

Effect of the loading rate on fibre reinforced concrete beams

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Abstract. Fibre reinforced concrete has become a widely used material since the end of the 20th century. The uniformly distributed steel or macro synthetic fibres in the concrete structures can give the concrete a residual flexural strength after the first cracks. The different behaviour of materials subjected to different loading rates is a well-known phenomenon, both with steel, synthetic and concrete materials. Standards usually present a recommendation for the loading speed in for different tests. Concrete elements show higher performance due to the high speed of loading or impact loads, their fracture energy and therefore their overall capacity appears greater than the specimens loaded at standard speeds. Fibre reinforced concrete structures are widely used in tramlines and railways, where the speed of the loading is high and therefore of impact by nature. It is important to know what the effect of this high speed loading is for fibre reinforced concrete structures: do these structures have additional capacity, or has the designer overestimated their performance? This article will present an investigation into the effect of the loading rate on case of using fibres with different materials in concrete beams.

1. Introduction

The behaviour of concrete structures is well-known to be highly influenced by their loading rate [1]. Numerical and experimental studies show that by increasing the loading rate there is also an increase in resistance, failure mode, crack pattern and speed of crack propagation. The influence of the loading (strain) rate on the tensile strength and fracture energy of concrete is not yet fully understood. Therefore, it has been one of the major subjects of intensive investigation in the scientific community over many years. Also, the knowledge with regards to the response of fibre reinforced concrete subjected to dynamic loading is still incomplete.

The two types of common structural fibres used for concrete reinforcement today are the steel and the macro synthetic fibres. These fibres increase the residual flexural strength of the concrete elements by adding an additional fracture energy to the concrete material [2]. The fibres during the load start to work after the first cracks appear in the concrete during loading. The bonding mechanisms of the fibres within the concrete are different for both steel and synthetic materials are also different, the steel fibres bearing the load with the anchorage of the hooked end, and the failure mechanism is pulling out from the concrete matrix (ie. the hook straightening) and in contrast to this the synthetic fibres have an anchorage capacity over their full length of the fibre with its embossed surface so that the failure mode is both pulling out and also the rupture of the fibres. There are many specifications available to test the fibre reinforced concrete elements [3] [4], and usually these guidelines also provides a recommendation for the loading speed of the tests. Usually, the typical test for fibre reinforced

concrete specimens is the three or four point bending beam tests with, or without a notch in the middle. The tests are always displacement controlled, and the recommended loading rate is 0.1 - 0.2 mm/min. According to this the determined fibre capacity is valid just for this loading rates, which corresponds to a dead loads, static live loads, soil pressures and meteorological loads.

Fibre reinforced concrete is widely used in structures where the loads are mostly impact by nature, such as railways and tracks slabs. In these cases the speed of loading and unloading the structure is very high, and thus it is very important to know what the effect of the fibres in these situations is.

Because the steel and synthetic materials have different behaviour characteristics at different speeds, it is important to analyse the effect of a particular type of fibre reinforcement on the fibre reinforced concrete acting as a composite material. This paper outlines the undertaken on steel and synthetic fibre reinforced concrete beams under different loading rates.

2. Effect of the loading rate in fibre materials

Before examining the effect of the loading rate on fibre reinforced concrete beams it is important to understand the behaviour of the materials of the fibres on a wide range of loadings.

The influence of the loading rate on the tensile strength characteristics of steel members is a well-researched field in the material science since the middle of the 20th century and such as a wide range of tests and formulas can be found in the literature which define and describe the behaviour of steel materials at high speed loading [5].

