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TRANSVERSE REINFORCEMENT EFFECTS ON THE LOADING BEHAVIOUR OF HIGH PERFORMANCES CONCRETE BEAMS

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Abstract: This work reports on an experimental investigation dealing with the effects of transverse reinforcement, in the form of stirrups, on the behaviour under load of high performances concrete (HPC) beams. The crack patterns and crack widths, the failure modes, the shear strengths and the ductility of HPC beams containing transverse stirrups were assessed and compared to those in ordinary concrete beams. The test results show that the use of transverse reinforcement in the form of stirrups restrains efficiently the inclined cracking and enhances the aggregate interlocking, known to be weaker in HPC without transverse reinforcement, and thus improves the shear strength of HPC beams. They also improve the contribution of the main longitudinal reinforcement to the shear strength through the dowel action. Finally, the transverse reinforcement improves appreciably the ductility of HPC beams at the ultimate state. In some cases, they changed the failure mode from a brittle shear to a markedly ductile flexure with an increased ultimate carrying capacity. The test results concerning the transverse reinforcement contribution to the shear strength are compared with those predicted by Eurocode 2. The comparison reveals a considerable overestimation of the contribution of the transverse reinforcement to the shear strength of HPC beams by the Eurocode 2. This reduces the safety margin required against shear failure, often catastrophic, and may even lead to unsafe shear design for high performances concrete.

1. INTRODUCTION

A large number of experimental and analytical investigations have been carried on the shear strength of reinforced concrete beams. However, despite the important research effort, there is still a lack of a simple analytically derived formula to predict accurately the shear strength of beams with transverse reinforcement. This is even more so for high performances concrete beams and empirical ordinary concrete beam models continue to be used in the absence of a clear understanding of the structural behaviour of high performances concrete despite its wide-spreading use today in all the fields of constructions. Indeed, the continuous search for improved mechanical properties and a better durability at the longer term to ensure a sustainable construction have made of high performances concrete the ideal material for the construction industry.

In most current design procedures for shear analysis, the shear strength of reinforced concrete beam is taken as the sum of the concrete contribution ($V_c = V_{cz} + V_a + V_d$) and the transverse reinforcement contribution (V_s) as in Figure 1. The concrete contribution is considered to be the shear of a beam without transverse reinforcement [1, 2]. The transverse reinforcement contribution to shear strength is determined by the Ritter-Morsch truss model, which is based on the assumption that the shear capacity is reached when the transverse reinforcement yields, corresponding to a shear force of:

$$V_s = \frac{A_v.f_{vy}.d}{s} \qquad (1)$$

Or in terms of stress:

$$t = \frac{A_v.f_{vy}}{b.s} = \rho_v f_{vy} \qquad (2)$$

Where A_v, s, and f_{vy} are the area, the spacing, and the yield strength of the transverse reinforcement, respectively.

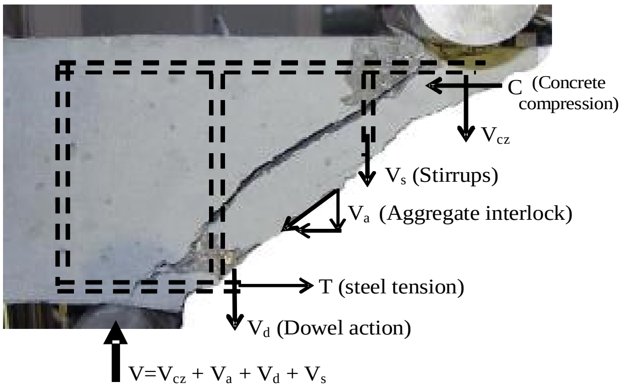


Figure 1: Mechanism of shear forces in a beam with transverse reinforcement

The transverse reinforcement is supposed to enter into action from the start of the development of a diagonal or inclined crack [3, 4]. In fact, the transverse reinforcement starts to resist some shear stresses even before inclined cracking appears [5]. After the formation of diagonal cracking, most of the shear force is resisted by the transverse reinforcement [6].

