THE EFFECT OF SYNTHETIC FIBRE REINFORCEMENT ON THE FRACTURE ENERGY OF THE CONCRETE

A brief summary of the dissertation submitted to the Budapest University of Technology and Economics in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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1. Introduction

Fibre reinforced concrete (FRC) belongs to the group of composite materials, where matrix means the concrete, and fibres mean the various shaped (straight, hooked, wavy, etc.) and material (steel, polypropylene, glass, etc.) fibres, which are short compared to the size of concrete elements. Fibres are mixed in fresh concrete which supposedly provides a perfect and uniform mix. Although when casting the concrete the orientation of the fibres that are near the formwork changes, it becomes directional. This phenomenon is called the wall-effect (or boundary effect) by the literature. Wall-effect is currently not taken into consideration regarding the evaluation of the standardized beam experiments.

In the first part of the thesis a model is presented to analyse the mixing of rigid (steel) and flexible (synthetic) fibres and also to observe the wall-effect. Values calculated based on this analytical model were verified by the experimental results. On the basis of this analytical model a new evaluation method was developed, which considers orientation of the fibres thus provides more accurate results.

The mixed fibres increase the fracture energy of the concrete when cracking. Therefore energy of the fibre reinforced concrete can be divided into two parts: fracture energy of the plain concrete and fibre added fractured energy. So the question might arise: is the value of the added fracture energy depends on the fibres only or on the concrete as well? Matrix concrete is a bi-component material in itself, consisting of aggregate and cement mortar (of which cement mortar is made up of cement paste and sand). The relation of fibres to the matrix concrete depends on the link between the fibres and the cement mortar. The analysis takes the connection between the fibres and cement mortar into consideration, while also focusing on the effect of size of the aggregates, the link between the fracture energy of the concrete and the added fracture energy of the reinforced concrete, as well as the impact of the length of the fibres.

In the second part of the thesis a newly developed material model based on the modification of the concrete fracture energy is presented. The similarities and differences in the behaviour of the steel and synthetic fibre reinforcements are researched and discussed. The effect of the fibres in concrete with different aggregates, but with same mortar are researched, such as the effect of the dosage and the length of the fibres.

2. Fibre materials and its properties, testing methods of fibre reinforced concrete

On the basis of their material, ACI Committee 544 (2002) classifies fibres into four major groups (SFRC – steel fibres, GFRC – glass fibres, SNFRC – synthetic fibres, NFRC – natural fibres), while polypropylene fibres are classified based on their geometric size (diameter of the fibre) by the British BS EN 14889 standard (B/517 Technical Committee, 2006) into two other main groups: micro (diameter < 0.30 mm) and macro fibres (diameter > 0.30 mm).

Based on their material, the most common fibre types are steel fibres and synthetic fibres. By comparing these, both advantages and disadvantages can be found when using these two fibre types. By analyzing carbon footprint values synthetic fibres provide better result than steel fibres (Bernard, 2009). From the aspect of construction synthetic fibres are also more favorable regarding transportation and casting (Juhász, 2014). However, analyzing material properties of fibres steel fibres provide more favorable values. The viscoelastic property of the synthetic fibres, its low elastic modulus (steel: 210 GPa, polypropylene: 3-10 GPa) and its low melting point compared to the steel fibres (steel: +1500 C°, polypropylene: +120-200 C°) do not support its usage (Zheng and Feldman, 1995; Kusterle, 2009). Despite this, fibre reinforced concrete as a composite material is different than what can be concluded generally by the properties of the constituent materials.

One of the main advantages of synthetic fibre is being non-corrosive. Corrosion could also occur at cracked steel fibre reinforced concrete elements (Jen and Ostertag, 2016), even a crack width of 0.1 mm could cause corrosion (Nordström, 2000). Corrosion of steel fibres would diminish the structure strength, which may lead to rust spots appearing at the surface (Balouch, 2010).

