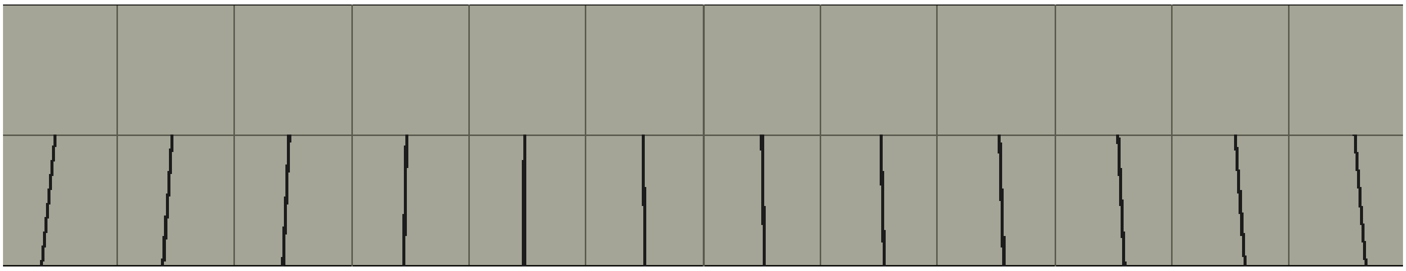

Figure 5.4: Crack forming at 900 kN with element size of 150 mm.

Table 5.1 presents an overview of the crack width for each element from left to right as shown in Figure 5.4. The total crack width at a load of 900 kN is 2.704 mm. This value is as expected, due to a lower load, a lot lower than the measured value of 4.521 mm. The total crack width after the factor of $\frac{26}{15.7}$ is 4.478 mm. This is really close to the measured value.

Table 5.1: Crack width model element size 150 mm.

Element number	**Crack width [mm]**	**Crack width after factor [mm]**
1	0.202	0.335
2	0.219	0.363
3	0.231	0.383
4	0.24	0.397
5	0.235	0.389
6	0.23	0.381
7	0.233	0.386
8	0.231	0.383
9	0.233	0.386
10	0.227	0.376
11	0.216	0.358
12	0.207	0.343
Total crack width	2.704	4.478

5.2.2 Element size of 100 mm

The model with the element size of 100 mm did, unlike the model with an element size of 150 mm, reach the load at which the crack width was measured. Figure 5.5 displays the 18 elements used to calculate the total crack width over a length of 1800 mm.

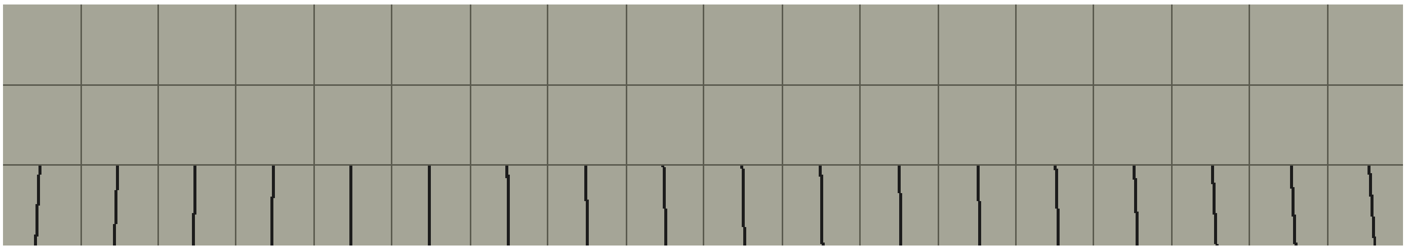

Figure 5.5: Crack forming at 1100 kN with element size of 100 mm.

Table 5.2 presents an overview of the crack width for each element from left to right as shown in Figure 5.5. The total crack width at a load of 1100 kN is 4.239 mm. This value is a good prediction for the total crack width.

Table 5.2: Crack width model element size 100 mm.

Element number	**Crack width [mm]**
1	0.21
2	0.227
3	0.243
4	0.253
5	0.262
6	0.264
7	0.267
8	0.262
9	0.257
10	0.252
11	0.25
12	0.244
13	0.237
14	0.227
15	0.217
16	0.204
17	0.191
18	0.172
Total crack width	4.239

5.2.3 Element size of 75 mm

The model with the element size of 75 mm did also reach the load at which the crack width was measured. Figure 5.6 displays the 24 elements used to calculate the total crack width over a length of 1800 mm.