According to a number of researchers [7-10], the transverse reinforcement performs a multiple functions to improve the shear behaviour of reinforced concrete beams made of high performances concrete, as it has been found for beams with normal strength concrete [11-13]. Indeed, transverse reinforcement restrains the growth of inclined or diagonal cracking and confines concrete around the main longitudinal reinforcement, preventing the two composite materials from splitting longitudinally and improving the dowel action of the tension reinforcement. The clamping action of the transverse stirrups helps in arresting the progress of any predominant diagonal crack and hence avoids the triggering of any premature failure [14] and consequently increases the strength capacity and improves the ductility of the beam [15].

Test results of high performances concrete with minimum amount of shear reinforcement indicated that this minimum quantity was enough to prevent brittle shear failures through transgranular cracking due to poor contribution from aggregate interlocking [16, 2]. This suggest that in high performances concrete, transverse reinforcements are more useful in stitching the inclined cracking, improving the post cracking behaviour of the beams, particularly the post-peak deformation characteristics and the load capacity [17]. Such improvement is believed to be due to the better quality of the bond between concrete and the reinforcing steel. It should be noted, however, that due to the relatively higher tensile strength of high performances concrete, a higher cracking shear force is expected and hence, this would require a relatively larger amount of minimum transverse reinforcement than in normal strength concrete to take on the load afterwards [18].

Studies from the litterature have reported that [19-21] the transverse reinforcement contribution to the shear strength of large reinforced concrete beams is considerably lower than the strength predicted by the ACI code provisions. In this sense, it is worth noting that the major codes in use throughout the world take into consideration the contribution of the tranverse reinforcement as being proportional to $\rho_v f_{vy}$ in a manner similar to the that given in Eurocode 2 below:

$$V = \frac{0.0525}{\gamma_c}(f_c^{'})^{2/3}(2.5d/a)(1.6-d).(1.2+40\rho_l).bd+0.9\rho_v f_{vy} bd \qquad a/d < 2.5 \qquad (3)$$

$$V = \frac{0.0525}{\gamma_c}(f_c^{'})^{2/3}.(1.6-d).(1.2+40\rho_l).bd+0.9\rho_v f_{vy} bd \qquad a/d \geq 2.5 \qquad (4)$$

Initially, the models given in these universal codes were developed for normal concrete; their extension to higher performances concrete is recommended in the latest versions of these codes. Thus, in the absence of sufficient test data, the application of these models to reinforced concrete beams with higher compressive strengths ($f_c^{'}$ >40MPa) needs to be carefully examined.

This study treats the influence of the transverse reinforcement on the crack patterns, the ultimate carrying capacity and the ductility of beams made of high performances concrete and for beams made of normal strength concrete for comparison purposes. The test results for the contribution of shear reinforcement to the shear strength are compared with the theoretical predictions from Eurocode 2, the latest design tool to make its way into the design practice. The shear reinforcement effects are considered in conjunction with other parameters such as the compressive strength of concrete f'_c, the shear-span to depth ratio a/d and the main tension reinforcement percentage ρ_l.

2. TEST PROGRAM

Twenty six beams were tested to failure in this study. The 26 reinforced concrete beams were divided into three series:

- The first series of beams were designed to have a concrete strength of 44 MPa,
- The second series of beams were designed to have a concrete strength of 65 MPa,
- The third series of beams were designed to have a concrete strength of 86 MPa.

Each series was divided into two groups: group N beams without transverse reinforcement and group W with transverse reinforcement. The beams in group W (44W, 65W, and 86W) had the same transverse reinforcement consisting of 6 mm diameter stirrups spaced at 90 mm.