Significant time-dependent mechanical qualities of fibre reinforced concrete are creep and aging. Fibre reinforced concrete, as the creep of composite material, is present both in the case of steel- and of synthetic fibres. Therefore, creep is not only caused by the creep of the fibres on the material level, but more by its mechanical behaviour in the concrete: the pulling out of the fibres. Currently, creep of fibre reinforced concrete is a relevant research field. Aging of steel- and of synthetic reinforced fibres was analyzed by Bernard (2008). Based on his research, in time steel reinforced concrete lose from their ductility, while ductility of concretes reinforced by synthetic fibres is either unchanged or increased by a small extent.

Major testing methods of fibre reinforced concrete are direct tensile test, beam test, panel test, splitting tensile test and the wedge splitting test. I used three point bending beam test based on the recommendation of RILEM TC 162 (Vandewalle et al., 2000) (Figure 1).

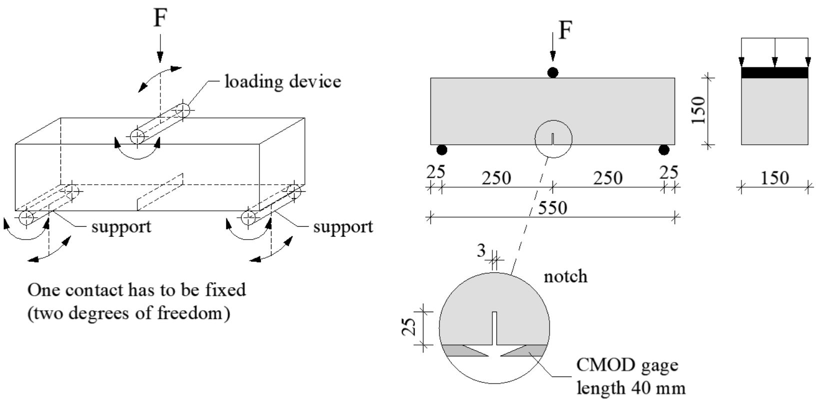

Figure 1. Three point bending beam test according to the recommendation of RILEM TC 162

3. Analytical model for fibre mixing in concrete

Quantity of the fibres intersecting the unit cross section is a relevant parameter. Romualdi and Mandel already worked on determining this quantity at the primary scientific research of fibre reinforced concrete (Romualdi and Mandel, 1964), where the behaviour of the fibre reinforced concrete and the quantity of fibres intersecting the cracked cross section of the test specimen are analysed through experiments. In 1972 Naaman (1972) determined the quantity of fibres intersecting the cross section by supposing uniform distribution and applying probability analysis in his doctoral thesis. Krenchel, who provided a calculation method based on empirical results (Krenchel, 1975), introduced the orientation factor for describing the orientation of the fibres, which became the base for fibre reinforced material models.

Orientation of the fibres changes near the formworks, and by that the orientation factor is altered as well, which affects the quantity of the fibres intersecting the unit cross section. The literature calls this phenomenon wall-effect. In literature, beams with square cross section are usually examined, in which case the wall-effect is present at the sides (one side of the mould) and at the corners (two sides of the mould) (Figure 2). Dupont and Vandewalle (2005) investigated how wall-effect influenced the orientation factor in the case of steel fibres.

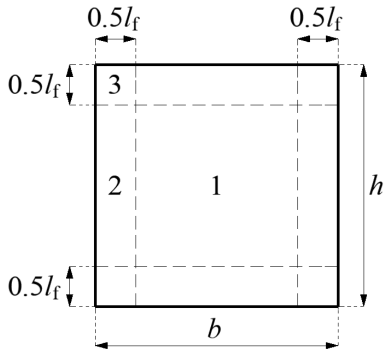

Figure 2. Cross section zones (Dupont and Vandewalle, 2005)

