FIBRE CONCRETE 2015
September 10-11, 2015, Prague, Czech Republic

EXPERIMENTAL ANALYSIS OF THE SHEAR CAPACITY OF PRESTRESSED FRC BEAMS

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Abstract

During the design of reinforced concrete beams at least a minimum amount of shear reinforcement must be applied according to the detailing rules of EC2. However, the assembly of shear reinforcement is usually a time and labour-intensive process which may reduce the effectiveness of the mass production of prefabricated concrete elements. A possible way to improve the overall performance of concrete members is to use fibre reinforced concrete for the construction. The objective our research was to find out, whether the use of appropriate fibre reinforcement could fully replace the conventional shear reinforcement in prefabricated beams for building construction. An experimental program was carried out on 32 full-scale concrete beam specimens to test their shear capacity with different type and amount of fibre reinforcement. For the purposes of comparison, several beams were manufactured with conventional stirrups and without fibre reinforcement. Load carrying capacity, deflection and failure mechanism of the different beams were recorded during the tests. Measured shear capacity values were analysed and compared to each other, as well as to the standard shear capacity of the beams according to EC2.

Keywords: building construction, prefabrication, prestressed beam, steel fibres, plastic fibres, shear capacity

1. Introduction

The construction techniques and materials for prefabricated, prestressed concrete beams have evolved substantially over the past decades. However, the assembly of supplementary reinforcement – such as shear reinforcement – is still a time and labour consuming part of the construction process, which has certain economical drawbacks during the mass production of the elements.

Fibre reinforcement in concrete can be used to improve the behaviour of structural elements both in serviceability and ultimate limit states, where they can partially or totally substitute conventional reinforcement [1], [2], [4]. Based on the latter a possible solution for decreasing the amount of statically necessary shear reinforcement in concrete beams

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could be the use of fibre reinforced concrete material. ASA – CONSOLIS Construction Ltd. – as one of the largest manufacturers of prefabricated concrete elements in Hungary – has decided to experimentally analyse the effect of the fibre reinforcement on the shear capacity of prefabricated, prestressed beams. Key issue of the research was to find out whether the minimum shear reinforcement prescribed by EC2 could be completely replaced by the use of appropriate steel or plastic fibre reinforcement.

To find the fibre type that is best suited to the objective set in terms of performance, workability and efficiency an extensive experimental program was carried out at the Laboratory of Materials and Structures, Budapest University of Technology and Economics [3]. Based on the results of these experiments, two types of fibres – a steel and a plastic fibre – were selected and used for the construction of full-scale prestressed concrete beam specimens. 8 different types of beams (4 pieces of each type, altogether 32 pieces) were constructed by ASA – CONSOLIS Construction Ltd.

The I shaped concrete beams were 6.00 m long and 0.40 m high. Longitudinal reinforcement of the beams consisted of Fp93 and Fp52 type 7-wire prestressing strands. Initial prestress of the wires was typically 950 N/mm^2. One series of beams (type 3000) had a complete shear reinforcement according to the detailing rules of EC2, the rest of the beams had shear reinforcement at the end of the beam only. The typical cross-section of the analysed beams and the arrangement of the shear reinforcement at the beam end are illustrated in Fig. 1.