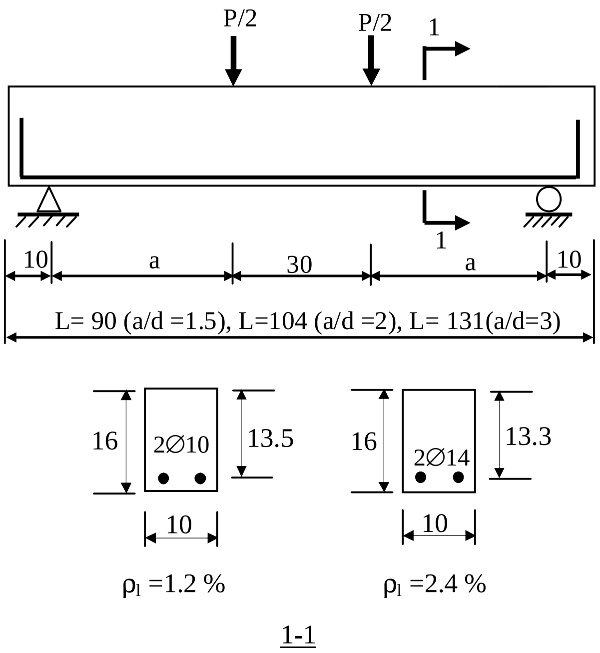
In groups W and N beams of the first series (44MPa) and those of the third series (86MPa), three shear-span/depth ratios were considered for the testing conditions (a/d=1.5; 2.0 and 3.0). The second series (65 MPa) of beams had only one shear-span/depth ratio (a/d = 2.0).

Each group was divided into two sub-groups: specimens of sub-group A were reinforced with 2∅10 as main longitudinal bars giving a longitudinal steel ratio ρ_l of approximately 1.2%, while those in sub-group B were reinforced with 2∅14 as main longitudinal bars giving a steel ratio of approximately 2.4%.

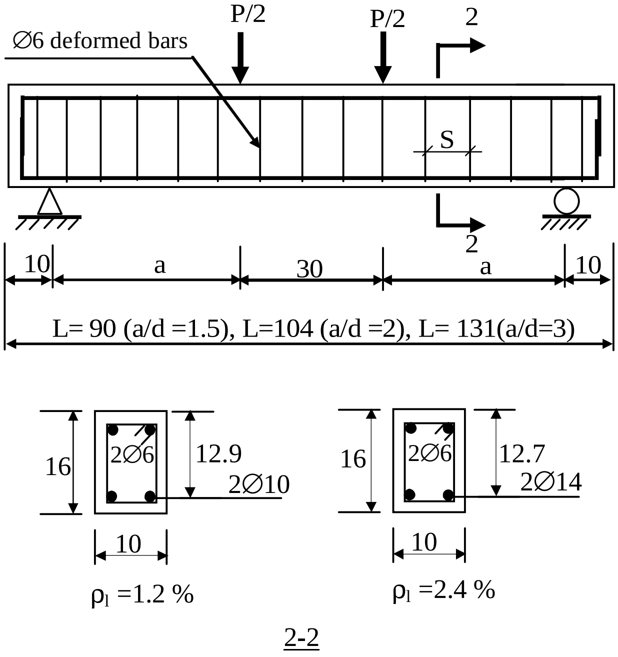
In the second series of beams (65MPa), all the beams specimens were reinforced with 2∅10 as main longitudinal bars (ρ_l =1.2 %).

The notation of the specimens reflects the main testing parameters. For example, in A86-2N, ‘A’ stands for the sub-group having main longitudinal steel ratio ρ_l equals 1.2%, the number ‘86’ is the target cylinder compressive strength of concrete in MPa, the number after the hyphen gives the a/d ratio, and ‘N’ designates beams without transverse reinforcement. Figure 2 and Table 1 show the details of the three series of beams, which were tested with different a/d values.

The load was applied using a 250 kN servo-controlled hydraulic jack. The specimens were tested under monotonic loading. One LVDT was attached to the bottom surface at mid-span of the test specimen to measure the mid-span displacement of the beam. A Video Gom-Aramis system was used to measure crack widths and to monitor the development of the diagonal cracking as the load is increased.



