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MODIFIED FRACTURE ENERGY METHOD FOR FIBRE REINFORCED CONCRETE

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Abstract:

Fibre manufacturers specify different parameters for measuring the performance of their fibres, e.g. Re3 number or σ-ε diagram. However, these parameters depend largely on the strength class of the concrete; most specifically on the fracture energy, which is in itself a variable from cement manufacturer to manufacturer, even within the same class. It follows therefore that any fibre performance parameters as specified by the manufacturer's laboratory may vary significantly for the same concrete class in the user's laboratory. The ideal would be to find a performance parameter that is fibre specific and at least partially independent of the concrete, which could then be used for characterizing and comparing the various fibre types. In this paper I present a fibre added energy that could be used to characterize the fibres in this way.

Keywords: steel- and macro fibre reinforced concrete; fracture energy; FRC modelling

1. Introduction

The fibre reinforced concrete in question is a short fibre composite, where the matrix is a quasi-brittle material: concrete, and the fibres are made of different materials (e.g. steel, polypropylene, etc.) with different shapes (e.g. round, oval, etc.), random but uniformly distributed, relatively short fibres. The behaviour of the fibre reinforced concrete is influenced by the fibres and matrix together. The concrete itself is a bi-component material: consisting of a gravel frame filled by cement grout. The gravel frame and the cement grout together provide the tension strength and ductility of the matrix. The fibres start to work after the crack of the matrix and gave added ductility. The energy-absorbing function of the fibres could be according to Zollo [1]: 1) fibre bridging, 2) fibre pull-out, 3) fibre failure. The bridging and pull-out of fibres could give the highest added ductility for the concrete, whilst fibre failure will decrease it. For steel fibres, the fibre pull-out will have a major role even from small crack opening, while synthetic fibres function more through a bridging mechanism. Both of these mechanisms depend mainly on the cement grout. The strength of the cement grout, working together with the fibres mainly depends on the type of cement and the water/cement ratio.

Based on the foregoing, it would be appropriate to create a parameter which is a function of the cement grout. This parameter can be assigned to the properties of the concrete matrix, and could be received as the final parameters of the composite.

In this article I will investigate this relationship and the possibilities of the application.

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2. Ductility of the concrete

Due to the tensile stresses in the concrete a thin band with micro-cracks will appear: this is called the *crack process zone*. Increasing the stress the concrete reaches its tensile strength when the micro cracks touch each other. After this point the tensile capacity of the concrete will decrease, the cracks will bypass or cross the aggregates and then slowly the entire section will be crossed by the crack (Fig. 1). The area under the tensile stress (σ) and the crack mouth distance (w) function is the fracture energy (Fig. 2).

