Experiments and FE-Modelling of Fibre Reinforced Concrete Beams Exposed to Impact

L Ågårdh, Defence Research Establishment, Sweden
L Laine, Defence Research Establishment, Sweden

1. INTRODUCTION

1.1. Background

Fibre reinforced concrete (FRC) has a favourable performance when used in protective elements, designed to sustain blast and debris. The problem with blast loads in the "near field", or penetration of fragments with high velocity, is the shock waves introduced into the material, invoking high order stresses and strain rates. In the design of protective structures, the numerical calculations should be based on codes and material models, that can take those effects into consideration, see [1]. For the validation of numerical models, experiments with loads spanning from static to impulsive loads on small concrete beams were performed at FOA:s Research Centre in Märsta and the responses were simulated with LS-DYNA3D and the "Winfrith Concrete Model", see [2] and [3].

1.2. Definitions

The test specimens were concrete beams, with and without steel fibre reinforcement. The dimensions were $850 \cdot 100 \cdot 100$ mm^3. There are two options to model the FRC-beams. In the first option the beam is modelled with material test data for plain concrete and the fibres added as a smeared reinforcement all over the beam volume. This will be denoted the "Model with Fibre Reinforcement" or model A below. The other option is to use material test data from fibre reinforced concrete samples. It is primarily the Fracture Energy that differs. This model will be denoted the "FRC- Model" or model B below.

The case denoted "1.3 kg Striker" involved the impulsive force from a 1.3 kg steel cylinder, dropped on a load cell at the centre of the beam. By using a rubber interface on the striker, the wave transition time is short in comparison with the duration of the load pulse. This is also called "Soft Impact", because the deformation of the interface must be considered in the calculations. The response was recorded by non contacting displacement gauges and folio strain gauges. The second case is denoted "31 kg Striker", and both "Soft" and "Hard" impacts from a 31 kg striker were performed. The event studied was of shorter duration than the wave transition times. In this case, only recordings with a high-speed film camera were taken.

For the 1.3 kg striker case, the boundary conditions were "Simply Supported" with fixtures on top of the beam-ends to keep the beam on the supports during the event. Those had to be modelled carefully, see below, because they did not permit free rotation around the neutral layer. A proper support condition should be designed as pendulum hangers, fitted to the beam-ends, see [4]. For the 31 kg striker case, the boundary conditions were "Simply Supported" without fixtures because the duration of the event was too short for the uplifting of the beam-ends to be of importance.

2. EXPERIMENTS

2.1 Material specifications

Fibre reinforced (FRC) beams were used for all load cases except for the 31 kg striker case, where plain concrete beams were used as well. The concrete was of a "Bridge-Deck Concrete"-type with the following specifications: Cement type: "Std P". Aggregates: "Porfyr" 0-20 mm. Steel fibres type: "Dramix ZC 30/.50, 55 kg/m^3 fresh concrete. Proportions: 440 kg cement/m3. Cube strength (Nominal) 90 MPa. Water 7.6 %, wct = 0.38, Air 5-7 %. Three different series of beams were produced and tested 1996-97:

Table 1. Results from material sample tests

Type of Concrete	Compressive strength (MPa)	Splitting Strength (MPa)	Mod. of Elasticity (GPa)	Fracture Energy (N/m)
Series B (FRC)	81.3 (150 mm cube)	7.3 (150 mm cube)	52.9 (ISO 6784)	2500 (estimated*)
Series C (FRC)	80.4 (150 mm cube)	6.1 (150 mm cube)	44.0 (ISO 6784)	2500 (estimated*)
Series D (Plain Concrete)	87.5 (100 · 150 mm cylinders)	6.0 (150 mm cube)	37.8 (ISO 6784)	156 (CEB)

* Estimated from similar types of fibre reinforced concrete tested in [5]

2.2 Test arrangements and results – 1.3 kg striker

One FRC beam (Series B) was loaded impulsively by a striker with a mass of 1.3 kg. A 5 mm thick rubber pad of Neopren type was used as interface between the load cell and the striker. The contact force is strongly influenced by the interface material. The striker was dropped from various heights giving impact velocities 2, 3, 4, 5, 6 m/s. Contact force, strains and displacement time histories were recorded. The strains were measured by three strain gauges glued to the concrete at the lower surface of the beam, see Figure 1.