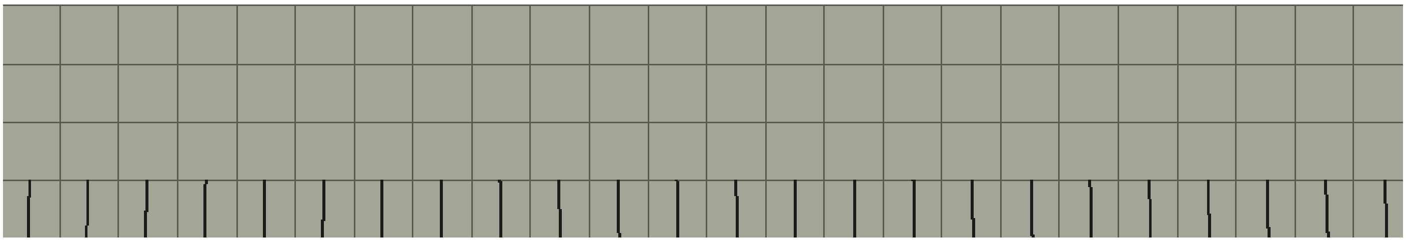

Figure 5.6: Crack forming at 1100 kN with element size of 75 mm.

Table 5.3 presents an overview of the crack width for each element from left to right as shown in Figure 5.6. The total crack width at a load of 1100 kN is 4.398 mm. This value is a better prediction than the prediction made with an element size of 100 mm.

Table 5.3: Crack width model element size 75 mm.

Element number	**Crack width [mm]**
1	0.164
2	0.173
3	0.18
4	0.188
5	0.194
6	0.198
7	0.202
8	0.204
9	0.205
10	0.202
11	0.2
12	0.197
13	0.197
14	0.194
15	0.193
16	0.19
17	0.186
18	0.183
19	0.176
20	0.17
21	0.164
22	0.156
23	0.147
24	0.135
Total crack width	4.398

5.2.4 Element size of 60 mm

The model with the element size of 60 mm did also reach the load at which the crack width was measured. Figure 5.7 displays the 30 elements used to calculate the total crack width over a length of 1800 mm.

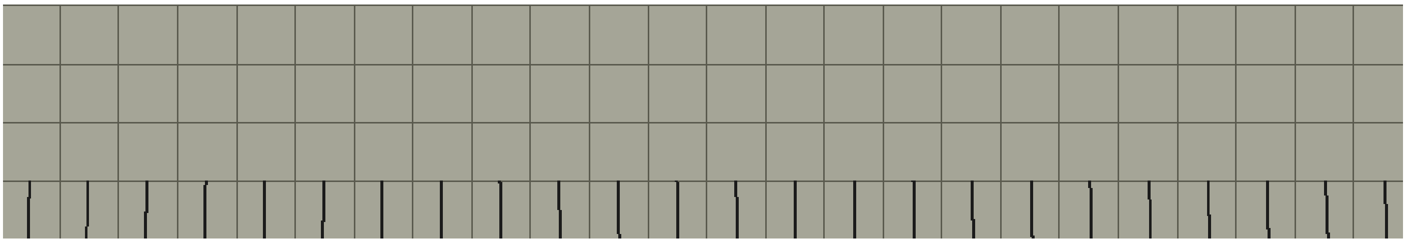

Figure 5.7: Crack forming at 1100 kN with element size of 60 mm.

Table 5.4 presents an overview of the crack width for each element from left to right as shown in Figure 5.7. The total crack width at a load of 1100 kN is 4.557 mm. This value is the best prediction for the total crack width.

Table 5.4: Crack width model element size 60 mm.

Element number	**Crack width [mm]**
1	0.13
2	0.137
3	0.142
4	0.15
5	0.153
6	0.158
7	0.162
8	0.163
9	0.17
10	0.166
11	0.173
12	0.166
13	0.173
14	0.163
15	0.17
16	0.161
17	0.167
18	0.159
19	0.164
20	0.156
21	0.159
22	0.151
23	0.155
24	0.141
25	0.145
26	0.132
27	0.134
28	0.123
29	0.122
30	0.112
Total crack width	4.557

5.3 Comparison element sizes

The smaller the element size the closer the expected total crack width is to the measured crack width. But the smaller the element size the longer it takes for the model to run the analysis. For a quick estimation, the element size of 100 mm can be used. For a more accurate estimation the element size of 60 mm or even lower can be used. Table 5.5 shows for each element size the total crack width.

Table 5.5: Total crack width for each element size.

Element size [mm]	**Total crack width [mm]**
150	2.704, after factor 4.478
100	4.239
75	4.398
60	4.557
Measured	4.521

6. Discussion

This chapter discusses various aspects of the creation of the model and the testing of the model that could have been changed to get better results.

During the creation of the model, the prestressing loads were simplified. The prestressing loads were modelled as an initial load and a load that increased every step during the analysis.

