SIZE EFFECTS OF PRETENSIONED ULTRA-HIGH PERFORMANCE CONCRETE BEAMS

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ABSTRACT

Ultra High-Performance Concrete (UHPC) is a high-tech material opening new opportunities especially for slender constructions. Within the priority program[1] supported by the German Research Foundation (Deutsche Forschungsgemeinschaft DFG) several shear tests on prestensioned beams have been carried out at the Institute of Structural Concrete at RWTH Aachen University. The latest tests are focused on the size effect. Generally, the effective depth is the most used influencing factor for size effects in shear models. In this case, a further size effect due to the web thickness occurs, which is based on different fiber orientations close to the formwork surface.

Since 2005 more than 40 shear tests have been conducted on pretensioned beams with a cross section 40 cm high and a web thickness of 6 cm. Different amounts of steel fibers have been added to the concrete to ensure a sufficient ductility and also to serve as shear reinforcement. To investigate the influence of size effects the height of the cross section and the web thickness were varied in the following tests. The investigations, which were carried out between 2006 and 2010, have been presented amongst others in Kassel (UHPC 2008), Amsterdam (fib 2008), Tokyo (HPC/HSC 2008), London (fib 2009) and Washington DC (fib 2010). An overview of shear tests on beams with a height of 40 cm is given in the SCC2010 proceedings[2].

Keywords: Research, Ultra-High Performance Concrete, Steel Fibers, Shear, Size Effect, Pretensioning

INTRODUCTION

A priority program[1] on UHPC with over 20 projects in Germany started in 2005. The shear behavior of pretensioned beams made of UHPC as well as the bond behavior of strands in UHPC have been investigated in one of these projects at the Institute of Structural Concrete at RWTH Aachen University.

The compressive strength of UHPC is about five times the strength of conventional normal strength concrete. Therefore, a high degree of prestressing can be applied and thus, more slender structures are feasible. This leads to significant savings in dead load and transportation costs which is an important issue especially for precast members. The stringent production requirements for UHPC restrict the main field of application to precast members, e.g. roof girders of large span. Adding steel fibers to the concrete contributes to the shear resistance and improves the post-cracking behavior. Thus, steel fibers eliminate the need for conventional shear reinforcement. Generally, this is allowed in Germany according to the guideline for steel fiber reinforced concrete[3], which contains additions to the German Design Code[4]. In order to accommodate building utilities, web openings influencing the ultimate shear carrying capacity are frequently arranged in the girders. It is therefore necessary to investigate the shear behavior of UHPC beams with and without web openings. In order to investigate the shear strength of such beams, an extensive experimental program consisting of a total of 42 tests on beams with and without web openings was carried out. Some main results of the previous project phase are given in the Figures 1 and 2, more detailed data was already published[2]. The investigated test parameters were the fiber content, the grade of prestressing applied, the shear slenderness as well as the location and number of web openings in the beams. Furthermore, different shapes of additional shear reinforcement close to the openings were investigated and compared to the bearing capacity of beams without such reinforcement. In this phase, the cross section was always 40 cm (15.75 in) high and the web thickness was 6 cm (2.36 in) (2nd cross section in Fig. 3).

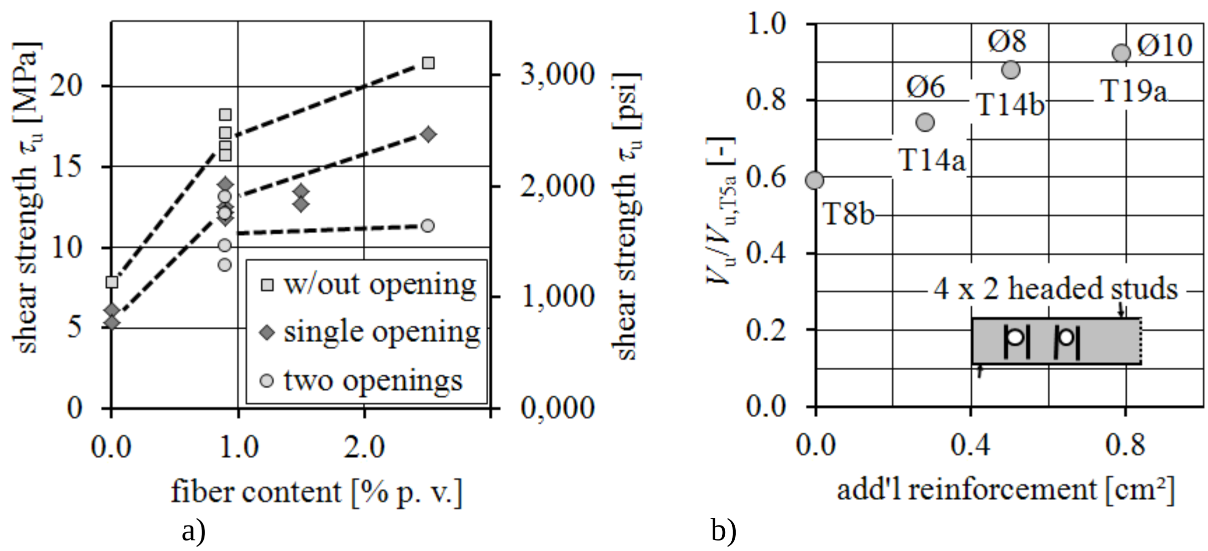

Figure 1: Ultimate shear strength $\tau_u = V_u/(d \cdot b_w)$ a) as a function of the fiber content with and w/out web openings, b) as a function of the additional shear reinforcement beside the openings and 0.9 % fibers