a) Group N (44MPa, 65MPa and 86MPa)



b) Group W (44 MPa, 65 MPa and 86MPa)
all dimensions are in cm

Figure 2: Dimensions and reinforcement of the test beams of N and W Groups

Table 1: Specifications of test specimens and material properties

Beams	f'_c MPa	f_t MPa	d mm	a/d	Long. steel	Transv. Reinf		
					ρ_l %	S^* mm	$\varnothing_t$ mm	ρ_t^{**} %
A44-1.5N	44	3.37	135	1.5	1.2	--	--	--
B44-1.5N			133	1.5	2.4	--	--	--
A44-2N			135	2.0	1.2	--	--	--
B44-2N			133	2.0	2.4	--	--	--
A44-3N			135	3.0	1.2	--	--	--
B44-3N			133	2.0	2.4	--	--	--
A44-1.5W			129	1.5	1.2	90	∅6	0.63
B44-1.5W			127	1.5	2.4	90	∅6	0.63
A44-2W			129	2.0	1.2	90	∅6	0.63
B44-2W			127	2.0	2.4	90	∅6	0.63
A44-3W			129	3.0	1.2	90	∅6	0.63
B44-3W			127	3.0	2.4	90	∅6	0.63
A65-2N	65	3.74	135	2.0	1.2	--	--	--
A65-2W			129	2.0	1.2	90	∅6	0.63
A86-1.5N	86	4.50	135	1.5	1.2	--	--	--
B86-1.5N			133	1.5	2.4	--	--	--
A86-2N			135	2.0	1.2	--	--	--
B86-2N			133	2.0	2,4	--	--	--
A86-3N			135	3.0	1.2	--	--	--
B86-3N			133	3.0	2.4	--	--	--
A86-1.5W			129	1.5	1.2	90	∅6	0.63
B86-1.5W			127	1.5	2.4	90	∅6	0.63
A86-2W			129	2.0	1.2	90	∅6	0.63
B86-2W			127	2.0	2.4	90	∅6	0.63
A86-3W			129	3.0	1.2	90	∅6	0.63
B86-3W			127	3.0	2.4	90	∅6	0.63

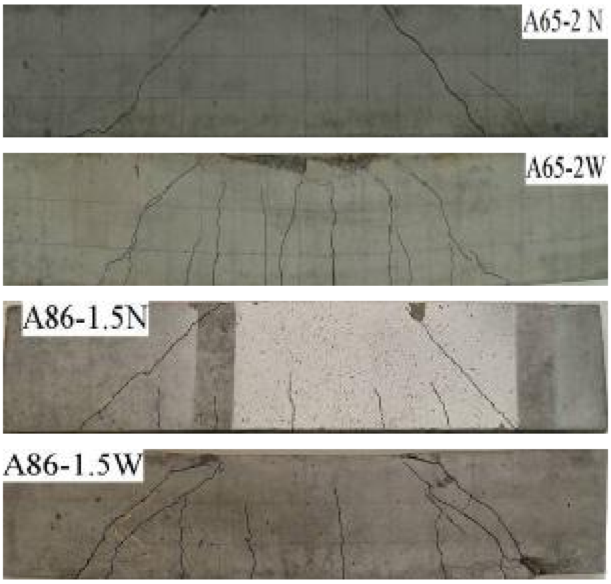
[*] Stirrups spacing, [**] Transverse reinforcement ratio

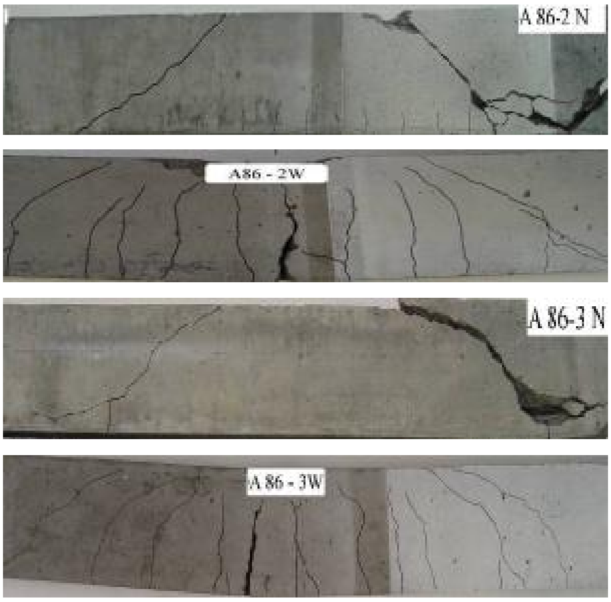
3. TEST RESULTS AND DISCUSSION

The primary objective in this paper is to study the contribution of transverse reinforcement in resisting shear in high performances concrete and compare it to that in or normal strength concrete. This evaluation is assessed for reinforced concrete beams having different a/d ratios, different compressive strengths of concrete and with different quantities of longitudinal steel.