The major difference between the steel and synthetic fibres regarding their behaviour in concrete is the rigidity of discrete fibres: while steel fibres can be regarded as rigid, then synthetic fibres can be flexible. Oh, Kim and Choi (2007) did not take this effect into consideration when analysing synthetic fibre reinforced beams, however Alberti, Enfedaque and Gálvez (2017) made a recommendation to consider flexibility of the fibres in modelling. Orientation changes near the formwork, it becomes partly directional. This directionality is different for steel fibres as it is for synthetic ones, therefore the quantity of fibres intersecting the cross section also changes in a different way near the formwork. Suggested model is adequate for considering mixing of rigid and flexible fibres.

In the case of steel fibres the suggested model is the development of the deduction of Naaman (1972). The model examines the probability of stabbing of fibres located in the delineated space, during which penetration from adjacent space is also considered (Figure 3). For the formwork located at the border of the space I introduce the quasi-wall effect, which is generated by the limitation of the penetration of fibres located next to the formwork. I demonstrate that this way effect of the formwork is present at the deeper parts of the cross section as well. I modify the orientation factors of Dupont and Vandewalle (2005) based on the results of the model.

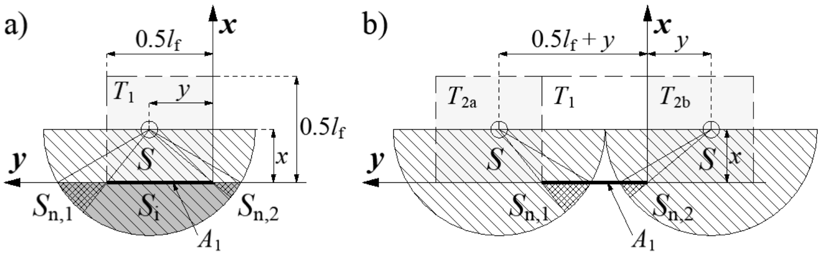

Figure 3. a) Interpretation of fibres intersecting the face A_1 from space T_1 b) Penetration from the adjacent spaces T_{2a} and $T2_b$

In the case of flexible (synthetic) fibres the suggested model assumes the bending of the fibres instead of rigid rotation when coming in contact with the wall. Due to this, the quasi-wall effect does not apply (Figure 4), also, the wall-effect influences the quantity of fibres intersecting the cross section to a smaller extent (Figure 5).

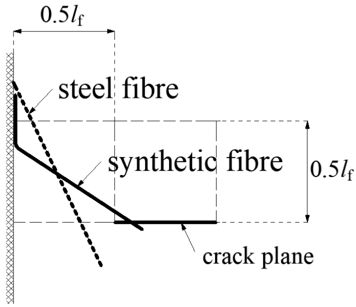

Figure 4. Over-reaching of steel and synthetic fibres to the adjacent cross section zone when the wall-effect is active

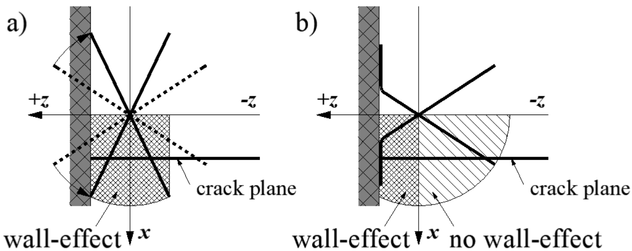

Figure 5. The impact of wall-effect on the quantity of fibres intersecting the cross section in the case of a) steel fibres and b) synthetic fibres

Based on the results of the model I provide orientation factors in the various zones of the cross section (Figure 6). I verified the results with numerous bending beam tests.