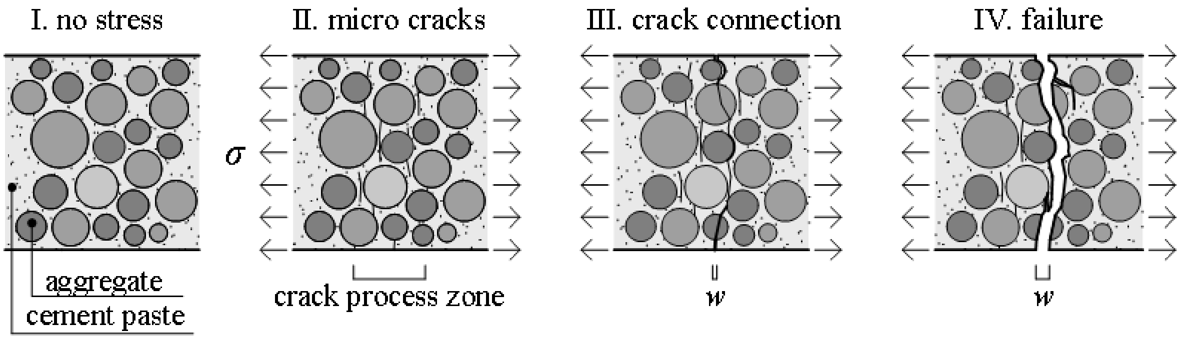

Fig. 1 – Crack spreading in the concrete

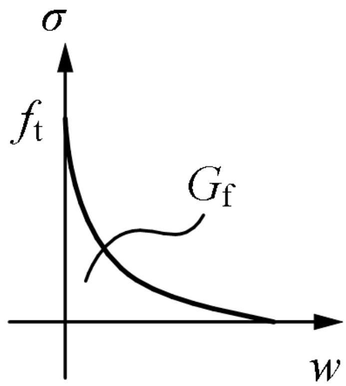

Fig. 2 – Fracture energy

The fracture energy of the concrete is influenced by a number of factors which are clearly not related to the concrete strength class. Most of the existing design methods neglect the fracture energy of the concrete and do not pay much attention to the tensile strength. However, when designing fibre-reinforced concrete structures these parameters can not be ignored.

3. Ductility of the fibre reinforced concrete

The fibre reinforced concrete's tensile strength will be the same as plain concrete, the effect of the fibres in the linear phase being limited. The fibres start to work when the micro cracks start appearing, first the fibres detaching from the concrete matrix. This is an important phase of the mechanism, because if this cannot happen the fibres will break. This may justify a reduction in ductility of steel fibre reinforced concrete in time, according to Bernard[2]. After the detachment there is the pull-out phase (Fig. 3).

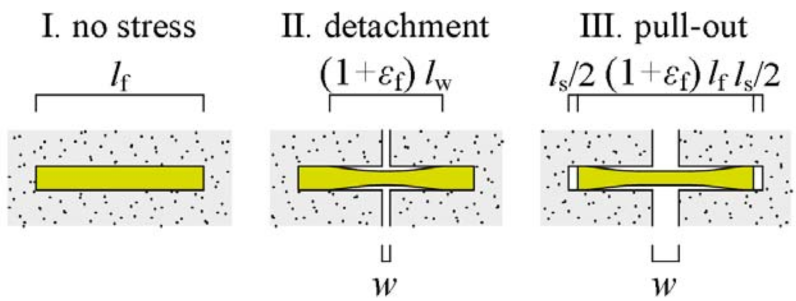

Fig. 3 – Mechanics of the fibre

Thus the following formula for crack opening can be written:

$$w = l_w\, \varepsilon_f + l_s \tag{1}$$

where:

l_w : working length of the fibre ($l_w \leq l_f$)

l_f: length of the fibre

l_s: slip distance

$$l_s = 0 \qquad \text{if} \qquad l_w < l_f \tag{2}$$

$$l_s = w - l_w\, \varepsilon_f \qquad \text{if} \qquad l_w = l_f \tag{3}$$

which means that it is assumed that the fibres will pull-out if the working length (l_w) reach the fibre length (l_f).

In this model I neglect the influence of the unsymmetrical anchoring and different direction of the fibre. This model is made only for comparing the steel- and synthetic fibre mechanics during the crack opening.

The fibres give added fracture energy via detachment, bridging and pull-out. The detachment depends on the connection of the cement grout and the surface of the fibre, the bridge process on the detachment, while the pull-out phase depends on the surface of the fibre and the end-hook configuration.

4. Ductility of the steel- and synthetic fibre reinforced concrete

I have researched different steel- and synthetic fibre reinforced concrete beams in the research called: The Big Crack at the Budapest University of Technology and Economics. The beams were made in the same circumstances, the dosage of the steel fibres was 20 and 40 kg/m^3 while the macro and micro synthetic have 5 and 1 kg/m^3, respectively. The beams were tested according to RILEM recommendations by 3 point beam test and the load, deflection and the CMOD were measured. From these series I selected steel and synthetic beam test results where the force-CMOD results are similar. (Fig. 4.)