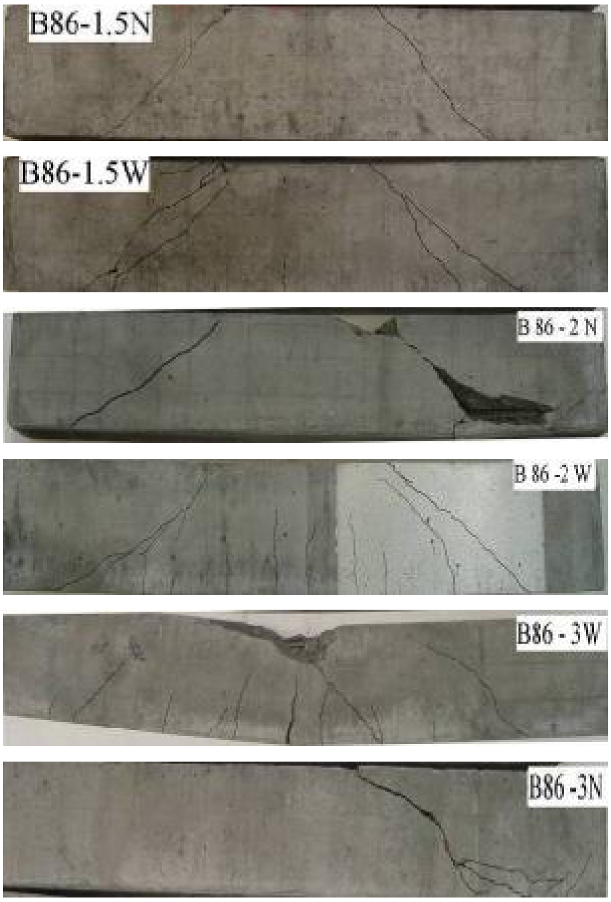
3.1. Crack pattern, crack width and failure modes

The crack patterns observed at failure are shown in Figure 3 for all the tested beams. All the beams of group N, with no transverse reinforcement (44N, 65N and 86N), failed in shear in a brittle manner with the formation of a single significant diagonal crack symmetrically on both sides of the shear spans, resulting in the splitting of the beam specimens diagonally along them. The diagonal cracks have often resulted in the destruction of the bond between the longitudinal reinforcement and concrete towards the adjacent support. The type of diagonal shear failure was identical for the two types of concrete, with relatively more concrete destruction for the case of high performances concrete. Very few flexural cracking developed before failure of all the beams without transverse reinforcement and the shear behaviour was the dominant one up to causing the rupture of all the beam specimens. The diagonal cracks were very wide prior to failure and clearly needed steel restraint. They were very straight, joining the support and loading points for the case of shorter shear spans (a/d = 1.5 and 2.0) and split the beams clearly along these critical lines as in beams A86-1.5N, B86-1.5N, A65-2N, B86-2N of Figure 3. For higher shear spans (a/d = 3), these diagonal cracks formed in two branches. The first branch, being a slightly inclined shear crack, is identical in height as a flexural crack. The second branch extends from the tip of the first branch at a relatively more inclined angle towards the compression zone at the loading point, resulting often in splitting of concrete when not restrained by transverse steel [2] as in Figure 3, A86-3N and B86-3N.





(a): ρ_l =1.2%



(b): ρ_l =2.4%

Figure 3: Typical crack patterns at failure for the tested beams

Generally, specimens of group W, with transverse reinforcement, showed the same development of cracks as the specimens of group N, without transverse reinforcement, until the formation of diagonal cracking with the difference that, with the presence of transverse reinforcement, diagonal cracking are relatively narrower at formation and more than one inclined crack develop as the load is increased.