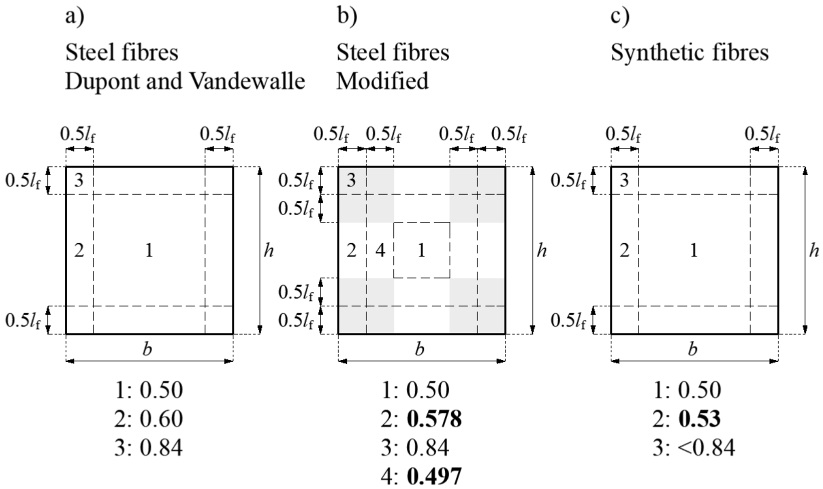

Figure 6. Cross section zones and their orientation factors

4. A new approach for evaluating the beam test results

The generally accepted testing method of fibre reinforced concrete are the three or four point bending beam tests, measuring the load, deflection and/or CMOD. These standard testing methods can be easily performed in most of the laboratories, although the scattering of the results could be high, even if everything is done in order to achieve the perfect mixing. These test results include the wall-effect of the formwork, which modify the values. Based on this research two parameters were defined, called fibre-work and fibre-moment, which could eliminate this effect. A new evaluation method was presented where location of the fibres was considered during evaluation. This method could lead to achieving more accurate data with less physical tests.

5. Material parameters

Elastic modulus of the synthetic fibres (8-12 GPa) is much smaller than the elastic modulus of the steel fibres (210 GPa), despite this fact with the proper dosages similar load-CMOD diagram is received at beam tests. The reason for this is the different energy-absorption mechanism of the fibres: while steel fibres pull-out from the matrix, synthetic fibres bridge the crack. These two kinds of behaviours were analysed with beam tests.

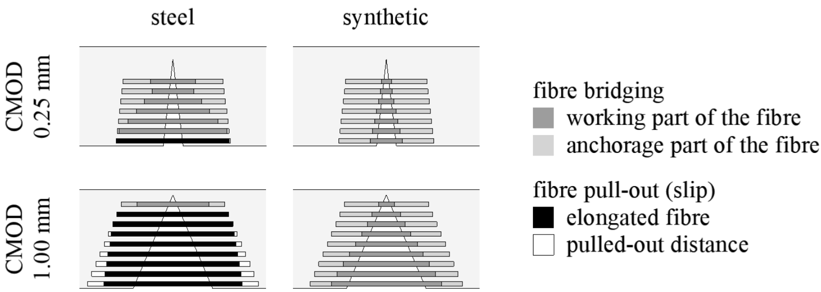

Figure 7. Fibre bridging and fibre pull-out of steel and synthetic fibres

Effect of fibres can be defined by analysing fracture energy of fibre reinforced concrete, which can be divided into two parts: fracture energy of the concrete and added fracture energy of fibres. There are numerous recommendations in literature defining the value of fracture energy of plain concrete, of which the most relevant models were introduced. By knowing the fracture energy of the concrete and the added fracture energy of the fibres the material model of the fibre reinforced concrete can be easily defined.