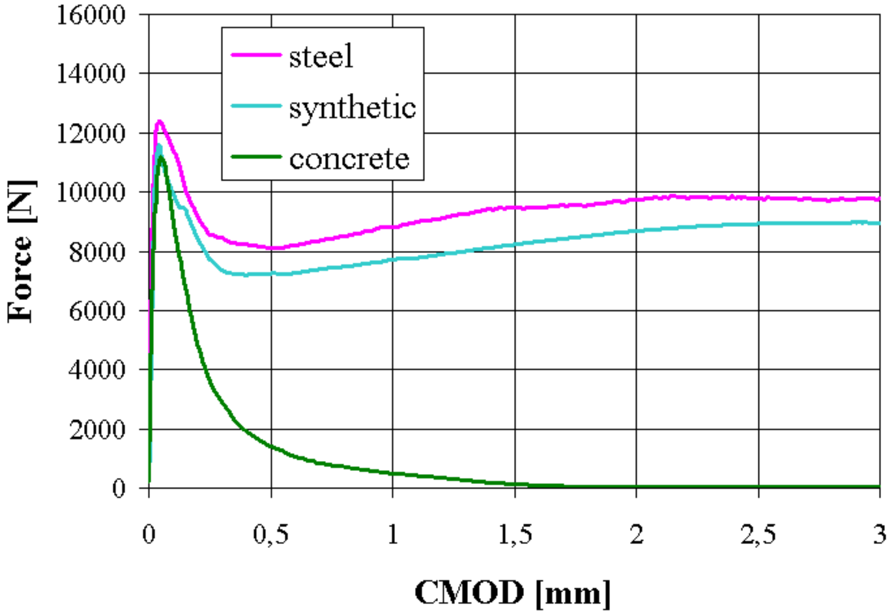

Fig 4.: Load-CMOD diagram for steel and synthetic fibre reinforced concrete

I have defined the stress-crack opening law for these beams and from this diagram I have defined the stress-strain with a characteristic length. With the help of this it is possible to find out the stress distribution on the section. If the location of the fibres are known on the section than the stresses in the fibres (σ_f), the working length of the fibre (l_w) and the slip distance (l_s) could be calculated. We can estimate that we have the same stress-crack opening law for the same force-CMOD curve (Fig. 5.).

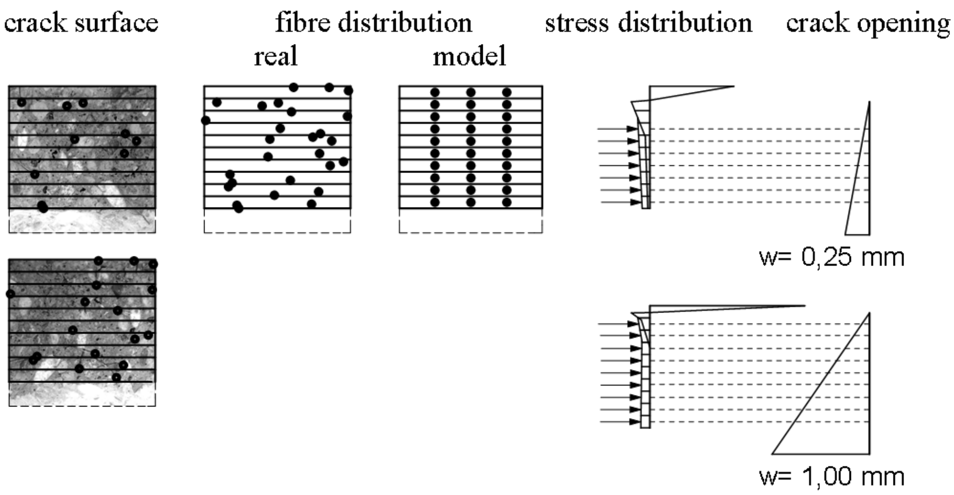

Fig. 5.: modelling the stress, strain and slip in the individual fibres

The method of calculation is the following: the value of the CMOD and the stress distribution on the section is known. From this the crack opening (with linear estimation) and the stress in the individual fibres (according to the distribution of the fibres) could be calculated. The working length and the slip could be calculated as per the following:

$$l_s = 0 \qquad \text{if} \qquad l_w = \frac{w}{\varepsilon_f} = \frac{w E_f}{\sigma_f} < l_f \tag{4}$$

$$l_w = l_f \quad \text{if} \quad l_w = \frac{w E_f}{\sigma_f} > l_f \text{ and } l_s = w - \frac{l_f \sigma_f}{E_f} \qquad (5)$$