Beams with shorter shear spans containing shear stirrups also had diagonal cracks straight covering almost the full depth from support to loading point as in Figure 3, A86-1.5W and B86-1.5W. However, in these beams with transverse stirrups, diagonal cracking developed narrower and did not widen so much up to failure. They also developed other diagonal cracks parallel to the first ones as the load was increased, defining clearly inclined concrete struts as in beams A86-1.5W, B86-1.5W and B86-2W. The transverse steel was so efficient in restraining diagonal shear cracking that failure changed from a splitting one in beams without shear reinforcement (beams of group N in Figure 3) into a crushing of concrete at the loading or support points after a diagonal crack penetrated into these highly stressed areas as in beams A86-1.5W, B86-1.5W and B86-2W.

For the case of beams with transverse stirrup and having relatively higher shear spans (a/d=3), diagonal cracking also involved two branches as in the corresponding beams without transverse steel with the difference that these two-branch diagonal cracks stayed narrower and did not cause failure; they were effectively retrained by transverse stirrups which are brought into action after the formation of the second branch of a diagonal crack, changing the behaviour from a shear one into a flexural one with more flexural cracks extending upwards and widening, pushing the neutral axis towards the compression zone and leading to flexural failure through crushing at the compression face as in beams A65-2W, A86-2W, B86-3W. In some cases, flexural tension failure occurred simultaneously as the concrete crushed at the compression face (A86-2W, A86-3W).

In general, beams with transverse reinforcement did not show any crack along the longitudinal reinforcement even at failure as shown in Figure 3, translating the effectiveness of the clamping action of the transverse stirrups, preserving the bond between the longitudinal reinforcement and concrete and improving the dowel action. The crack patterns in Figure 3 show that, with the presence of transverse reinforcement, the number of cracks increased with the increase in the compressive strengths of concrete from 44 MPa to 86 MPa, indicating an enhanced redistribution of internal forces in the beams made of high performances concrete (65 MPa and 86 MPa). This could be explained by the better bond between the reinforcing steel and concrete in the case of high performances concrete and translates a relatively better efficiency of the reinforcing steel in general when used in composition with this relatively new concrete material. For higher shear spans, the presence of the transverse reinforcement has changed the type of rupture from a typical shear failure (diagonal splitting) when no transverse steel was used as in group N beams to a typical flexural failure when transverse stirrups were used as in group W beams. For beams with shorter shear spans, the presence of the transverse stirrups has changed the typical shear failure through diagonal splitting into a shear-compression failure due to the efficient restraining action of the transverse reinforcement.

The maximum width of the diagonal cracks was always located near midheight of the section and was measured during the tests, using Video Gom-Aramis system [2]. Figure 4 presents the measured crack widths of all the tested beams; the 0.3 mm crack width limit for serviceability is indicated on Figure 4. It can be clearly seen that this serviceability limit is reached at a higher load when transverse reinforcement is used for both high performances concrete and for ordinary concrete. However, for high performances concrete (concrete of 86 MPa), this limit was practically reached at ultimate if not at all and the beam specimens stayed serviceable up to just prior to failure. From this, it can be deduced that, by comparison to ordinary concrete, the service load of high performances concrete with transverse reinforcement could be relatively higher. When taking this service load as equal to 70% of the ultimate load, the width of the major diagonal shear crack for the different beams is shown in Table 2. In general, at this load, the serviceability limite state of cracking is not reached when transverse reinforcement is used, particularly for high performances concrete where 50% of the 0.3mm serviceability crack width limit is reached only. This suggests that, high performance concrete, when reinforced with transverse steel, could stay serviceable up to the ultimate state. This is attributed to the better quality of the bonding between concrete and the reinforcing steel in the case of high performances concrete.