When measuring the crack width for the SR1M1 test, a portion of the slab was not visible on camera. This obscure area is highlighted in figure 6.1 with a red square. Consequently, it was not possible to observe whether cracks formed in this part of the slab. As a result, any cracks that formed in this area were not included into the measured total crack width. This means that the measured total crack width is an underestimate of the real total crack width.

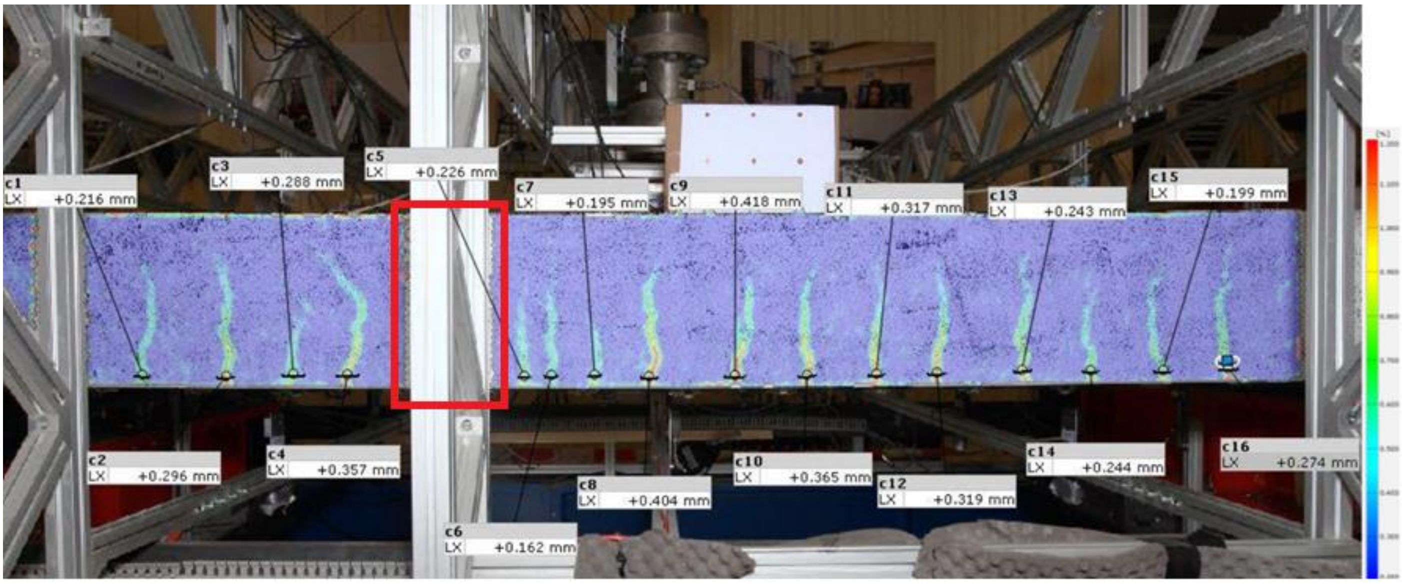

Figure 6.1: Crack width at 1100 kN with highlighted obscure area (Zarate Garnica & Lantsoght, 2021).

For this study, a relatively small sample size was used. All the measurements used in this report are on the same type of slab, which had the same reinforcement structure. To configure the model, three different situations, where the point load was applied at various locations, were looked at. However, the data used to compare the crack width was only available from one of the tests.

To optimise the calculation time, element sizes smaller than 60 mm were not considered. The usage of smaller element sizes could lead to a better prediction of total crack width. As shown in table 5.5, a decrease in element size leads to a more accurate prediction. However, reducing the element size would increase the computation time so much that it has not been considered in this report.

7. Conclusion and recommendations

This chapter answers the research questions are provides recommendations for further research. Starting with the three sub-questions after which the main research questions is answered.

The three sub-questions have been defined as follows:

- *How to set up a model in ATENA?*
- *How to determine the crack width?*
- *What effect does element size have on the crack width?*

The first step in Atena was to create the cross section of the concrete slab. A solid could be formed by using the extrude function on the cross section. After defining the concrete properties and creating a finite element mesh, load cases and boundary conditions need to be added. To start the analysis a task was setup.

ATENA uses the Exponential Crack Opening Law as its softening model for concrete. The crack width w is calculated by the following formula:

$$w = \varepsilon_{cr} L_t$$

where: $w\ [mm] = crack\ width$
$\varepsilon_{cr}\ [-] = crack\ opening\ strain$
$\mathrm{L}_t\ [mm] = characteristic\ length\ of\ a\ finite\ element$

ATENA calculates for each element its crack width. To compare the crack width during the test and the crack width calculated by the model, the cracks in each element were summed up over a length of 1800 mm.