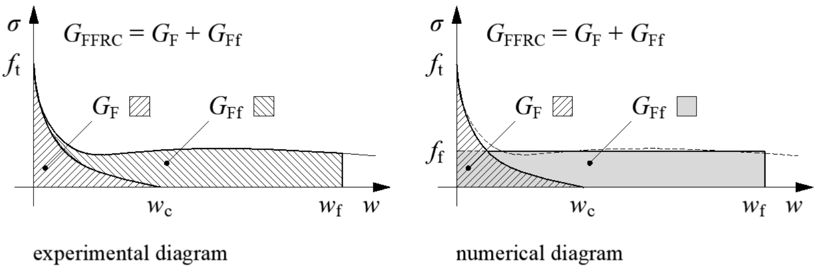

Figure 8. Experimental and numerical diagram of fibre reinforced concrete

6. The correlation of added fracture energy and the aggregates

In the case of the synthetic fibres the energy absorption mechanism is mostly manifested by the fibres pulling out from the matrix and the fibre bridging, which is defined primarily by the connection of the fibres and the mortar phase of the concrete. The question arises whether the aggregate mixed in the mortar has an effect on the absorption mechanism of the fibres, i.e. to the added fracture energy. Effect of the added fibres was investigated in concretes made with the same mortar but with different aggregate, by which the experimental results were published herein.

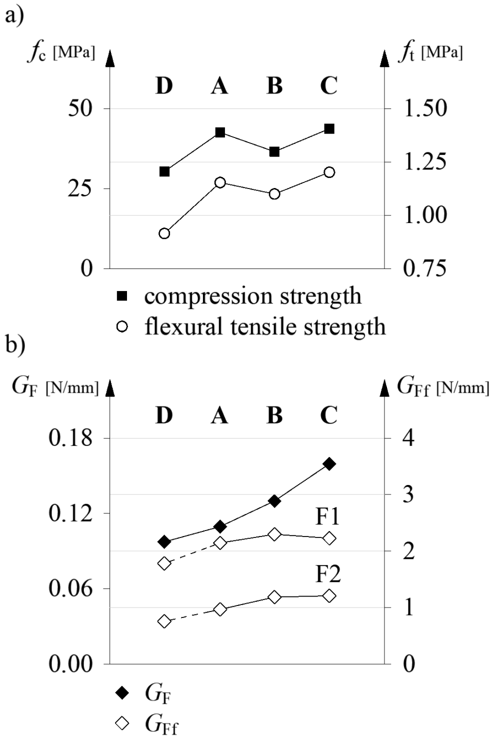

Figure 9. a) Compression strength and flexural tensile strength of concrete without fibre reinforcement [MPa];
b) Fracture energy of concrete (G_F)
and added fracture energy of fibre reinforced concrete (G_{Ff}) [N/mm];

7. The effect of fibre length to the added fracture energy

A relevant parameter of fibres is fibre length. Above a certain anchorage length fibre will not pull-out from the matrix, but will rupture instead. This fibre length is called critical fibre length (l_c) in the case of steel fibres, which can be considered similarly in the case of synthetic fibres. Definition of critical fibre length occurs by an experimental method. Optimal fibre length (l_{opt}) is twice of the critical fibre length, which ensures that all fibres intersecting the cross section will pull-out from the matrix instead of rupturing.

Optimal fibre length was tested for synthetic fibres by fibre reinforced concrete beam test made of synthetic fibres of different length but identical material. I indicated the largest fibre-work during the test to be optimal. Experiments demonstrated that the largest fibre-work was in the case of synthetic fibres longer than the optimal fibre length derived from critical fibre length, although it has an upper limit as well.

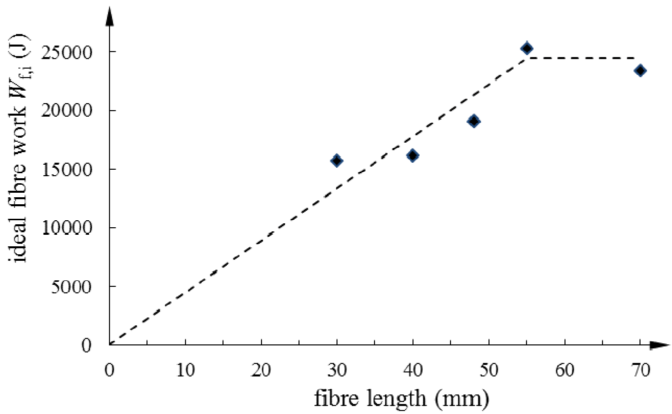

Figure 10. Fibre length and fibre-work correlation

8. Summary and principal results

Principal result 1

(relevant publication: Juhász, 2018)

I introduced an analytical model for determining the quantity of fibres intersecting the unit cross section, which differentiates between rigid (steel) and flexible (synthetic) fibres.