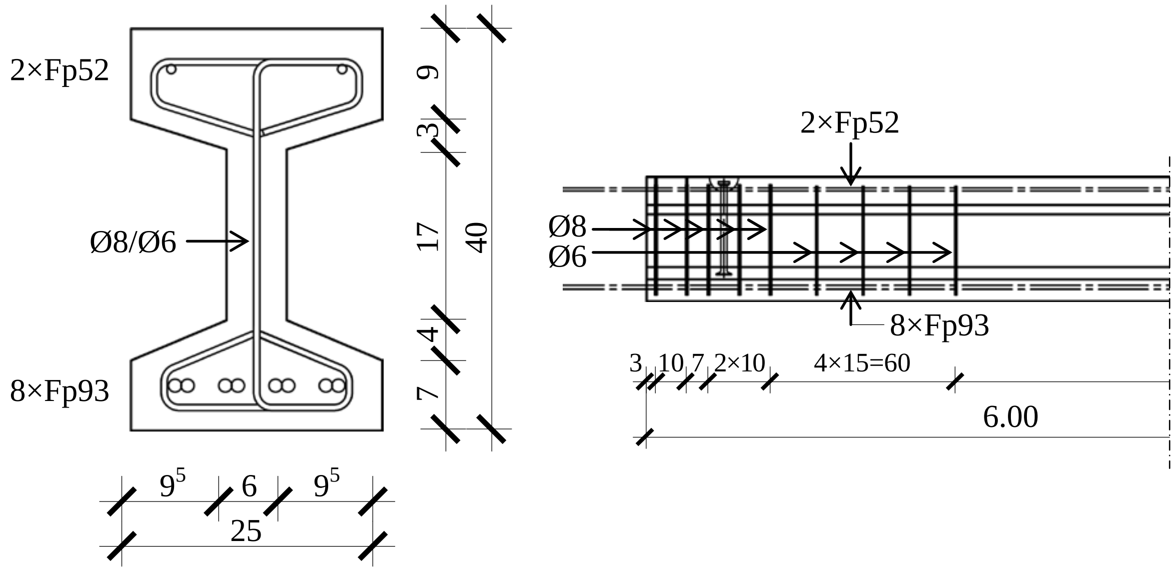

Fig. 1: Typical cross-section and reinforcement of the analysed beams

Beam specimens were mostly made of concrete grade C40/50-XC1-16 except of one series (type 3008) where C50/60-XC1-16 concrete grade was used in order to be able to assess the influence of the concrete strength on the shear capacity of the beams. Two types of fibres (EPC-Barchip48 plastic fibres and Dramix5D 65.60BG steel fibres) with different dosage were applied as fibre reinforcement in certain series of beams. The most important characteristics (concrete grade, longitudinal and shear reinforcement, type and dosage of fibre reinforcement) of the examined beams are presented in Tab. 1. The beams specimens were manufactured by ASA – CONSOLIS Construction Ltd. at their prefabrication plant in Hódmezővásárhely. The specimens were tested in the Structural Laboratory of the Faculty of Civil Engineering, Budapest University of Technology and Economics. Load test of each specimen was performed at the age of 28 days of the particular beam.

Tab.1: The main characteristics of the examined beam specimens

Type of beam	Concrete grade	Reinforcement				
		Longitudinal reinforcement (prestressing strands)	Initial prestress [N/mm^2]	Shear reinforcement (BSt500)		Fibre type and dosage
				Middle of the beam	Beam end	
3000	C40/50	8×Fp93/1860 2×Fp52/1860	950	Ø6/250	Ø8/100 Ø6/150	-
3002	C40/50	8×Fp93/1860 2×Fp52/1860	950	-	Ø8/100 Ø6/150	-
3004	C40/50	8×Fp93/1860 2×Fp52/1860	950	-	Ø8/100 Ø6/150	EPC-Barchip48 5 kg/m^3
3006	C40/50	8×Fp93/1860 2×Fp52/1860	950	-	Ø8/100 Ø6/150	EPC-Barchip48 2.5 kg/m^3
3008	C50/60	8×Fp93/1860 2×Fp52/1860	950	-	Ø8/100 Ø6/150	EPC-Barchip48 5 kg/m^3
3010	C40/50	8×Fp93/1860 2×Fp52/1860	950	-	Ø8/100 Ø6/150	Dramix5D 65.60BG 35 kg/m^3
3012	C40/50	8×Fp93/1860 2×Fp52/1860	950	-	Ø8/100 Ø6/150	Dramix5D 65.60BG 20 kg/m^3
3014	C40/50	8×Fp93/1860 2×Fp52/1860	475	-	Ø8/100 Ø6/150	EPC-Barchip48 5 kg/m^3