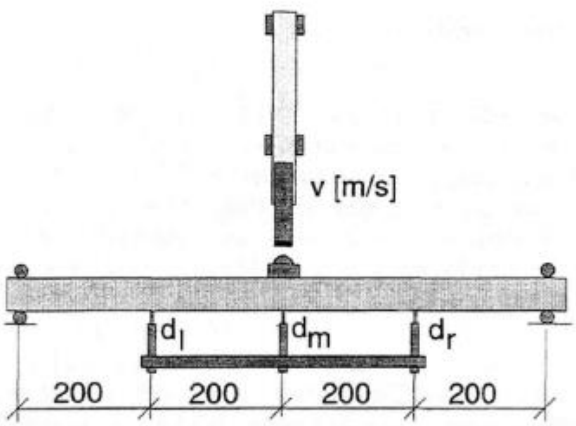


Figure 1: Test arrangement for the "1.3kg striker" case

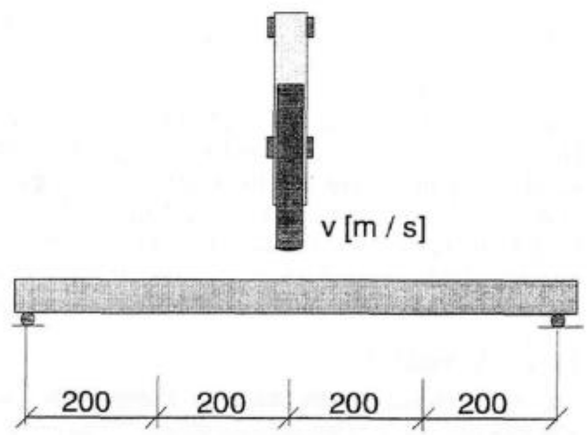


Figure 2: Test arrangement for the "31kg striker"case

As indicated in Figure 1, the beam must be locked for vertical displacements. This tends to "stiffen" the support, and energy is dissipating through friction, increasing the apparent damping. In Table 2 below, the results from the tests with impact velocities 2 - 6 m/s are shown. The basic frequencies are estimated from the displacement signal. Obviously the stiffness changes due to cracking at the force obtained at 4 m/s. The centre displacement signal *dm* from the load at 4 m/s is shown in Figure 3 compared with FE-calculations.

Table 2: Results from drop tests on a FRC -beams

Concrete	Loading rate (m/s)	Peak load (N)	Basic freq (Hz)	Duration (ms)	Peak displ (mm)	Displ rate (mm/s)	Peak strain (‰)	Strain rate (‰ /s)
Series B	2	2660	140	4.0	0.27	0.20	0.18	180
Series B	3	5880	140	3.0	0.45	0.37	0.30	290
Series B	4	10000	140	2.5	0.60	0.52	0.42	395
Series B	5	15000	132	2.0	0.79	0.65	0.55	600
Series B	6	19800	101	1.8	1.10	0.81	0.82	790

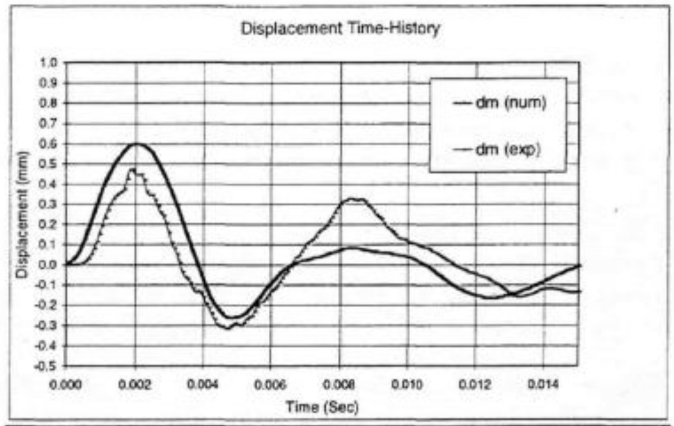


Figure 3: The centre displacement signal compared with FE-calculations.

2.3 Test arrangements and results - 31 kg striker

Fibre reinforced concrete from series C and plain concrete from series D were used in these load cases. In Figure 2 the test arrangements are shown. The striker was a steel cylinder, length 0.5 m, diameter 0.1 m and mass 31 kg. The head of the striker was shaped as a cylinder with a radius 0.2 m to accomplish a distributed load along a line perpendicular to the beam axis. The supports were stiff enough to be considered to be rigid but this does not effect the events studied here. The striker was dropped from different heights to obtain the impact velocities of 5 m/s and 10 m/s. For the case of 10 m/s, results from plain concrete beams were compared with the results from corresponding FRC beams. In the case of 5 m/s and plain concrete, the beams were tested with and without rubber pad. The rubber pad was of type "Euromex polymer, IRHD 40°", 20 mm thick, and diameter 100 mm.