The steel fibers were very effective in beams without and with single openings (Fig. 1 a). With 0.9 % p.v. (per volume) added, the shear capacity was more than doubled and tripled with 2.5 % p.v. compared to beams without fibers. When two openings were arranged, there was no further benefit of shear capacity after increasing the fiber content from 0.9 % to 2.5 %. In the case of several openings, 0.9 % fibers and additional shear reinforcement close to the openings were useful. Shear tests on beams with two rebars with anchorplates (similar to headed studs) on each side of an opening nearly reached the capacity of beams without openings. In Figure 1 b), the shear capacity of each beam is related to the beam T5a without opening.

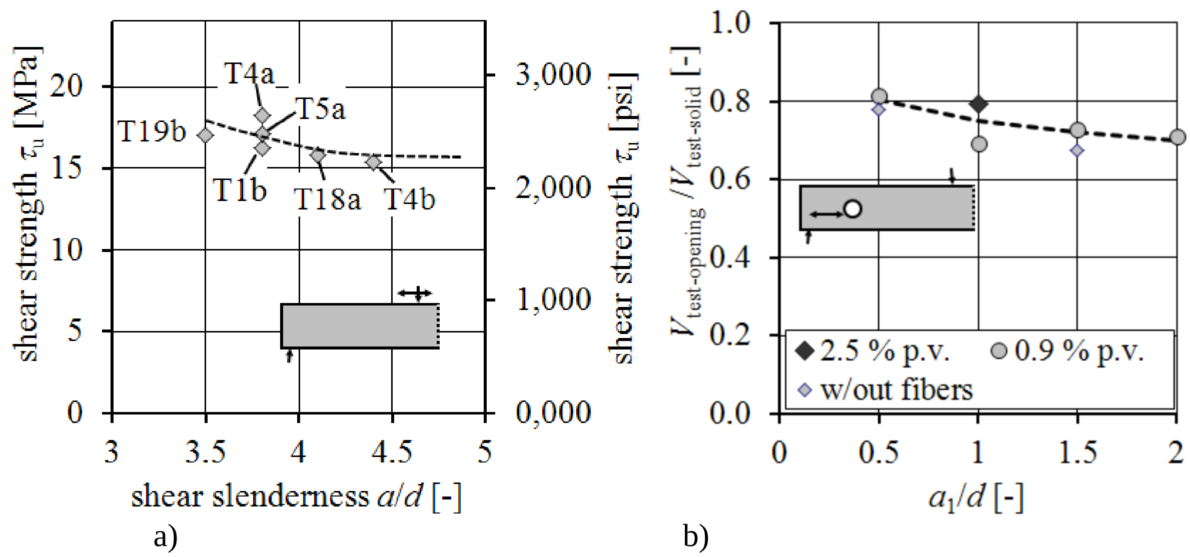

Figure 2: Ultimate shear strength $\tau_u = V_u/(d \cdot b_w)$ a) as a function of the shear slenderness and b) related to beams w/out openings as function of the clearance between opening and support line

The shear slenderness was tested in the range between a/d = 3.5 and 4.4 (Fig. 2a), where a is the distance between support and loading point and d is the effective depth. A slight impact inside this range could be observed, but it is comparable to normal or high strength concrete beams. In Figure 2 b), the shear capacities of beams with single openings are related to beams without openings. The shear strength is decreased to app. 70 %, when the clearance a_1 between opening and support line exceeds $1 \cdot d$ and app. 80 %, when the openings is close to the support. The effect was nearly independent from the amount of fibers.

To investigate size effects the web thickness was varied between 4 and 8 cm. Furthermore, the height was increased to 70 cm and beams with 100 cm height are scheduled. To transfer the results of the 40 cm beams, special parameter combinations with different fiber content, openings and additional reinforcement were planned.

EXPERIMENTAL INVESTIGATIONS ON SIZE EFFECTS

The shear tests on size effects are currently going on and the test program will be finished in 2011. In this paper, the results of the current shear tests and the main results of the related tests on 40 cm beams, required to figure out the size effects, are described.