2. Description of the load tests

For the examination of the 6.00 m long beams a loading frame was assembled (see Fig. 2). The ends of the beams were placed on supports that allowed the free rotation. The distance of the supports, thus the span of the beams was 5.60 m according to the support length recommended by the manufacturer. Beams were loaded by a concentrated force in the middle of the span. Before starting the load tests the concrete strength of the beams was estimated by non-destructive measurements using Schmidt-hammer, and furthermore main geometrical sizes (length, height, width of flanges and web) and deflections of the top and bottom flanges of the unloaded beams were measured.

Loading of the beams was done by a LUKAS 250/200 type hydraulic jack. The deflection of the beams was measured by HBM50 type inductive displacement pick-ups, which were placed in the middle and in the quarters of the span (see Fig. 2). Longitudinal displacement of the prestressing strands was measured by HBM20 type inductive displacement pick-ups which were placed to the protruding end of the strands. The loading force and displacement values were measured at 5 Hz sampling frequency using a 16-channel HBM Spider-8 electronic measuring system. Loading force was increased in steps with a speed of 0.1 kN/sec. The crack pattern and the maximum crack width was examined and recorded after each load step. After reaching a crack width of 0.1÷0.15 mm, the beams were unloaded so we were able to measure the residual deformations, too. After the complete failure of the beams (see Fig. 3) the type and location of the failure, as well as the inclination of the typical shear cracks were recorded.