A high-speed camera, with 2500 frames per second, was used to record the response and crack propagation in the beams. The test beams were painted white with a square mesh, size of 20·20 mm^2. In front of the beam a glasses plate with a square reference mesh, size 50·50 mm^2 was fixed. By this arrangement, measurements may be performed to verify the corresponding results from simulations. The film showed large differences in crack patterns between FRC- beams and plain concrete beams. The FRC- beams had only one tensile crack in the centre caused by the impact, see Figure 4. The plain concrete beam obtained shear cracks at the centre part of the beam. Tension cracks caused by the travelling shock waves propagated from the upper surface, approximately at the quarter points of the beam, see Figure 5.

Plain concrete beams were used in tests with and without interface material, in this case a rubber pad. The duration of the load pulse was increased by use of a rubber pad which lead to that no cracks occurred near the quarter points, see Figure 6. Those cracks initiated at the lower surface in the case without interface, se Figure 7.

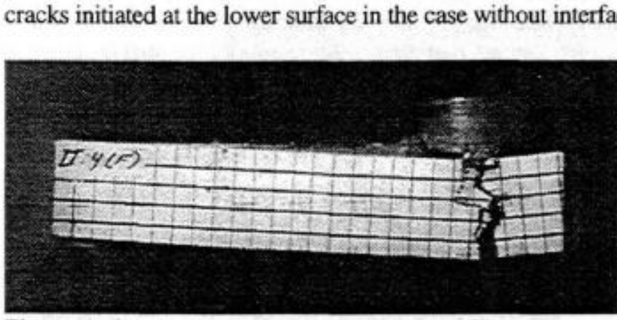


Figure 4: Crack pattern for the FRC–beam. Time 2.4 ms after the strike. (Striker m=31 kg, v=10 m/s)

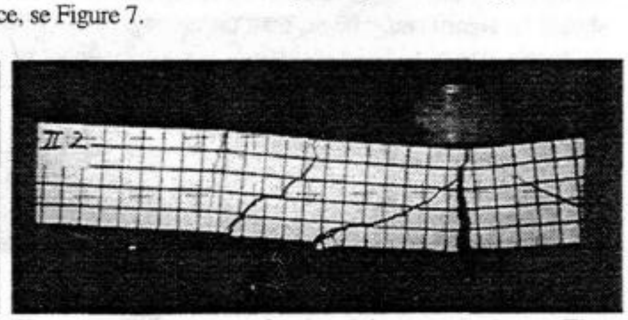


Figure 5: Crack pattern for the plain concrete beam. Time 2.4 ms after the strike. (Striker m=31 kg, v=10 m/s)

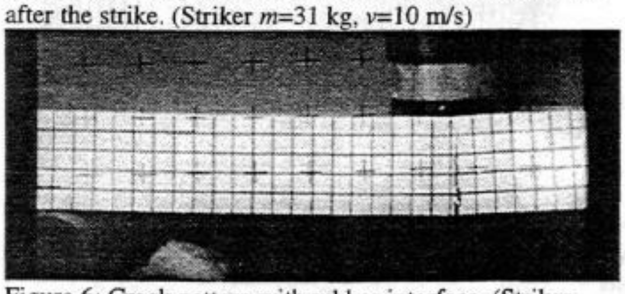


Figure 6: Crack pattern with rubber interface. (Striker m=31 kg, v=5m/s). Time 3.0 ms after the strike.

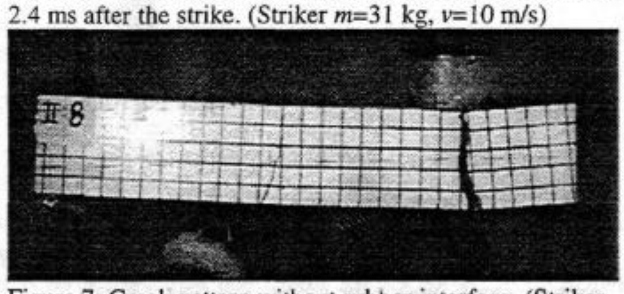


Figure 7: Crack pattern without rubber interface. (Striker m=31 kg, v=5 m/s). Time 3.2 ms after the strike.