SPECIMEN DESIGN

Due to the high compressive strength of the UHPC, a high prestressing can be applied. The 40 cm (15.75 in) cross section with 6 cm (2.36 in) web thickness in Figure 3 was pretensioned with nine 0.5'' strands, each one with the maximum initial prestressing of 125 kN ($0.9 \cdot f_{pk} \cdot A_p = 0.9 \cdot 1500 \cdot 0.93 \cdot 10^{-1}$) according to the German Design Code[4] and a total initial prestressing of P_0 = 1125 kN. The specific concrete cover was c/d_p = 2.5 as well as the specific clearance between the strands. These are the minimum dimensions to avoid splitting cracks during the release, which were determined in preliminary tests. The results were presented in Rotorua[5] and in a journal paper[6]. Additionally, two stirrups Ø6 were arranged at each end, anyway, splitting cracks were not observed. A further pretensioning of 50 kN in the upper chord was applied to avoid longitudinal tensile stresses in the upper extreme fiber. In the lower extreme fiber, the compressive stresses were 42 MPa (6,090 psi) after the release of the full prestress and the elastic shortening was about 1.0 ‰. The effective depth of this cross section is 31.7 cm.

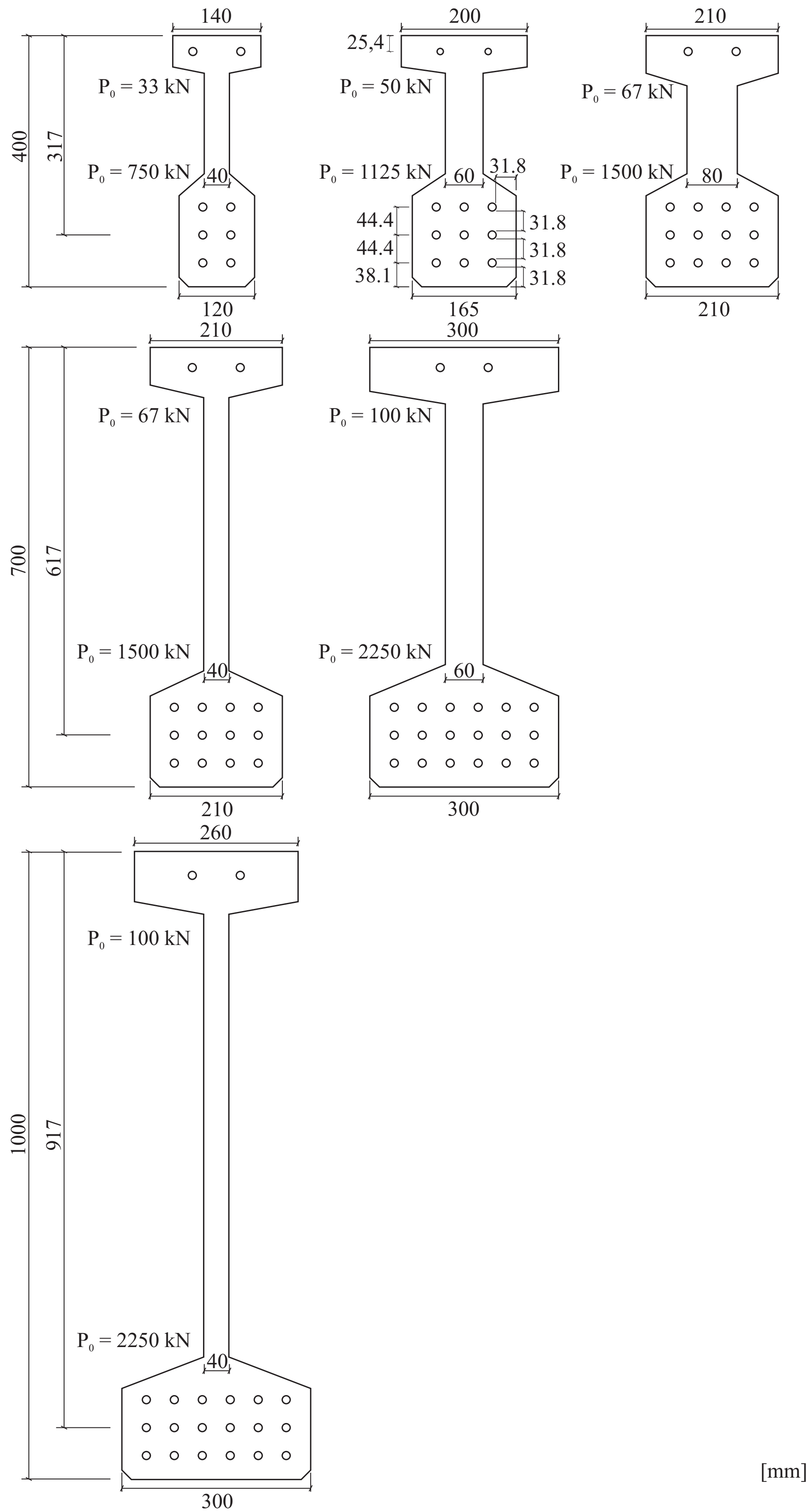

Figure 3: Cross sections of the beams and initial prestressing

To investigate the size effects, the other parameters should remain constant. When the web thickness was varied, the prestressing was adapted. With 4 cm web thickness six strands were arranged respectively twelve strands with 8 cm (3.15 in). The compressive chord was dimensioned in the same way. The effective depth and the concrete compressive stresses due to pretensioning remained the same. In the 70 cm (27.6 in) beams, the effective depth was doubled (61.7 cm; 24.3 in) and in the 100 cm (39.4 in) beams it was