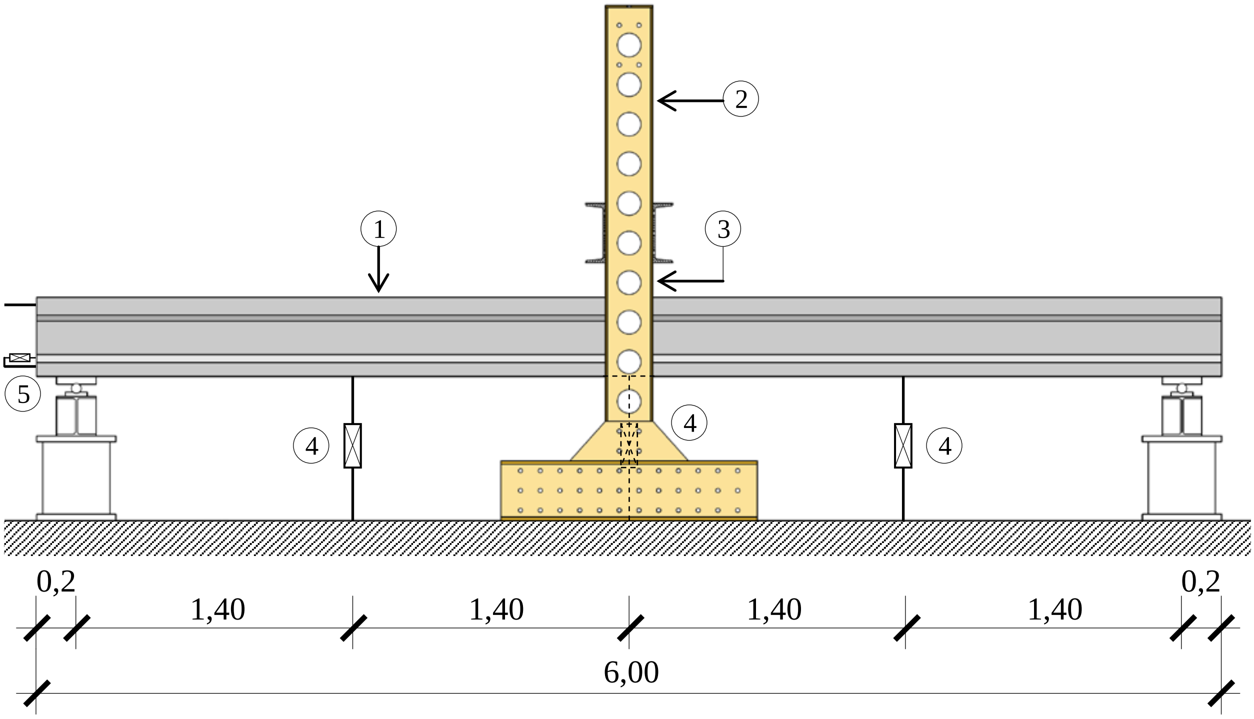

Fig. 2: Arrangement of the load test (1–reinforced concrete beam specimen; 2–loading frame; 3–LUKAS 250/200 hydraulic jack; 4–HBM50 inductive displacement pick-up; 5–HBM20 inductive displacement pick-up).

Fig. 3: Shear failure of the 8000/1 beam specimen

3. Initial experiences of the load tests

The measured failure loads are presented in Fig. 4. Displayed values represent the mean value and standard deviation of failure load considering four specimens from each series.

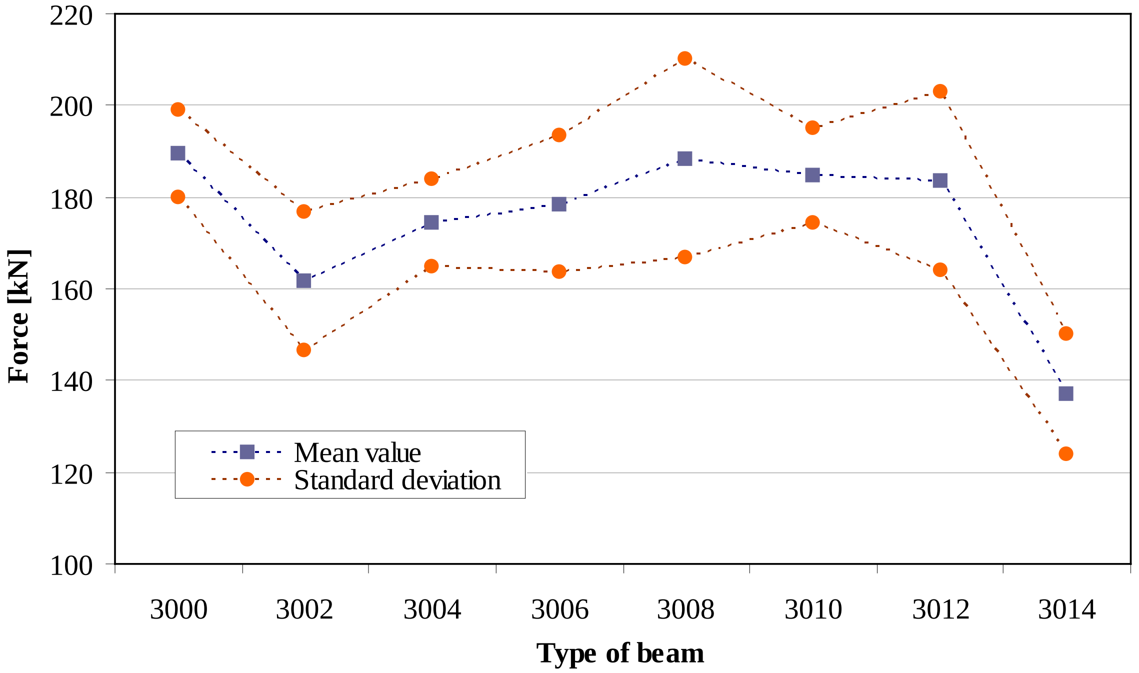

Fig. 4: Mean value and standard deviation of failure load in case of different beam types

Design values of failure load and shear capacity were calculated for each beam type (see Tab. 2). According to the static scheme applied during the tests, the design value of shear capacity of different beams ($V_{Rd,test}$) could be determined as half of the design value of failure load (F_{Rd}). Shear capacities calculated from the test results were also compared to the shear capacity ($V_{Rd,cs} = 63{,}8$ kN) of the control beams (type 3000) that was calculated using the standard design approach of EC2.