3. FE-MODELLING

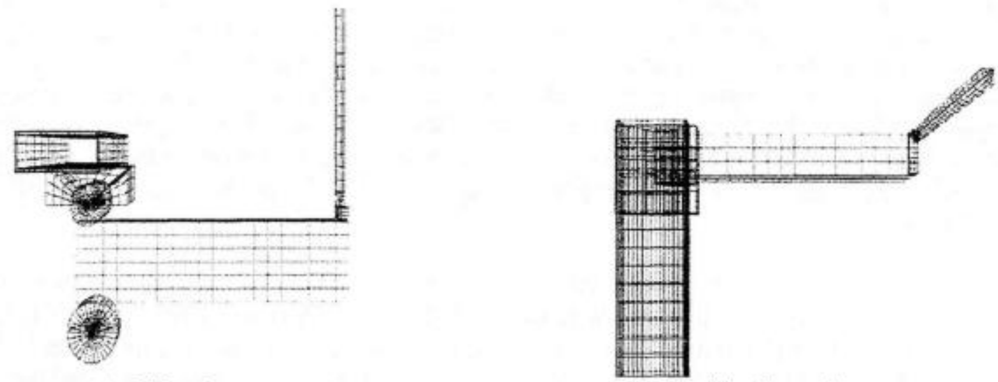
3.1 Program code and platform

The explicit FE-code LS-DYNA3D was used on a workstation, type AlphaStation 255 4/233 with UNIX operating system. A material model denoted the "Winfrith concrete model" was implemented into the code. It is a smeared crack and smeared reinforcement model, with strain rate enhancements of the strength levels according to CEB, see [6].

3.2 Simulations – 1.3 kg striker

Two types of models were generated, the first with the supports modelled with boundary conditions at specific nodes. This model gave accurate peak displacements but the resonance frequency of the first mode was too high and the introduced damping was too low. In the second model the supports were modelled as in the test, see Figure 8.

Between the solid parts, contact surfaces were defined with static and dynamic friction. The total number of brick elements used was 4232. The load cell was modelled as a sphere. Two effects affect the load pulse, the interface material and the contact surfaces. The load pulses in the simulations were calibrated for an impact velocity of 4 m/s. The shear modulus of the rubber interface was calibrated to get the same duration and peak value for the load pulse as in the test. For this calibration the beam model with fibre reinforcement, model A, was used.



(a). Side view. (b). From above.

Figure 8: FE-model (1/4 of the beam) for the "1.3 kg striker case", including the support arrangements.

3.3 Simulations – 31 kg striker

In this case 45000 brick elements have been used for 1/4 of the beam model. The purpose was to capture the shock waves due to the impact that travels along the beam. The elements are cubes with a length of 4 mm. The element size should be significantly larger than the aggregate size in the concrete, see [3], here 20 mm. In the input data a fictitious aggregate size of 0.1 mm was used. The total number of brick elements that were used to model the striker, beam and supports was 59466, see Figure 9.