1.1. Uniform distribution at orientation of fibres can be achieved by defining the orientation of the fibres by uniform distribution of the azimuthal angle and the height of the endpoint. I demonstrated that the deduction of the quantity of the fibres intersecting the unit cross section by Romualdi and Mandel (1964) will be equal to the deduction of Naaman (1972) if the orientation of the fibres is defined this way.

1.2. I improved the orientation factors of Dupont and Vandewalle (2005) recommended for rigid (steel) fibres, and proved theoretically that the impact of the wall-effect influences wider areas of the cross section, which I named quasi-wall-effect zone. I derived the orientation factor of rigid (steel) fibres in the wall-effect and quasi-wall-effect zones.

1.3. In the case of flexible (synthetic) fibres the suggested model assumes the bending of the fibres instead of rigid rotation when coming in contact with the wall. I demonstrated that in this case the quasi-wall-effect does not occur. I derived the orientation factor of flexible (synthetic) fibres in the wall-effect zones.

Principal result 2
(relevant publication: Juhász, 2013c; Juhász, 2015a; Tóth, Juhász and Pluzsik, 2017)

2.1. I introduced the definitions of fibre-moment and fibre-work, which can be defined by using the results of three-point bending beam tests. I introduced the definitions of ideal fibre-moment and ideal fibre-work, which are derived from the result of the analytical model assuming uniform mixing, which is supposed to be the ideal case.

2.2. I demonstrated experimentally that with the tested fibre types, at the tested dosages of fibres and at the tested concretes fibre-work increased in linear proportion to fibre-moment both in the case of steel- and synthetic fibres.

Principal result 3
(relevant publication: Juhász, 2013a)

I demonstrated experimentally that with the tested fibre types, at the tested dosage of fibres and at the tested concrete steel fibres pulled out from the concrete matrix even at low crack width, while synthetic fibres bridged the crack (the lengths of the steel- and synthetic fibres were roughly identical). This different energy absorption mechanism is the reason why the load-CMOD diagram of steel- and synthetic fibre reinforced concrete, as a composite material, was similar for the bending beam test.

Principal result 4
(relevant publication: Juhász, 2013a)

I introduced a simplified material model for tension for fibre reinforced concrete. I introduced the definition of added fracture energy (G_{Ff}), which is defined by two parameters: the post-cracking tensile strength of f_f and the maximum crack width of w_f. Engineers in practice can define the material model of fibre reinforced concrete easier by using this two-parameter model.

Principal result 5
(relevant publication: Juhász, 2013a)

I tested experimentally the effect of aggregate on the added fracture energy of synthetic fibre reinforced concrete. Mortar phase of the four different types of concretes in the experiment was identical, while the aggregate was different. In each of the cases the concrete was gap-filled, so embedding of the fibres was provided. I verified experimentally that in the case of fibres, fibre dosages and concretes used in the research, for concrete made of identical mortar phase the effect of aggregate on added fracture energy was negligible, however its effect was significant on the compressive strength and flexural-tensile strength.

Principal result 6
(relevant publication: Juhász and Kis, 2017)

I verified experimentally that in the case of concrete, synthetic fibre types and dosages used in the research for standard bending beam tests, the optimal fibre length for synthetic fibre is longer than the optimal fibre length defined at steel fibres: twice the critical embedded fibre length.

Publications connected to the principal results

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