With this approximations I have calculated the strain and slip of the fibres at CMOD=0,25 mm and 1 mm in the case of steel- or synthetic fibres. I show the results at the Fig. 6.

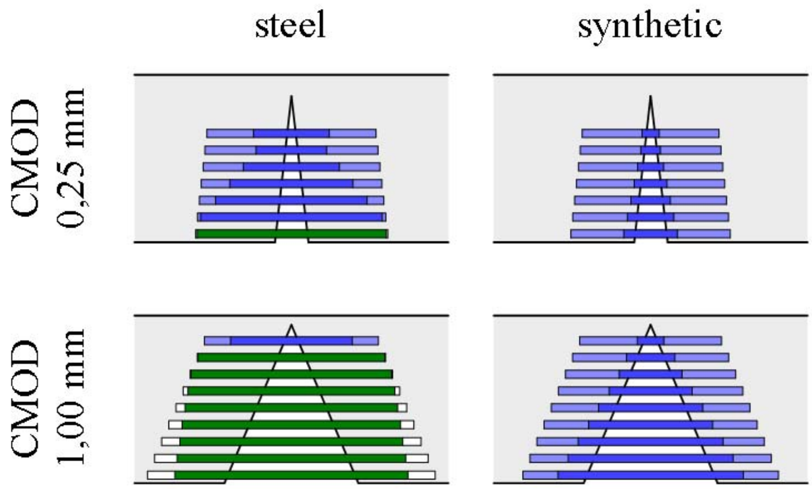

Fig. 6.: fibre bridging (blue) and fibre pull-out (green) of steel and synthetic fibres

It can be seen in the Fig. 6. that the steel fibres because of their small strain capacity must start to slip at small crack opening, while the synthetic fibres are still in bridging. If the material is still in its elastic range after unloading it will want to close the crack. At bridging fibres are equal to the whole crack opening, e.g. it wants to close the whole crack, while at slipping, fibres could close only with their strain energy and the slipping cannot be reversed. If the detachment can't be set up than the fibre will break away and this mean the loss of ductility.

5. The fracture energy of the concrete and the fibre reinforced concrete

According to my assumption, the fracture energy of the concrete (G_f) depends on the gravel frame and cement grout, while the added energy of the fibres (G_{ff}) depends on the fibres and the cement grout. To demonstrate this, a series of concrete was made where the same cement grout was used with different gravel frames. I have calculated the fracture energy of the concrete and fibre reinforced concrete and the difference is the fracture energy of the fibres.

5.1. Description of the test series

We tried to reach the C30/37 concrete strength class so therefore we used a w/c ratio as 0.48. The cement type was CME I 42.5-R. These types of concretes were mixed with 3 different types of fibres. The types of the concretes and fibres are in Table 1 and 2, respectively.

Tab. 1: types of concretes

Concrete name	A	B	C	D
d_{max}	8	16	24	24
Aggregate type	Round	Round	Round	Crushed

Tab. 2: types of the fibres

Fibre name	(1)	(2)	(3)
Fibre length	48	42	24
Fibre type	embossed	waved	waved
Fibre material	polypropylene	polypropylene	polypropylene

The beams measured 150x150x600 mm, according to RILEM TC 162 [3] and were tested as 3 point bending tests, measuring the force-CMOD.

5.2. Results

All the results are the mean value of 4 beams. There is a clear increase of the fracture energy of the beam test series between the A and B, as well C and D. The increase between B and C is small (Fig. 7.).