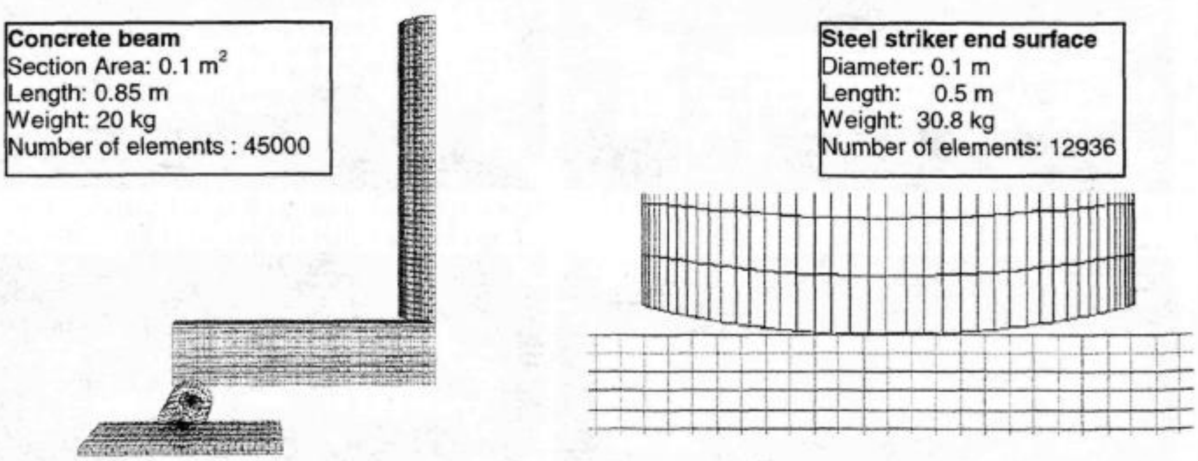
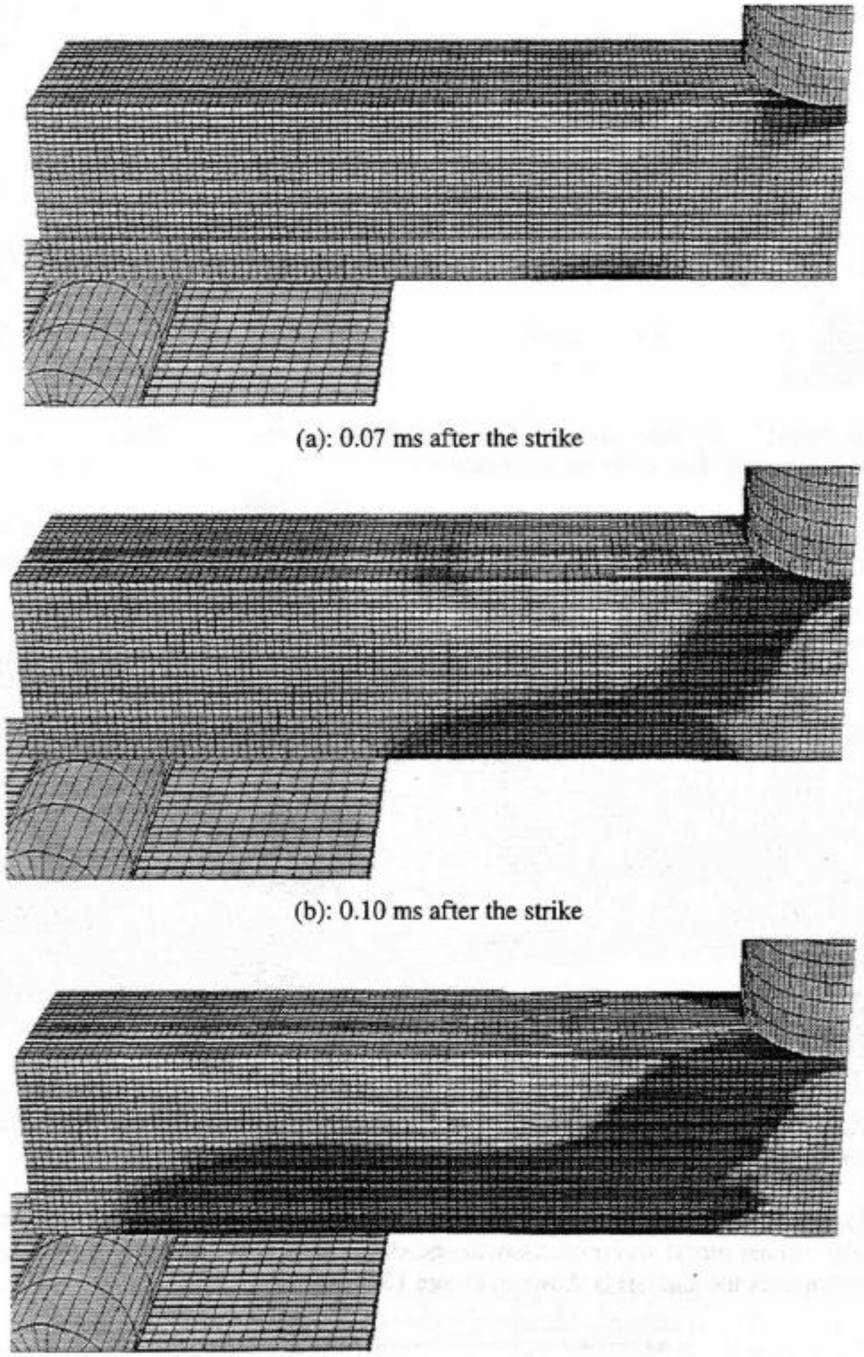


Figure 9: FE –model (one quarter of the problem) for the simulations – 31 kg striker, including the support arrangements. Notice the cylindrical striker head.

In Figure 10 the shock waves represented by the stresses along the beam axis are shown for the plain concrete beam. The dispersion of the waves becomes evident after 0.2 ms. The stress wave propagates to the supports and cracks initiate at the quarter's points on the top surface of the beam.