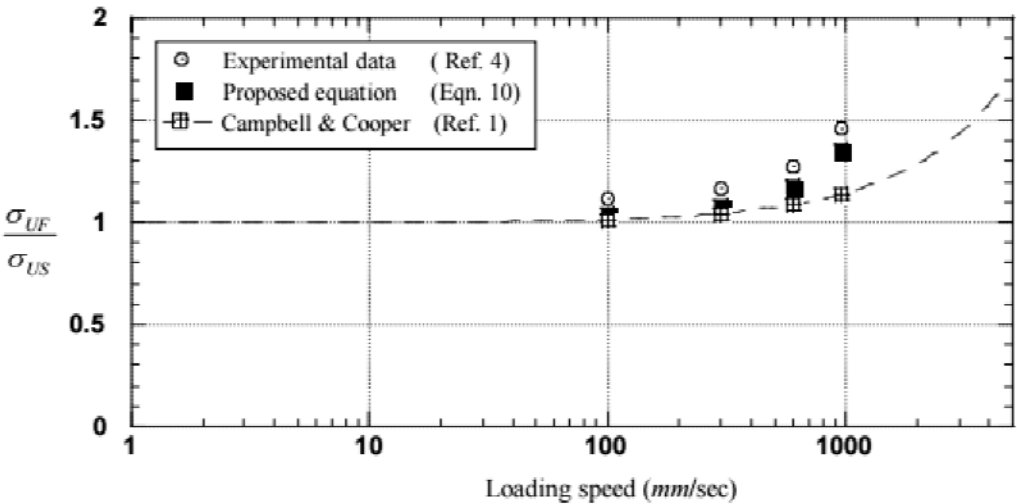


Figure 1. Effect of loading speed in steel elements [5].

Both the recommended formulas and the tests shows an increasing capacity of the steel element due to an increasing the load (figure 1). There is no significant influence of the speed up to 100 mm/sec, which means the steel structures under static loads show a constant behaviour. Over this limit the material’s tensile strength starts to raise significantly. It means the structure’s capacity will be higher if the type of load is impact in nature. It also means that the calculations are conservative if the designer has calculated with the low speed loading values.

The base material of the synthetic fibres is usually polypropylene (PP), which is a thermoplastic polymer and there are number of previous studies [6] available that document the test results of polypropylene at different loading rates.

Typical stress–strain curves of the tested PP at different speeds is shown in figure 2. The test showed that samples did not break even at 60% elongation and at crosshead speeds of up to 20 mm/min, but for the higher test speeds, the samples were ruptured at a lower elongation. Also, in these cases the ultimate strength of the samples was 45% higher than in the case of low speed loading.

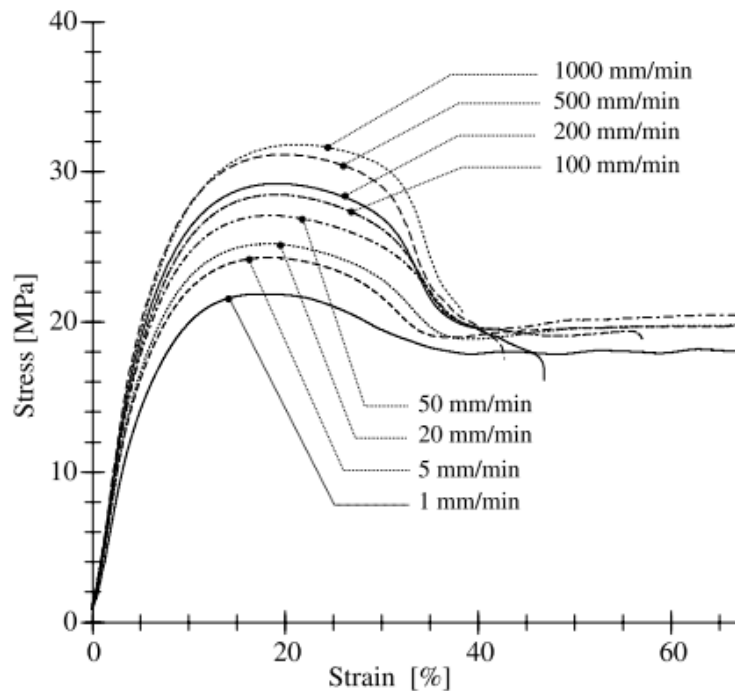


Figure 2. Effect of loading speed in polypropylene elements [6].

It can be seen, that both off the materials capacities rise if the loading speed is higher than a critical value and this critical value for steel is much higher for steel than for polypropylene. In the case of the steel there is no significant effect due to loading rate up to about 6000 mm/min (100 mm/sec).

3. Experimental program and testing method

To examine the behaviour of fibre reinforced concrete under different loading rates a three point bending beam test series was performed with steel and macro synthetic fibre reinforcement. The test matrix can be seen in table 3. The type of the reinforcement and the used dosage can be seen in table 2.

Prior to the beam tests single fibre tension test were carried out with the used fibres, to be able to verify the results of the fibre's capacity under different loading rates.

3.1. Specimen preparation and testing

Three points notched beam tests were made according to RILEM TC162 [3]. The load, the crosshead's vertical displacement and the beam's Crack Mouth Opening Displacement (CMOD) were measured for all of the beams. To be able to measure the CMOD a 25 mm deep notch was cut into the middle of the beams and two steel knives were glued on the bottom surface of the beam. The measuring clip was positioned between the two points. The test was performed by a universal testing machine ZWICK Z150 in the Laboratory of Department of Mechanics, Materials and Structures, Budapest University of Technology and Economics. The speed of the test was 0.2 mm/min and 900 mm/min up to 4 mm central deflection. The maximum speed of the testing machine was 900 mm/min.