tripled (91.7 cm, 36.1 in). Accordingly, the multiple prestressing was required. Due to the nearly constant ratio between prestressing moment and section modulus as well as the same strand density in the lower chord, the concrete compressive stresses as well as the relative prestressing losses were nearly the same independent of the cross section type (Figures 4 and 5). At the time, this paper was prepared, the cross sections with 70 cm height and 4 respectively 6 cm web thickness were already tested and the preparation of the beams with higher cross sections were still in progress.

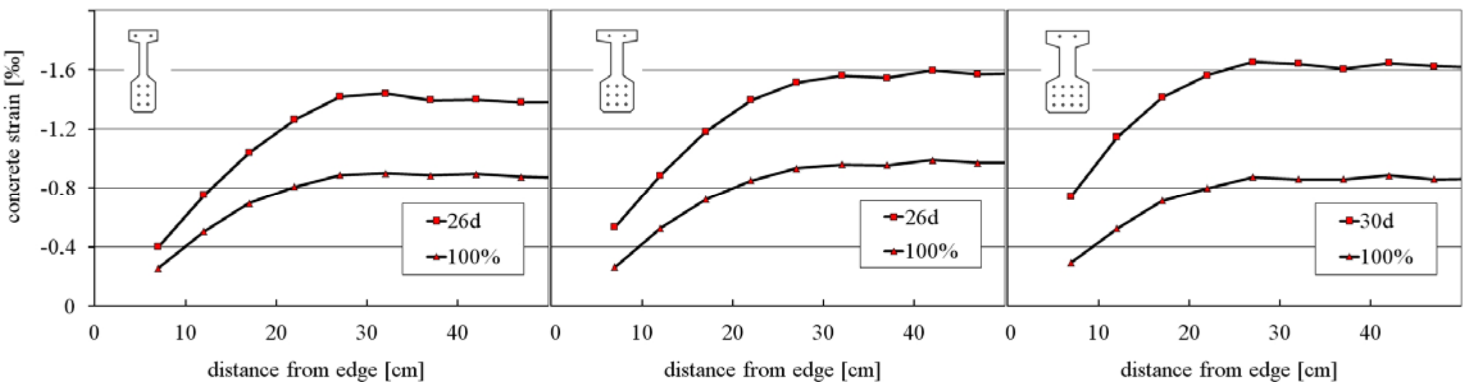

Figure 4: measured concrete strain at the time after 100 % release and about four weeks later in cross sections with 40 cm (15.75 in) height and different web thicknesses

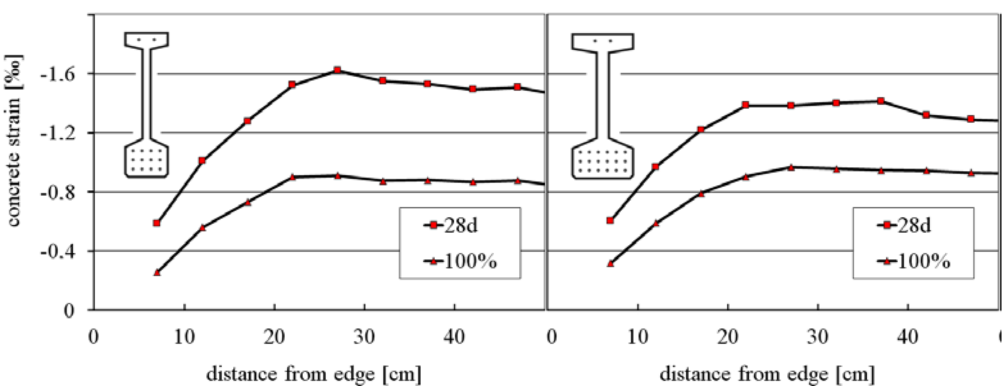

Figure 5: measured concrete strain at the time after 100 % release and about four weeks later in cross sections with 70 cm (27.6 in) height and different web thicknesses

SPECIMEN FABRICATION

The UHPC is flowable and nearly self-compacting. No concrete vibrators were used, merely some poking to avoid air entrapments in the lower chord due to the lateral covering formwork and the density of strands. All specimens were cast with the concrete composition presented in Table 1. Merely, the fiber type and ratio were varied. All fibers were straight – without hooks – and of high strength steel (f_y^f > 2200 MPa). The diameter of 0.15 mm (0.06 in) is specified by the manufacturer and the margin is ±0.02 mm. In several spot tests the diameter was about 0.17 mm in average. The steel fibers had a length between 9 mm (3.54 in) and 17.5 mm (6.9 in). The reference composition MR contained no fibers. Two fiber ratios (0.9 % and 2.5 % per volume) were investigated.