(a): 0.07 ms after the strike

(b): 0.10 ms after the strike

(c): 0.18 ms after the strike

Figure 10: Stresses in the x-direction for the plain concrete beam. The graphical scale: red - max tension 10 MPa, blue - max pressures 10 MPa.

The tension stress in the x-direction at the quarter points on the top surface of the beam, reaches a peak value 7.8 MPa after 0.10 ms. For the simulation, the "Model with fibre reinforcement" was used, were all elements in the beam were given a smeared reinforcement (0.70 /3 %) in the x- y- and z- directions. The steel fibres were assumed to be pulled out before failure. In the model the pull- out strength was estimated to be equal the tensile strength of the concrete.

In Figure 11, the crack pattern for the model with fibre reinforcement, model A, is shown for the case with hard impact, compare with experiments in Figure 4. For the FRC- model (model B with the fracture energy 2500 N/m), the crack initiated at 2 ms was compared. Furthermore the propagation was slower than corresponding propagation from experiment. Thus the crack initiation and propagation in model B was not satisfactorily predicted with model B.

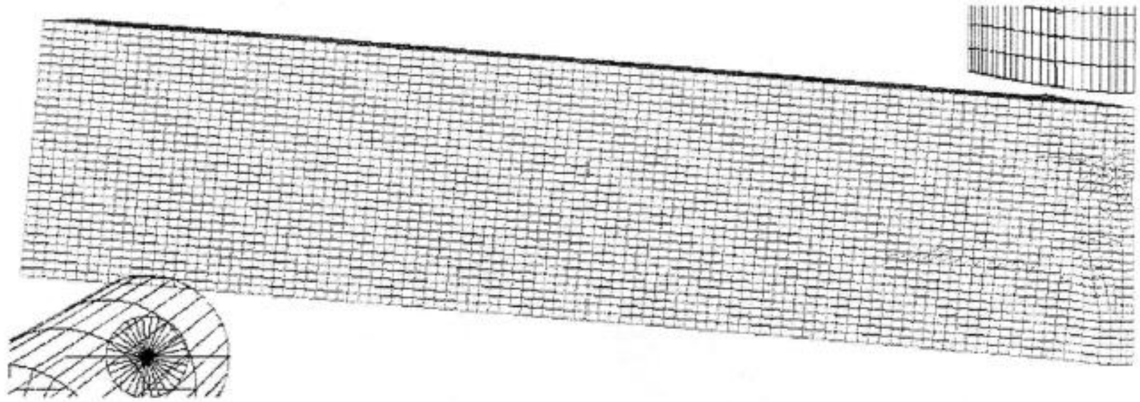


Figure 11: Crack patterns for the model with fibre reinforcement (model A), 2.4 ms after the strike. Compare with the test in Figure 4. Striker m=31 kg, v=10 m/s

In Figure 12 the crack pattern for plain concrete is shown, for the case of hard impact. Here the shock waves initiate cracks at the quarter points of the beam. The shear cracks near the centre of the beam under the impact point also appears.