Tab.2: Failure load and shear capacity of different beam types

Type of beam	N^{o} of speci-mens	Failure load				Measured design shear capacity $V_{Rd,test} = F_{Rd}/2$	$V_{Rd,test}/V_{Rd,cs}$
		Mean value	Standard deviation		Design value (p = 1‰) F_{Rd}		
		[kN]	[kN]	%	[kN]	[kN]	
3000	4	189,4	9,5	5,0	160,1	80,1	1,26
3002	4	161,7	15,0	9,3	115,2	57,6	0,90
3004	4	174,3	9,6	5,5	144,6	72,3	1,13
3006	4	178,3	14,9	8,3	132,4	66,2	1,04
3008	4	188,3	21,6	11,5	121,4	60,7	0,95
3010	4	184,7	10,3	5,6	152,9	76,5	1,20
3012	4	183,3	19,5	10,6	123,1	61,6	0,96
3014	4	136,9	13,1	9,6	96,4	48,2	0,76

According to the expectations, beams without conventional shear reinforcement and fibre reinforcement (type 3002) had the smallest shear resistance, since the shear capacity of these beams was mainly provided by the tensile strength of the concrete and the prestressing force. The control beams (type 3000) that were containing the minimum shear reinforcement prescribed by the detailing rules of EC2 had 8-18% more shear capacity than the beams without shear reinforcement, despite the fact that this minimum quantity of stirrups cannot be considered in the calculation of the standard shear capacity $V_{Rd,cs}$.

Beams containing 5 kg/m^3 EPC-Barchip48 plastic fibre reinforcement (type 3004) had definitely lower mean failure load than the control beams. Having the same amount of fibres, but increasing the concrete grade from C40/50 to C50/60 (beam type 3008) resulted in higher mean failure load, similar to the failure load of the control specimens. The standard deviation of failure load was, however, significantly higher for these beams, which eventually meant ~25% lower design shear resistance. Similarly to the previous specimen types, beams 3014 were made of grade C40/50 concrete and with the same amount of EPC-Barchip48 fibres as the previous beams (3004 and 3008), but this time a lower initial prestress was applied to the strands (475 N/mm^2 instead of 950 N/mm^2). The effect of the lowered prestress could be clearly observed in the results, since these specimens had the lowest failure load and thus the smallest shear capacity of all.

Beams containing 35 kg/m^3 Dramix5D 65.60BG steel fibre reinforcement (type 3010) have only slightly lower mean failure load than the control beams. This is also true for the design shear capacity of these specimens, which is only about 5% behind the capacity of the control beams. When the quantity of the steel fibres was reduced to 20 kg/m^3 (beam type 3012) then the design shear capacity was already 23% behind the capacity of the control specimens. In case of the steel fibre reinforced beams a more uniform crack pattern could be observed along the entire beam than in case of other beam types. This phenomenon was basically caused by the better anchorage properties and bigger length of the applied steel fibres [5].

If we compare the effect of fibre dosage on the failure load of the specimens we learn that the application of more fibres does not increase the mean value of failure load noticeably. Conversely, the effect of fibre dosage can be observed in the design shear capacity values. In case of plastic and steel fibre reinforced beams the higher fibre dosage resulted in 9% and 24% higher design shear capacity respectively. During the casting of the concrete the lower fibre content resulted in less uniform fibre distribution, thus higher deviation of failure load, which could be the reason for the previous phenomenon.

Concrete strength of each specimen was evaluated using the results of non-destructive measurements using Schmidt-hammer. Since we had concrete beam specimens without full conventional shear reinforcement, we expected that the concrete strength will have significant influence on the measured failure load values. For the reason of comparison the mean values of failure loads and concrete compressive cube strengths of different beam types are illustrated in Fig. 5. The diagram itself suggests that there is a correlation between the failure load and the compressive strength of the concrete. We performed a correlation analysis of the corresponding failure load and concrete strength values and it was found that the linear (Pearson) correlation coefficient is $r = 0.59$ which means that there is a quite good correlation between these quantities.