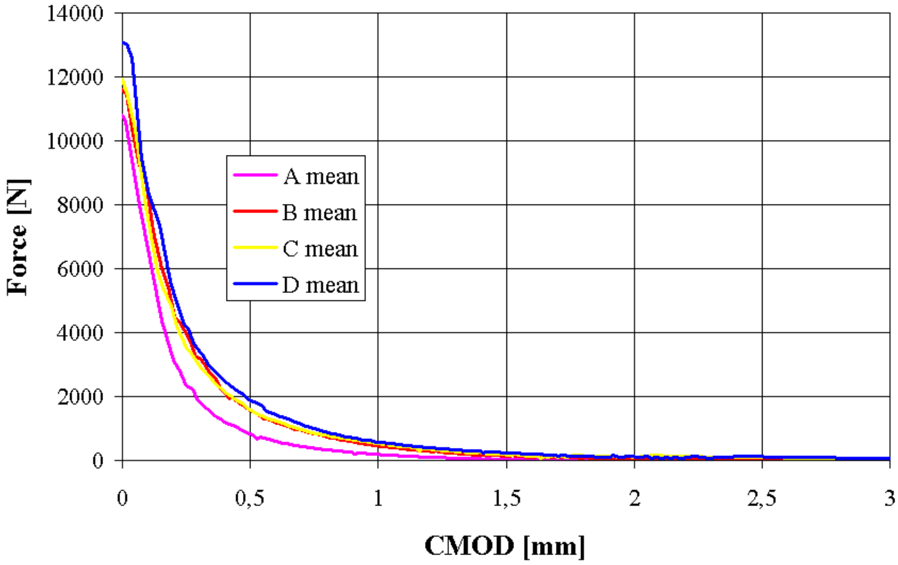

Fig. 7.: Force-CMOD diagram of the different concrete types

We can see a difference between the A(1,2,3) and D(1,2,3) FRC beam test, too, but at higher CMOD values this difference is lost (Fig. 8). The disappearance of the difference is in relation with the post tension capacity of the concrete: as it gets smaller the difference seems to be smaller, too. From this fact we can conclude that the added fibre fracture energy does not depend on the fracture energy of the concrete, only in relationship with the cement grout.

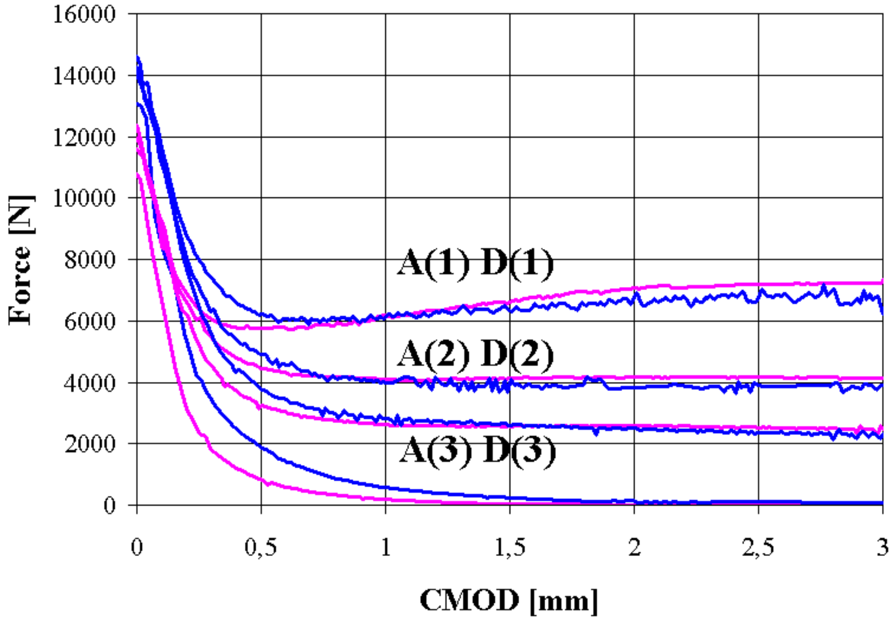

Fig. 8.: Force-CMOD diagram of concrete A and D and FRC A(1) and D(1)

6. Verification

The verification was made by inverse analysis, 3 point bending beam test was modelled and the results of the force-CMOD were fitted. With this analysis I was able to find the sigma-crack opening relationship for A and D concrete, and A(1) and D(1) FRC as well (Fig.9.).