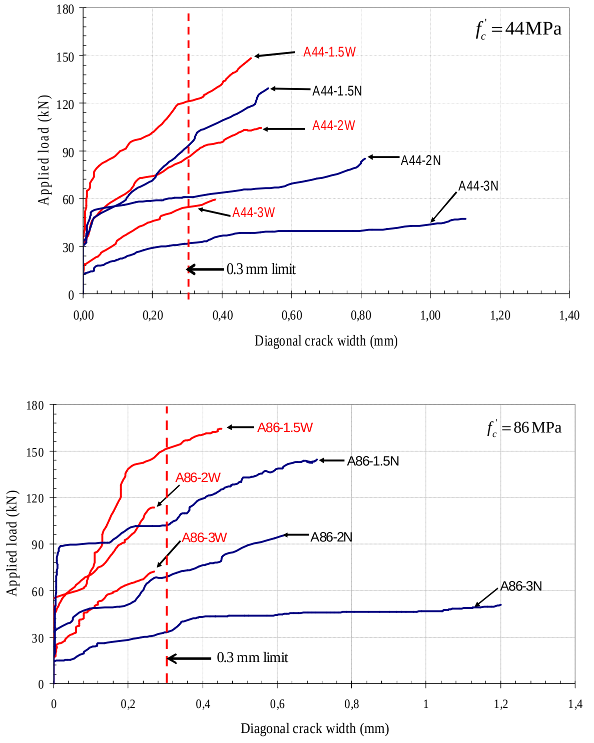


Figure 4: Diagonal crack width of the beam specimens (ρ_l =1.2 %)

Table 2: Measured widths of diagonal cracks at service and at ultimate loads

Beam	Crack width at service load	Crack width at ultimate load
	ρ_l = 1.2 %	
A44-1.5N	0.28	0.53
A44-2N	0.32	0.81
A44-3N	0.36	1.10
A86-1.5N	0.22	0.71
A86-2N	0.27	0.66
A86-3N	0.33	1.20
A44-1.5W	0.21	0.48
A44-2W	0.17	0.51
A44-3W	0.15	0.38
A86-1.5W	0.17	0.43
A86-2W	0.14	0.27
A86-3W	0.11	0.25
	ρ_l = 2.4 %	
B44-1.5N	0.34	0.69
B44-2N	0.47	0.90
B44-3N	0.39	1.05
B86-1.5N	--	--
B86-2N	0.42	0.74
B86-3N	0.46	0.84
B44-1.5W	0.26	0.46
B44-2W	0.19	0.75
B44-3W	0.17	0.40
B86-1.5W	0.22	0.43
B86-2W	0.16	0.32
B86-3W	0.10	0.20

3.2. Contribution of the transverse reinforcement to the shear strength

Figure 5 and Table 3 show the ultimate carrying capacity for the beams with and without transverse reinforcement. Figure 6 illustrates the ratios of ultimate loads: P_{uW}/P_{uN} (ultimate load of beams with transverse reinforcement/ultimate load of beams without transverse reinforcement).