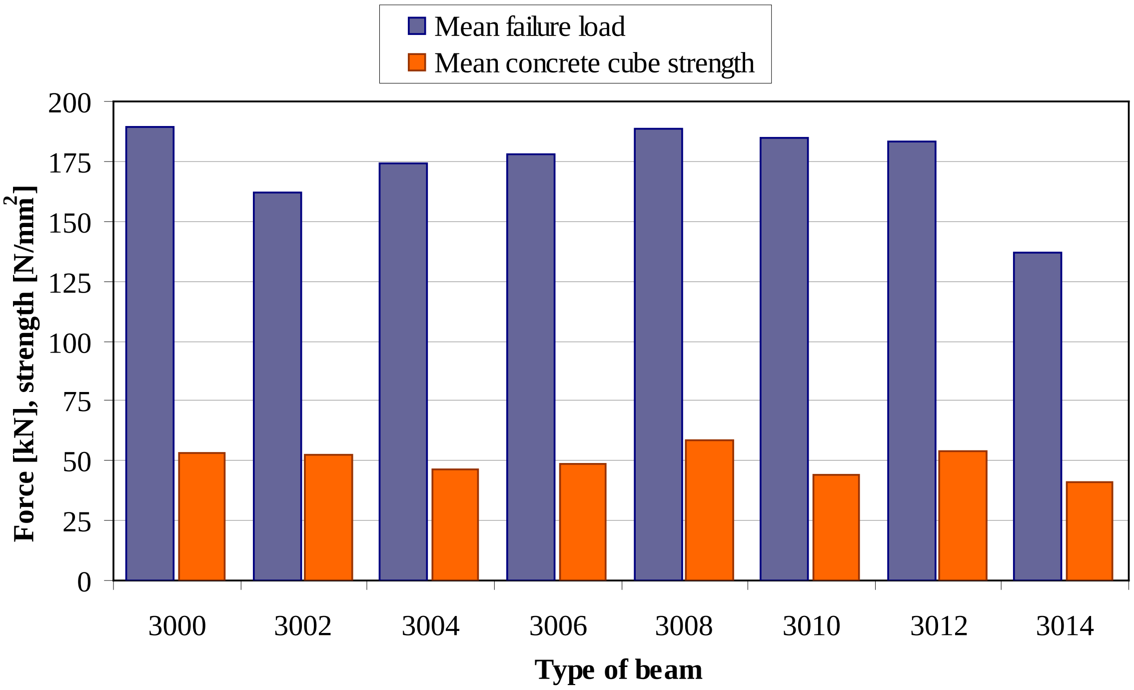

Fig. 5: Comparison of failure load and concrete strength in case of different beam types

Looking at the test results in Fig. 4 or Tab. 2 we may conclude that the minimum shear reinforcement prescribed by EC2 could be replaced by the use of appropriate fibre reinforcement since the shear capacity of some fibre reinforced beams is comparable to the shear resistance of the control beam which contains conventional stirrups. This conclusion seems to be, however, incorrect if we compare the probability of failure of different beams to the limit value defined by Eurocode (see Fig. 6).