For the single fibre tension tests one piece of fibre was clamped to the same universal testing machine. The snapping force and elongation was measured at loading rates of 200 mm/min, 50 mm/min, 20 mm/min, 10 mm/min and 2.0 mm/min loading rate.

3.2. Concrete mix

The concrete mix was designed to model a typical concrete industrial floor. Cement type was CEM III/A-42.5-N, water-cement ratio was 0.40. The aggregate was river gravel, with size 4-16 mm. The mixture design can be seen in table 1.

Table 1. Concrete mix

Concrete name	Cement type	w/c ratio	Aggregates (kg/m ³)			Admixtures
			0-4	4-8	8-16	
A	CEM-III-A-42.5	0.400	735	294	808	Dynamon NRG 1012

Table 2. Fibre reinforcing

Fibre sign/name	Fibre type	Fibre length mm	Dosage kg/m ³	Number of fibres Number/m ³
BC48 – 4.0	Synthetic fibre	48	4.0	240 964
Barchip48	Surface embossed			
AF – 25.0	Steel fibre	50	25	78 150
Armfib®	Hooked-end			

3.3. Fibre reinforcement

Two different types of fibre reinforcement were used during the experiment: steel and macro synthetic. The dosages of the fibres were 25 kg/m³ for steel fibres and 4.0 kg/m³ for synthetic fibres. The type of fibre and the research matrix can be seen in table 2 and 3, respectively. Seven beams were made with each type of the fibre reinforcement.

3.4. Beam casting

The aggregate, sand and cement were first mixed while the water was added continuously. Mixing was carried out with Collomatic XM3 forced action mixer. For the fibre reinforced concrete the fibres were dispersed by hand and mixed for approximately for one minute to achieve a perfectly uniform distribution. The concrete was casted into steel formworks and was demoulded after one day. The beams were kept at a temperature of 25 °C, and at a relative humidity of 50-60% for 28 days.

Table 3. Test matrix

Name of the specimen	Concrete	Fibre – dosage [kg/m ³]	Testing speed
AF25-A-L-number	A	AF – 25.0	0.2 mm/min
AF25-A-H-number	A	AF – 25.0	900 mm/min
BC48-A-L-number	A	BC48 – 4.0	0.2 mm/min
BC48-A-H-number	A	BC48 – 4.0	900 mm/min

4. Results

4.1. Single fibre tension test

To understand the fibre reinforced concrete's behaviour under different loading rates it was important to check the capacity of the discrete fibres under different speeds of loading. Testing of the macro synthetic fibres had to be done with some circumspection, because a local failure can occur close to the clamping head of the machine which can give misleading results. For case of every loading speed 5 pieces of fibres were tested to failure to be able to calculate the average value of the fibres' capacity.

The results shows that in case of synthetic fibres there is a high effect of the loading speed both at high and low speeds. By raising the speed of the test, the capacity and also the Elastic modulus of the fibres will be higher. This increase in the capacity is significant at more than 25%. It showed that the elastic modulus changed from 7.20 GPa to 11.77 GPa. The critical value for the loading speed which

was where the strength of the fibre started to increase significantly was approximately between 20 and 50 mm/min.