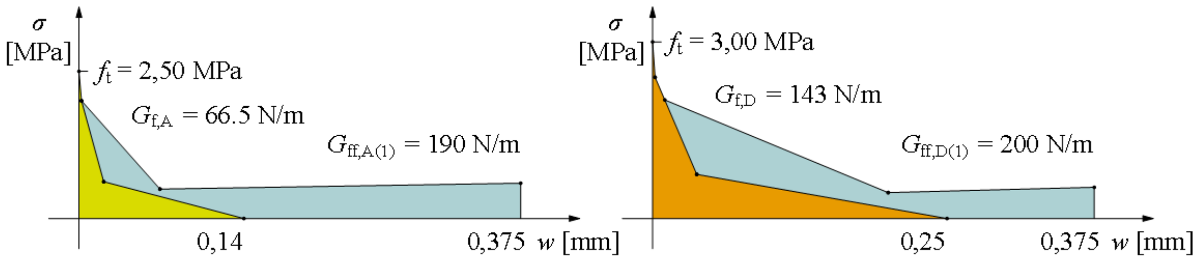

Fig. 9.: fracture energy (G_f) and added fracture energy (G_{ff}) of A(1), D(1)

The fracture energy of the concrete is in accordance with the recommendation of the Fib model code [4].

The added fracture energy was measured until 0.375 mm, after this point the sigma of the diagram at A(1) and D(1) was the same. Because of this reason this two G_{ff} result could be compared (Fig. 9). The difference between these two is 5%, which could be negligible.

The basic assumption was correct, however the value of this added fracture energy is not the same during the crack opening. For this reason the added fracture energy can't be used as a stand alone parameter to model the FRC, only to compare different kinds of fibres.

As I mentioned above there is a big difference between the steel and synthetic fibre mechanism: steel is absorbing the energy with pull-out mechanism after small crack opening, while synthetic with bridging. For this reason we can separate this added energy into two parts, so called: elastic and elasto-plastic energy. The elastic energy is where the fibre is bridging and has no splitting, and the elasto-plastic energy is where the fibre started the pull-out (Fig. 10). This is true only for perpendicular and symmetric anchored fibres, but also a good way to compare different materials, too.

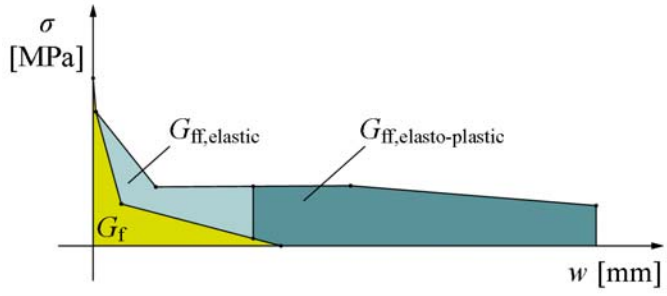

Fig. 10.: added elastic and elasto-plastic fracture energy of the fibres

7. Summary

In this article I showed a new model for FRC, called Modified Fracture Energy Method, which is based on the concrete fracture energy and its modification. The method is good to compare two different kinds of fibre, either steel or synthetic. The energy is independent of gravel frame and type, and only depends on the cement grout. With this method two different kinds of FRC could be compared, but for modelling this G_{ff} added energy is only a good approximation because it has a different shape during the crack opening. The added energy could be separated into two parts as an elastic and elasto-plastic region, where the fibres work as bridging or pull-out, respectively.

References

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