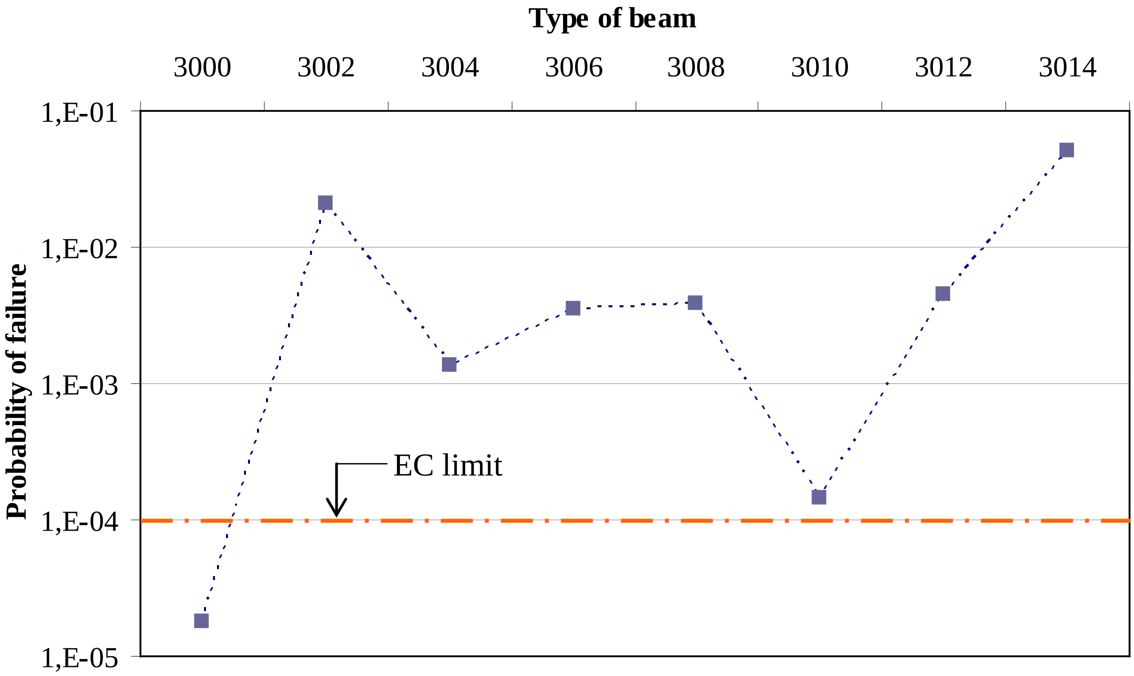

Fig. 6: Probability of failure of different beam types compared to the EC limit

According to Fig. 6 the control beam (type 3000) which contains the minimum shear reinforcement prescribed by EC2 has a satisfactory probability of failure below the limit value. All other beam types have a probability of failure above the limit value which means that they are not satisfactory in case of the given load effect. Probability of failure values given in Fig. 6 were calculated from the stochastic characteristics derived from the test results of different beams and from an assumed uniformly distributed load that can be characterized by normal distribution (p_m = 25 kN/m, ν_p = 5.5%).

4. Conclusions

The effect of different fibre reinforcement types and dosages on the shear capacity of prestressed concrete beams were tested. According to the test results, the application of plastic fibres – regardless of the amount of the applied fibres – could not provide the same level of shear capacity as of the control beams containing a minimum amount of conventional shear reinforcement that is prescribed by the detailing rules of EC2. This was primarily caused by the uneven fibre distribution and the relatively short anchorage length of the plastic fibres. The improvement of concrete quality leads to increased mean shear capacity of plastic fibre reinforced specimens; however, the problem of uneven fibre distribution applies even more resulting in significantly higher deviation of the failure load. This leads of course to decreased shear capacity on design level. The application of 35 kg/m^3 steel fibres resulted in an average shear capacity nearly equal to the average shear capacity of the control specimens. The anchorage properties of the steel fibres were much better [5], however, the problem of uneven fibre distribution leaded again to an increased deviation of shear capacity compared to the control specimens. If we compare the probability of shear failure levels of different beam types it becomes clear that all types of fibre reinforced beams have lower reliability than the control beam containing conventional shear reinforcement. It means that fibre reinforcement cannot completely replace the conventional shear reinforcement; although, the application of fibres has definitely positive impact on the overall performance of the analysed beams, therefore, it can still be used as partial replacement of conventional stirrups.

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