Due to the slenderness of the fibers and the short anchorage length (half of the fiber length), tensile failure of the fibers was not possible but rather a fiber pull-out failure was expected. This results in a ductile tensile behavior of the UHPC affecting the shear behavior of the beams as well. The slump flow spread of the concrete mixtures M0 as well as M1 ranged between 66 and 72 cm (26 to 28 in). In composition MR without fibers the slump flow spread was increased to 75 to 80 cm (30 to 31 in), which has led to a partial settlement of the basalt. In mixtures with fibers, segregations were not observed. 70 cm (27.6 in) or 100 cm (39.4 in) beams without fibers are not planned so far.

Table 1: Concrete mix

Material	Mix/fiber ratio	M0 2.5% p.v.	M1 0.9% p.v.	MR w/out
Cement CEM I	[kg/m³]	650	660	666
Silica fume	[kg/m³]	177	180	181
Quartz powder	[kg/m³]	456	463	467
Sand 0.125-0.5mm	[kg/m³]	354	360	363
Basalt 2-8mm	[kg/m³]	598	606	612
Steel fibers 9.0/0.15	[kg/m³]	194	-	-
Steel fibers 17.5/0.15	[kg/m³]	-	70	-
Steel fibers 13.0/0.16	[kg/m³]	-	-	-
Steel fibers 6.0/0.15	[kg/m³]	-	-	-
Water	[kg/m³]	158	161	162
Superplasticizer	[kg/m³]	31	32	32

The prestressing was released after three days, when the concrete compressive strength is about 100 MPa (14,500 psi). During the release, the longitudinal concrete strain along the transfer length was measured (Figures 4 and 5). In addition, the concrete strains at the day of testing were measured. In this way, the prestressing losses due to elastic shortening as well as creep and shrinkage could be estimated and the effective prestressing force acting on the beam could be determined.

The concrete strain in the lower chord was 0.9-1.0 ‰ after the release of prestressing. Until the shear tests at the age of about four weeks, the concrete strain increased to 1.45 to 1.6 ‰ due to creep and shrinkage. As a consequence, the loss of prestressing - time dependent and the elastic part – ranged between 1 – (6.75 –1.45)/6.75 = 21 % and 24 %, where 6.75 ‰ is the initial steel strain inside the prestressing bed.

SHEAR TESTS – SETUP AND RESULTS

The shear tests were carried out after four weeks, when the concrete compressive strength was about 180 MPa (26,100 psi). The test setups are illustrated in Figure 6 and the setup with a 70 cm high beam is shown in Figure 7. Two tests were carried out on each beam. The shear slenderness was constant $a/d = 3.8$ ($h = 40$ cm: $a/d = 1.20/0.317$; $h = 70$ cm: $a/d = 2.35/0.617$). The concrete strain along the lower and upper chord was measured with DEMEC strain gauges and the deflection was taken with an LVTD under the loading point. Additional LVTDs were applied on the web to investigate the crack growth. The testing parameters and the main results are listed in Table 2. The shear test on the first beam side is indicated with a, the second with b. The tests on the beams T2 to T5 were focused on the influence of the fiber content. T22b and T23b with a web thickness of 4 respectively 8 cm (1.57 resp. 3.15 in) can be compared with T5a (6 cm, 2.36 in) to investigate the size effect of the web thickness. The same tests were carried out with a single web opening (T22a, T23a). The size effect of the height was investigated with T24 and T25.