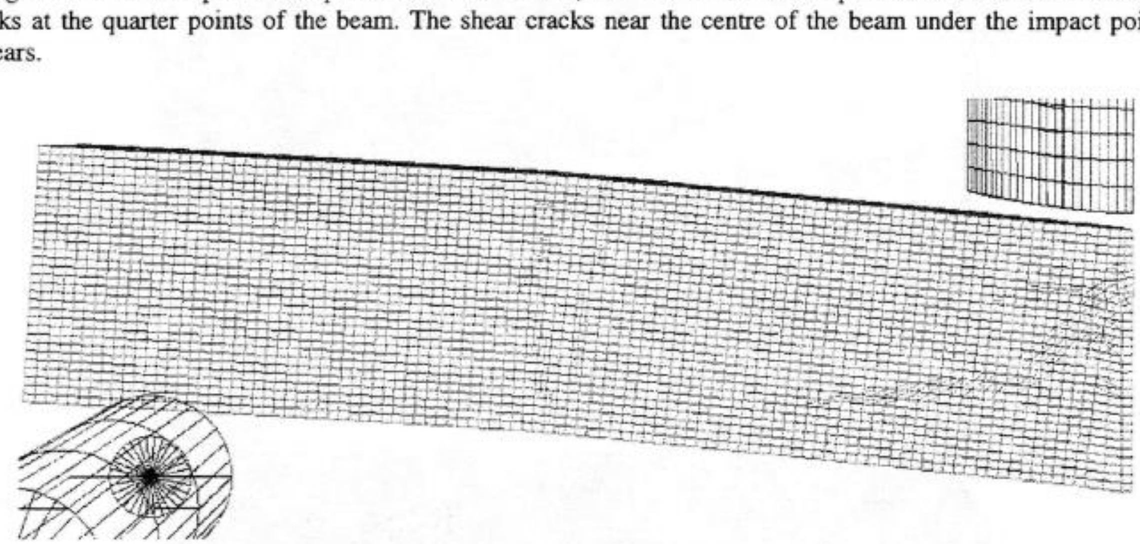


Figure 12: Crack pattern for the plain concrete model (no fibres), 2.4 ms after the strike. Compare with the test in Figure 5. Striker m=31 kg, v=10 m/s

When the soft impact was simulated, the rubber was modelled as a solid cylinder, height 20 mm and diameter 100 mm. The "Blatz-Ko" rubber model was used. Only the bending cracks at the centre of the beam appears and propagate. The crack pattern from the analysis is shown in Figure 13.

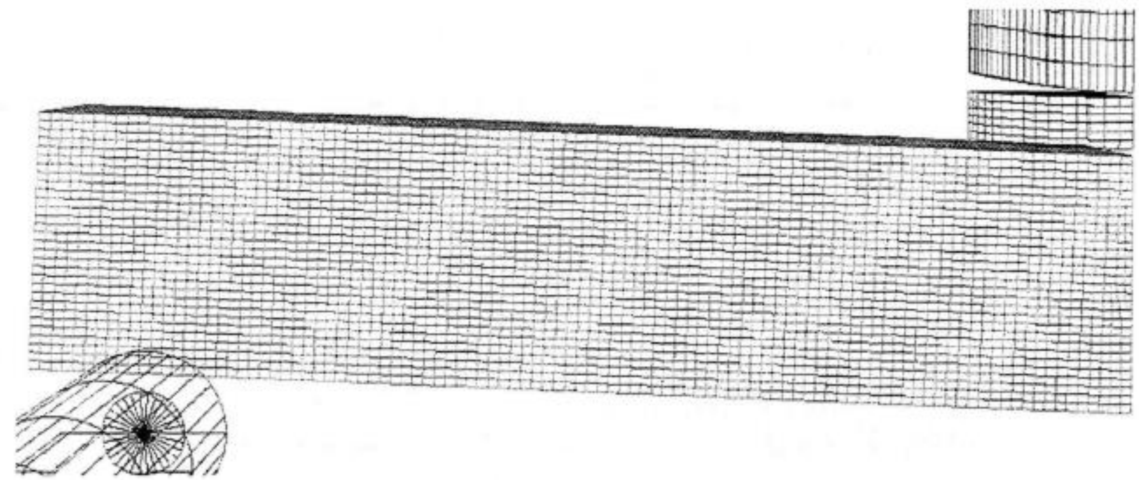


Figure 13: Crack patterns for the plain concrete model with soft impact (rubber as interface material), at analyse time 2.0 ms. Compare with experiments in Figure 6. (striker m=31 kg, v=5 m/s)

Figure 14 shows that the simulation without a rubber pad leads to crack propagation in the quarter points of the beam. The applied kinetic energy is ¼ of the earlier simulation. No shear cracks have developed for this load case.