The smaller the element size, the more accurate the prediction is. Table 5.5 shows that using an element size of 150 mm, ATENA's prediction is inaccurate. Using an element size of 75 mm or smaller results in an error margin of 3% or less. To optimise the calculation time, element sizes smaller than 60 mm were not considered. Further research should be done to determine whether the usage of smaller element sizes has an impact on the accuracy of the crack width prediction and whether it is worthwhile to use smaller element sizes.

The results and observations gathered in answering these sub-questions can be used to answer the main question, which is:

"Is ATENA capable to predict the crack width correctly?"

From answering these sub-questions, it can be concluded that ATENA is able to predict the crack width correctly when the element size is small enough and the load-deflection diagram aligns with the measured data. To obtain the correct load-deflection diagram for this test, the Young's modulus and the tension strength of the concrete were divided by a factor of three, and the fracture energy was increased to 165 N/m. Further research should be done on determine whether the division by a factor of three on the Young's modulus and the tension strength is only applicable to this model. Or if it holds true for all models in ATENA.

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Appendix

Problem analysis
Using a finite element analysis software presents certain limitations. One significant limitation is the occurrence of singularities. When a point load is applied on a slab, it creates a singularity near the point load. A singularity is a point where the stresses are infinite large. The computer approximates these infinity stresses with very large numbers. The extent of this number depends on the size of the elements. In reality, the stress is not infinite. This will lead to inaccuracies in the solution.

These inaccuracies give rise to the main research question:
“Is ATENA capable to predict the crack width correctly?”

The main research question will be answered through the examination of four sub-questions and comparing results from both the ATENA model and the test setup.
- How to set up a model in ATENA?
- How to determine the crack width?
- What effect does element size have on the crack width?
- What effect does the location of the point load have on the crack width?

Objective and approach

Objective
The objective of this project is to compare the crack width around a point load between ATENA simulation and experimental tests. This will be done by answering each sub-question:

1. **How to set up a model in ATENA?**

The first step of the report is setting up a model in ATENA. The model should have the same dimensions as the test specimen. The test specimen has a height of 300mm, width of 2500mm and a length of 5000mm. The model should also consist of the same reinforcement configuration. The test setup is a single loaded reinforced concrete slab. The slab is supported by a simple support and a continuous support. The concrete class used for the test specimen is C35/45.

2. **How to determine the crack width?**

ATENA can determine the crack width if the model is set up. ATENA has built-in functions that can calculate and visualize the crack width.

3. **What effect does element size have on the crack width?**

After the crack width is calculated from the model, the element size can be changed. In general, the smaller the element the higher the stress. This will lead to more singularities and inaccuracies in the solution. This will be checked by modelling with different element sizes and comparing the results. The element size also influences the time for ATENA to calculate the crack width. The more elements the longer it takes for ATENA to calculate the crack width.

4. **What effect does the location of the point load have on the crack width?**

After the crack width is calculated from the model, the location of the point load can be changed. G.I. Zarate Garnica has done multiple tests where the point load is at a different location each time. This can also be modelled in ATENA. It is expected that the crack width will decrease if the point load gets closer to the supports since the moment under the point load will decrease.

Comparing results ATENA and test setup
The model and test setup can be compared after each sub-question is answered model. From this the best element size, in terms of results and loading time, can be determined. And can be concluded if ATENA can correctly predict the crack width.

Planning

The planning per week is indicated in table 3.1.

Table 3.1: Planning per week

Week	Personal schedule	Date	Deadline
1	Drafting starting note and making Information Literacy II test	April 29th	Information Literacy II
2	Making model in ATENA	May 3rd	Starting note
3	Determining the crack width in ATENA / effect of singularities		
4	Changing element size and relocating the load	May 17th	Interim report
5	Implementing feedback and preparing interim presentation		Interim presentation
6	Comparing crack width model to tests		
7	Comparing crack width model to tests and changing model where needed		
8	Finalizing report, writing summary, conclusion and discussion		
9	Making and preparing presentation	June 17th	Final report
10	Preparing presentation	June 24th	Final presentation

Structure final report

The structure of the final report will look as follows:

- Cover page
- Title page
- Preface
- Summary
- Table of contents
- 1. Introduction
    - 1.1 Motivation
    - 1.2 Problem analysis
    - 1.3 Goal
    - 1.4 Reading guide
- 2. Creating a model
    - 2.1 Test setup
    - 2.2 Creating a model in ATENA
- 3. Changing boundary conditions
    - 3.1 Element size
    - 3.2 Location point load
- 4. Comparison ATENA to test
    - 4.1 Comparison crack width
    - 4.2 Best element size
- 5. Discussion
- 6. Conclusion and recommendation
- References
- Appendix