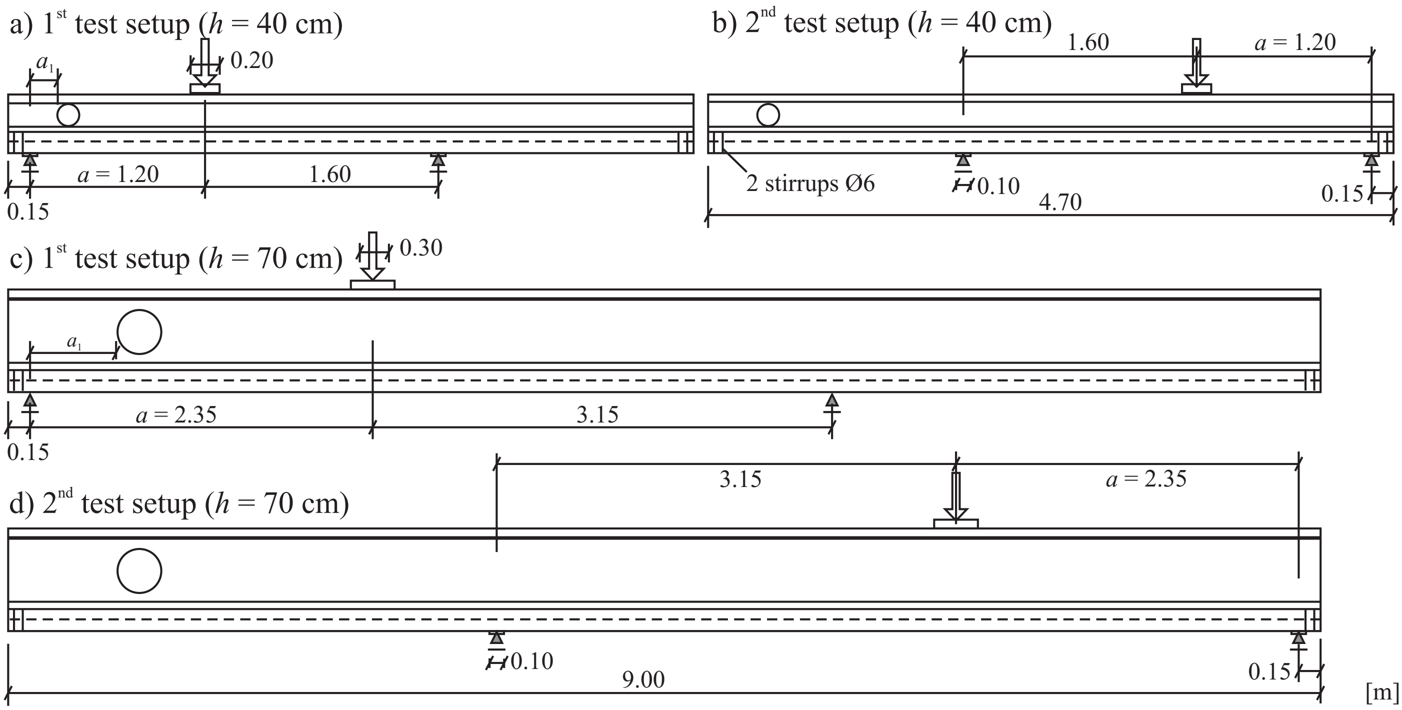

Figure 6: Test setup of the shear tests with different heights

Figure 7: Test setup of the shear tests with 70 cm (27.6 in) height (1st test setup)

Table 2: Parameters and main results of the shear tests

1	2	3	4	5	6	7		8		9	10	
test	mix	height	web		a_1/d	$f_{c,cube100}$ [MPa]		$f_{ct,fl}$ [MPa]		V_u	τ_u	
		[cm]	[cm]		[-]	release	shear test	release	shear test	[kN]	[MPa]	[psi]
T2a	MR	40	6	without opening	-	86.8	134	8.9	10.7	134	7.02	1018
T2b	MR	40	6		-		134		12.3	147	7.83	1136
T3a	M0	40	6		-	103.2	170	22.1	23.1	**		
T3b	M0	40	6		-		162		24.1	408	21.5	3119
T4a	M1	40	6		-	100.3	176	16.5	19.1	347	18.2	2646
T5a	M1	40	6		-	102.6	177	14.6	-	326	17.1	2487
T22b	M1	40	4		-	112.3	189	22.9	25.6	174	16.6	2405
T23b	M1	40	8		-	124.0	184	23.0	-	454*	17.9	2599
T24b	M1	70	4		-	102.8	178	23.8	29.6	316	12.8	1856
T25b	M1	70	6		-	103.2	169	20.9	23.7	465	12.6	1825
T26b	M0	70	6		-	110.4	172	26.4	31.5	521	14.1	2042
T6a	M1	40	6	single opening	0.5	89.0	142	18.8	22.8	266	14.0	2025
T6b	M1	40	6		1.0		155		23.0	226	11.9	1722
T7a	M1	40	6		1.5	112.8	192	16.9	26.0	234	12.5	1812
T7b	M1	40	6		2.0		183		24.7	232	12.2	1764
T12a	M0	40	6		1.0	123.6	181	24.6	30.0	323	17.0	2468
T22a	M1	40	4		1.0	112.3	187	22.9	31.9	210	13.7	1986
T23a	M1	40	8		1.0	124.0	178	23.0	25.2	361	14.2	2064
T24a	M1	70	4		0.5	102.8	179	23.8	29.6	319	12.9	1875
T25a	M1	70	6		1.0	103.2	172	20.9	24.9	344	9.3	1351
T26a	M0	70	6		1.0	110.4	178	26.4	36.8	368	9.9	1441

* Unexpected shear failure occurred on the second beam side

** Test abort due to bending failure

The compressive strengths in Table 2 were determined with 100 mm cubes (39.4 in) and the flexural strengths in 3-point bending tests on prisms 40x40x160 mm³ (1.57x1.57x6.3 in³). The ultimate shear forces V_u are listed in column 9 of Table 2. The high benefit of the fibers in shear capacity is obvious. More details regarding the fiber effect and further parameters are given in the SCC2010 proceedings[2]. To compare the results with different cross sections, the shear forces were normalized on the shear stress $\tau_u = V_u/(b_{web} \cdot d)$ in column 10. These shear stresses are plotted for the beams without openings against the web thickness as well as the height of the beams in the diagrams in Figure 8. While the web thickness seems to have a minor impact on the shear stresses, the beam height shows a significant effect. The shear stresses of the 70 cm (27.6 in) high cross sections were decreased down to about 70 % compared to the values of 40 cm (15.75 in) height. The ultimate shear stresses of beams with single openings have a larger scatter than the beams without openings (Figure 9). Nevertheless, the tendencies are similar. The evaluation related to the web thickness is less evident and the impact of the height seems diminished. It should be pointed out, that the number of tests is low so far and the results are not conclusive enough. Furthermore, T23b exceeded the calculated capacity but failed unexpected on the second side.