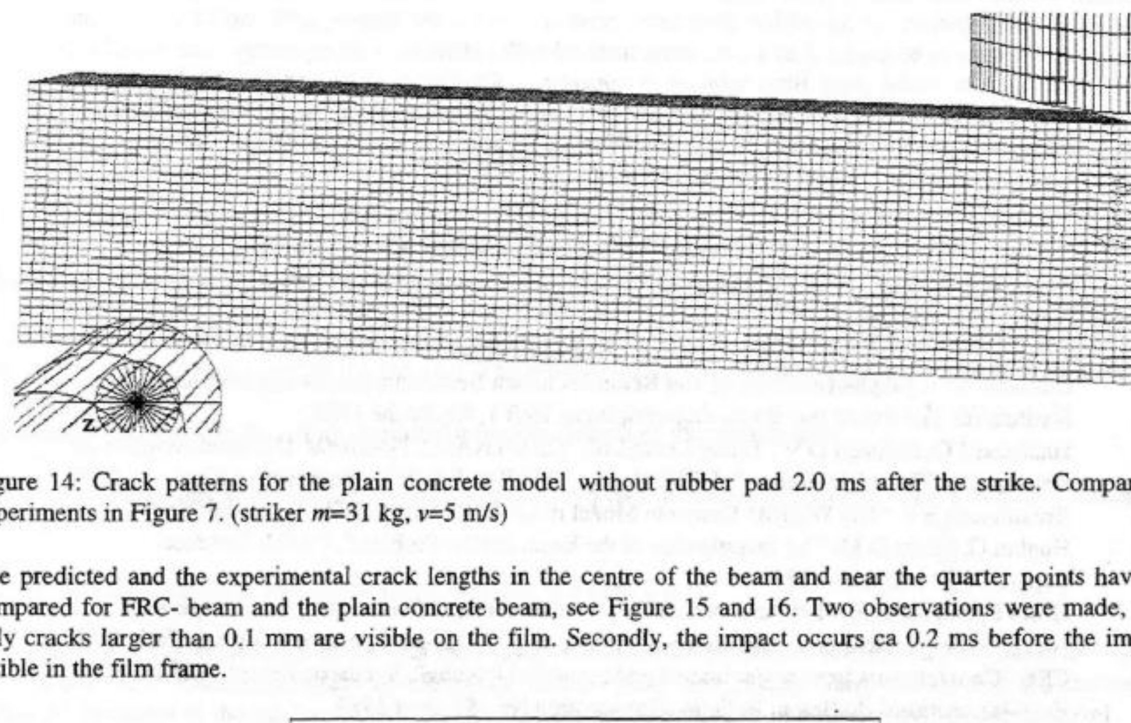


Figure 14: Crack patterns for the plain concrete model without rubber pad 2.0 ms after the strike. Compare with experiments in Figure 7. (striker m=31 kg, v=5 m/s)

The predicted and the experimental crack lengths in the centre of the beam and near the quarter points have been compared for FRC- beam and the plain concrete beam, see Figure 15 and 16. Two observations were made, firstly, only cracks larger than 0.1 mm are visible on the film. Secondly, the impact occurs ca 0.2 ms before the impact is visible in the film frame.

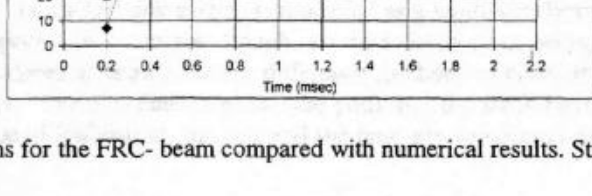


Figure 15: Crack lengths for the FRC- beam compared with numerical results. Striker m=31 kg v=10 m/s

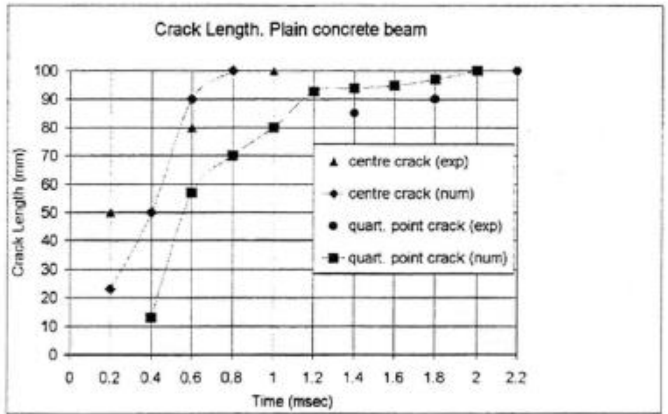


Figure 16: Crack lengths for the Plain concrete beam compared with numerical results. Striker m=31 kg v=10 m/s

4. CONCLUSION

Experiments and simulations with impact loads on small FRC -beams were performed. The responses were measured in various ways and recorded with a high speed camera. For the simulations, LS-DYNA3D with the "Winfrith Concrete model" was used. Failure modes, crack patterns and displacements were fairly well predicted in the simulations. Two options of modelling fibre reinforced concrete were investigated; model A with the fibres as a smeared reinforcement or model B as a composite material with enhanced fracture energy. The model A turned out to be the best way to model steel fibre reinforced concrete if the failure development should be predicted. This conclusion should however be validated from more tests with different aggregate sizes and steel fibre contents. In the case of simulating wave propagation a large number of elements should be used, and for this case a fictitious aggregate size less than the element size should be used.

5. ACKNOWLEDGEMENTS

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