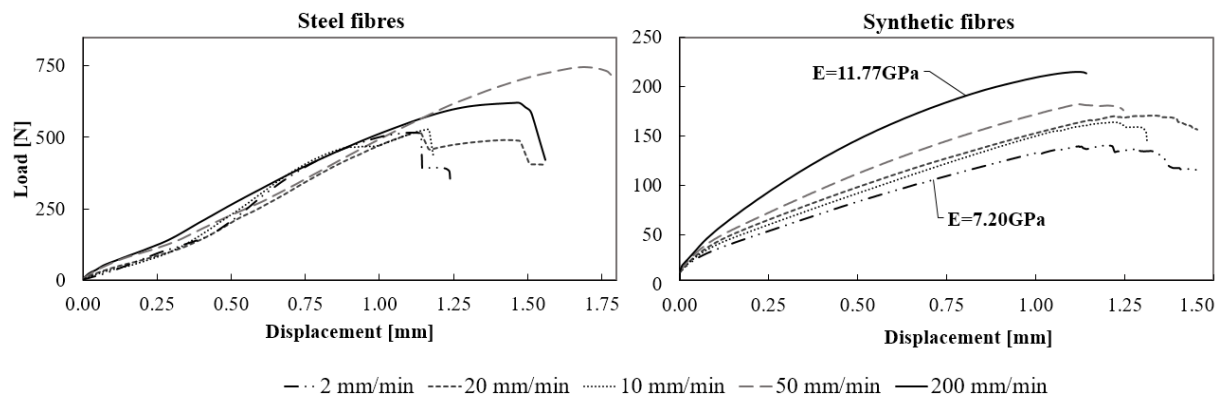


Figure 3. Results of the single fibre tests in different loading rates

The results in case of steel fibres are different. The test did not show any difference in elastic modulus at the various loading speeds. The elastic modulus and the tensile strength of the fibre is almost the same in every load rate. This is because the critical speed for steel material is much higher than what was used.

4.2. Three point bending beam test

The mixing of the concrete for the beams was good for all fibre dosages. The beams were tested at 28 days, and the necessary steel pointers for CMOD measuring were glued after 27 days. The loading schema and the geometry of the beams can be seen in figure 4. The data recovery was displacement controlled, which ensured that enough data would be available for the high speed loading test as well.

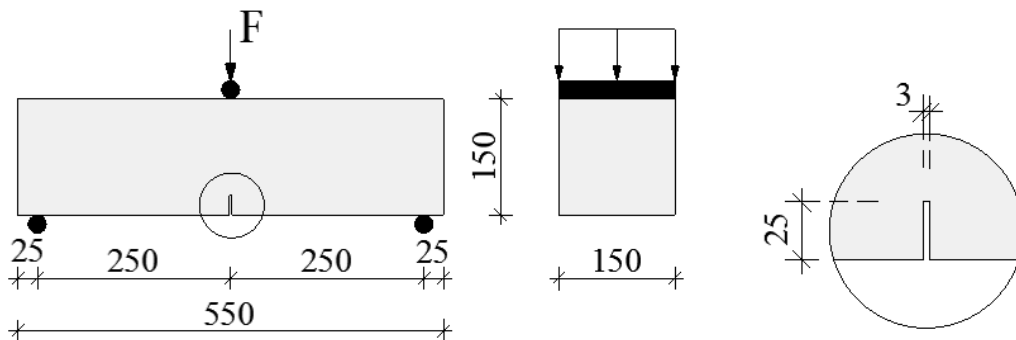


Figure 4. Three point bending beam test according to RILEM TC 162

The beams show different behaviour at different loading rates. The figure 5 shows the average values of the Load-CMOD diagram of the 7-7 beams in every case. With the standardized loading speed (0.2 mm/min) the steel (SFRC) and the synthetic (SYFRC) fibre reinforced concrete also have a drop of after the peak point. The average peak load and the elastic modulus was almost the same for both reinforcements. The residual flexural strength is higher in case of SFRC, and also the drop off is smaller. This difference can be caused by the lower elastic modulus of the synthetic fibres as well. It also can be seen, that the residual flexural strength in case of SFRC is monotone decreasing in contrast to this, the SYFRC's residual flexural strength has first a valley but then it increase as the crack opens and the fibres take load, and at 3.5 mm CMOD it is approaching the steel's curve.

By increase the speed of the load to 900 mm/min both of the curves have changed. The similarity between the steel fibre reinforced and the synthetic fibre reinforced concrete was, that the residual

flexural strength increased in every case. With this the fibre-work of the FRC, which is the area under the force-CMOD diagram increased as well. This increase compared to the original curves is higher in the case of synthetic fibres. The peak load will be higher in case of steel fibres, but lower in the case of synthetic fibres. However as the figure 6 shows the elastic modulus of SYFRC increased in contrast to SFRC where it decreased. It is important to notice that this occurred in the linear phase where the fibre should not have a significant effect on the concrete's behaviour. There is also a significant changes in the curvature of the flexural strength of synthetic fibre reinforced concrete. The drop off at 0.5 mm CMOD value disappears and the curve is similar to that of the SFRC. This is very important because the normal crack width in structures is close to this value, and the synthetic fibres worked better under high speed loading. However, the increasing curve is missing after 2.5 mm CMOD and the curve starts to decrease after this CMOD.