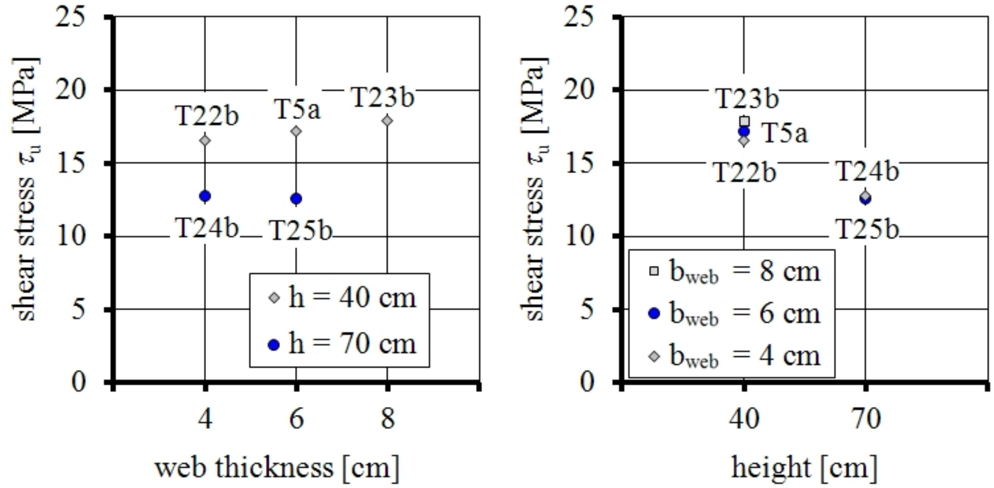

Figure 8: Influence of the web thickness and the beam height on the ultimate shear stresses of beams without openings

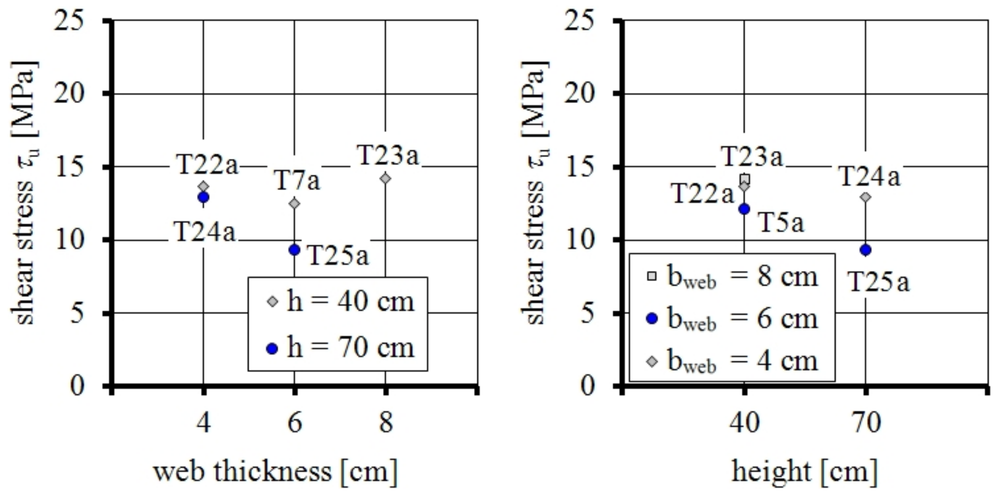

Figure 9: Influence of the web thickness and the beam height on the ultimate shear stresses of beams with single openings

In Figure 10, the crack patterns of beams with 40 cm (15.75 in) and 70 cm (27.6 in) height are compared. While the smaller beams showed a quasi-ductile behavior with continuous crack development, the beams with 70 cm height showed a more brittle failure. With the shear crack ignition the cracks developed over the full height of the web, especially in beams without openings. The number of cracks was reduced as well. The upper phote in Figure 10 shows a leading single crack of the higher beam. A reason for that can be traced in the fiber action along the crack and the development of the crack width. Contrary to the 40 cm beams, all fibers must be activated at the same time along the full crack length due to the sudden crack development. In beam T26 the fiber content was increased on 2.5 % p.v. to find out, if the minimum fiber amount in the 70 cm beams is higher than in the 40 cm beams. This would explain the changed cracking behavior. But the results were similar to beams with 0.9 %. The fibers have not been able to bridge the increased crack width adequately, neither with 0.9 % nor 2.5 % fiber volume. Therefore, the fiber length and diameter will be enlarged in the next step. Tests with additional shear reinforcement are scheduled as well. The coming results will be presented at the conference. A total of 18 shear tests on size effects are planned and 4 remaining tests will be conducted until the end of 2011.

The crack patterns with openings seem similar, but only the number of cracks. The crack spacing depends on the height. This becomes even more obvious comparing the crack patterns of beams with 2.5 % fibers. While the crack spacing in 40 cm beams ranged between 2 and 3 mm (!) resulting in very small crack widths about 0.05 mm, the higher beams showed a similar cracking behavior as T24b in Figure 10. Crack patterns of several beams were already published in recent conference proceedings[7-9].

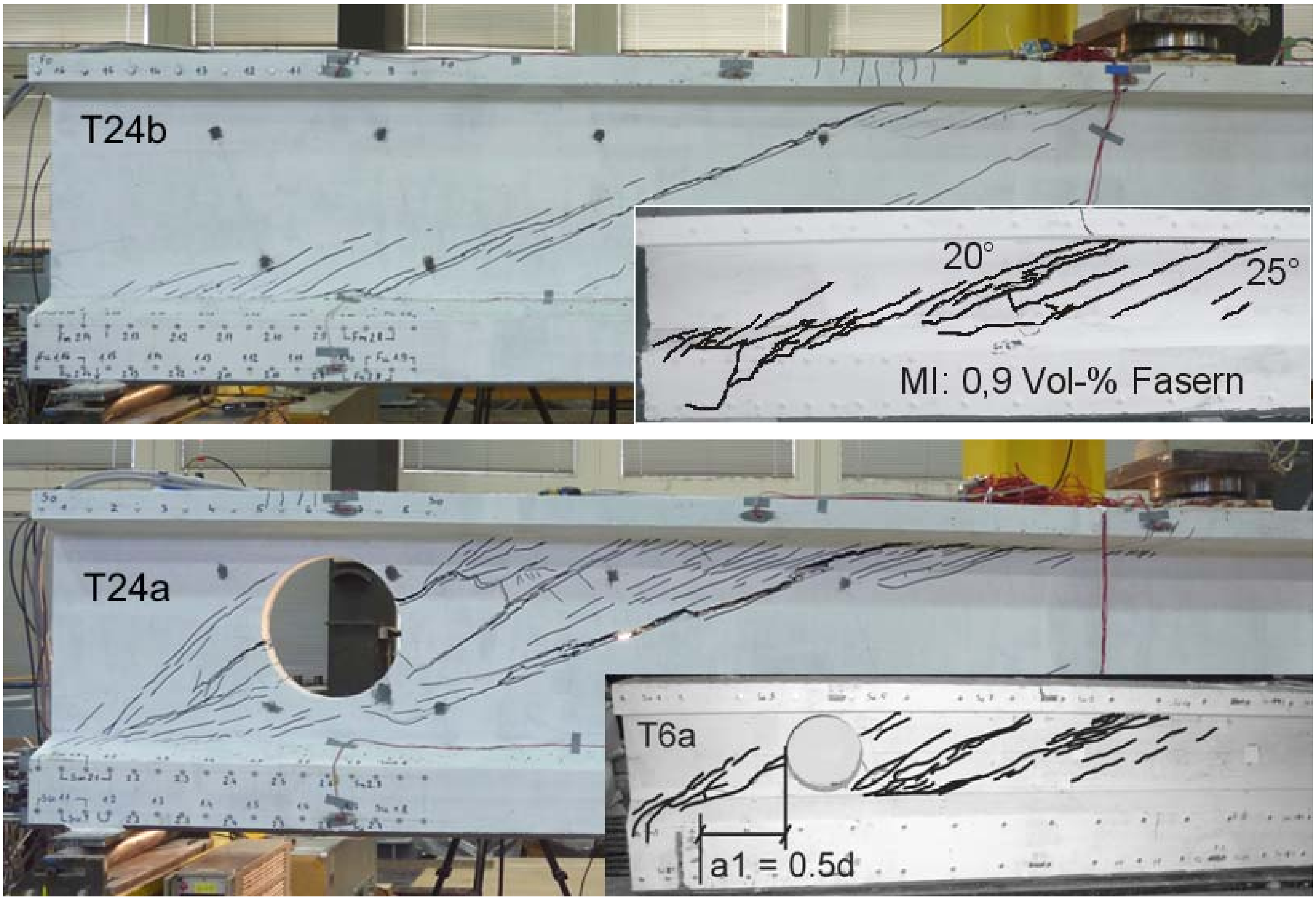

Figure 10: Crack pattern of 40 and 70 cm high beams with and without openings and 0.9 % p.v. fibers

ACKNOWLEDGEMENTS

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