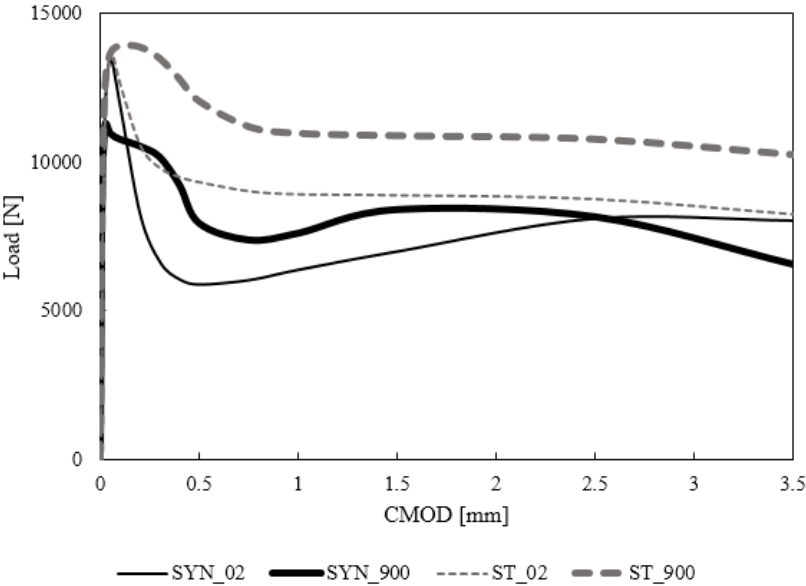


Figure 5. Result of three point bending beam test in 0.2 mm/min loading rate

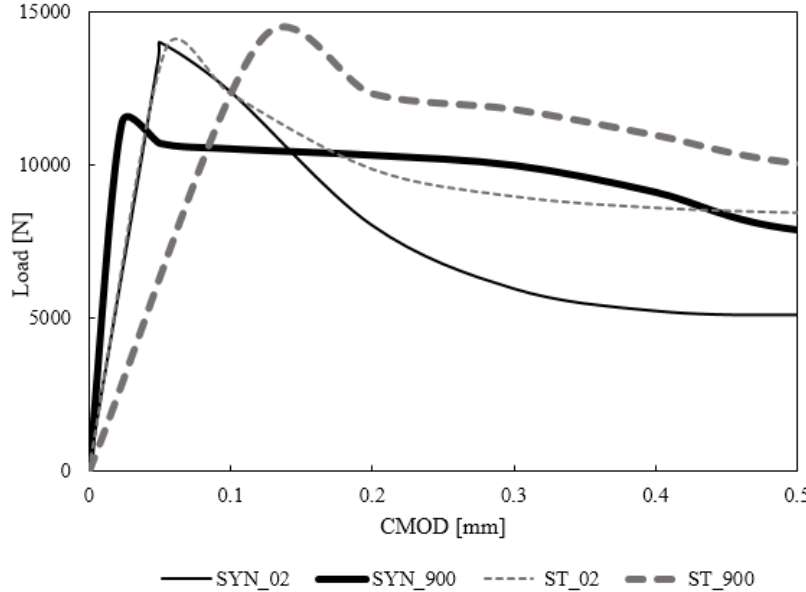


Figure 6. Result of three point bending beam test in 900 mm/min loading rate

5. Conclusion

Steel and synthetic fibre reinforcement are a well-used materials for concrete structures, where the loading rate can be significant higher (e.g. railways, tramlines etc.), than the static loading used in standard laboratory tests. It is important to know the fibre reinforced concretes' behaviour at this high loading rate.

Individual steel and synthetic fibres and fibre reinforced concrete beams were tested with different loading rates. The single fibre tension tests show a significant rise both in capacity and in case of the elastic modulus of synthetic fibres. This capacity raised by 25% and the elastic modulus changed from 7.20 GPa to 11.77 GPa. There was no significant effect of the speed on the tensile capacity or the elastic modulus in the case of steel fibres.

A three point bending beam test series was done according to the RILEM recommendation with using steel and synthetic fibre reinforcement in concrete beams. The beams were loaded with the standardized 0.2 mm/min speed and with a maximum loading capacity of the machine, i.g. 900 mm/min. Using synthetic fibre reinforcement, the elastic modulus and the residual flexural strength of the SYFRC beams increased, but the value of the peak load was lower than with the low loading rate. Also, the capacity at 0.5 mm CMOD almost reached the performance of the SFRC at low speed. The residual flexural strength of the SFRC also increased, but not as significantly as in the case of SYFRC. With steel fibres the elastic modulus of the FRC decreased significantly.

The research showed that the effect of the loading rate is significant for steel and synthetic fibre reinforced concrete. The fibre reinforced concrete's capacity increased in both cases and it can be seen that the structures under high speed loading have a higher capacity than in static loading.

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