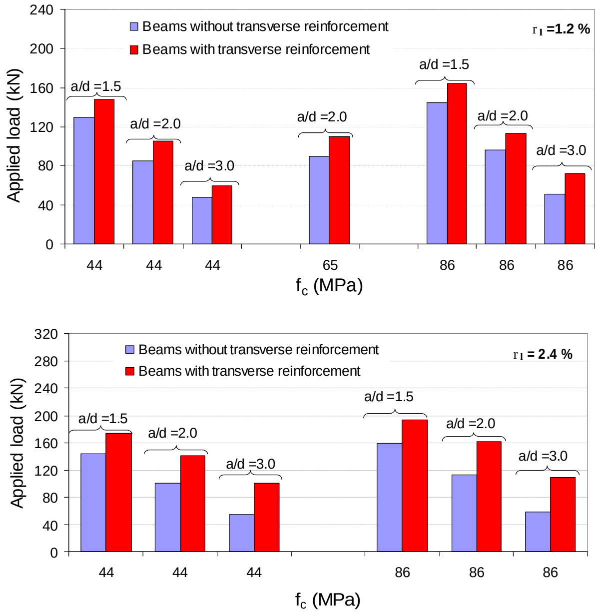


Figure 5: Ultimate strength of beams with and without transverse reinforcement

Table 3. Ultimate loads and failure modes of the tested beams

Beams	P_{uN} (kN)	P_{uW} (kN)	P_{uW}/P_{uN}	Mode of failure
A44-1.5N	129.4	--	--	S (DS)
B44-1.5N	143.6		--	S (DS)
A44-2N	85.1	--	--	S (DS)
B44-2N	100.5	--	--	S (DS)
A44-3N	47.3	--	--	S (DS)
B44-3N	55		--	S (DS)
A44-1.5W	--	148.2	1.15	SC
B44-1.5W	--	173.7	1.21	SC
A44-2W	--	104.5	1.23	F
B44-2W	--	140.9	1.40	SC
A44-3W	--	59.1	1.25	F
B44-3W	--	100.9	1.83	F
A65-2N	89.5	--	--	SC
A65-2W	--	109.2	1.22	F
A86-1.5N	144.3	--	--	S (DS)
B86-1.5N	158.3	--	--	S (DS)
A86-2N	95.5	--	--	S (DS)
B86-2N	113.6	--	--	S (DS)
A86-3N	50.7	--	--	S (DS)
B86-3N	59.03	--	--	S (DS)
A86-1.5W	--	164.2	1.14	SC
B86-1.5W	--	192.9	1.22	SC
A86-2W	--	113.2	1.19	F
B86-2W	--	161.6	1.42	SC
A86-3W	--	72.5	1.43	F
B86-3W	--	109.8	1.86	F

SC: Shear-compression, S(DS): Shear (Diagonal Splitting), F: Flexure

The ultimate loads of beams with transverse reinforcement having 1.2 % of longitudinal tensile steel were greater than those beams without transverse reinforcement; an average increase of 25 % for beams made of high performances concrete. For comparison purposes, 20 % increase was recorded for the corresponding beams made of normal strength concrete. The improvement in the strength capacity was even greater for beams containing 2.4% of longitudinal reinforcement; an average increase of 50% is recorded for high performances concrete beams as shown in Figure 6. For example, the ratios P_{uW}/P_{uN} of beams having a/d of 1.5, 2.0 and 3.0 were 1.22, 1.42 and 1.86, respectively for high performances concrete (Figure 6). This increase could be explained by the fact that the effectiveness of the longitudinal reinforcement in contributing to shear strength improvement is higher in the presence of transverse reinforcement going around them and clamping them resulting in highly confined concrete added to the better quality of the bond between concrete and the reinforcing steel. In general, the ratio of the ultimate loads (P_{uW}/P_{uN}) increases as the shear-span to depth ratio (a/d) increases for beams made of high performances concrete; that is as the behaviour of the loaded beams changes from an ‘arch action’ for the smaller a/d values to that of a ‘beam action’ for the higher a/d values (Table 3 and Figure 6).

The same trend is exhibited by those beams made of normal strength concrete with the difference that the rate of increase is lesser in the latter type of concrete. The relatively better effectiveness of the transverse steel, and indeed of the longitudinal steel, when composed with high performances concrete is justified by the better quality liaison between the two distinct materials after the hardening of concrete. Internal forces are better transmitted from concrete to steel in the case of high performances concrete than in ordinary concrete. Therefore, the effectiveness of transverse reinforcement in improving the shear strengths of concrete beams is better in high performances concrete. Such effectiveness increases as the a/d value increase, that is as the behaviour changes from an ‘arch action’ for smaller a/d values where the shear cracks are more inclined to the vertical hence almost parallel to the vertical stirrups to a ‘beam action’ for higher values of a/d where the shear crack are less inclined to the vertical, hence better restrained by the vertical stirrups. In this sense, previous works [22, 23] have shown that a reinforcing bar is more effective in restraining and arresting a crack when it crosses the crack perpendicularly. It can be conclude from this that, for smaller a/d values, the stirrups may not develop their full yield capacity as suggested in an earlier work [24]. This analysis is supported by Haddadin et al [25] who reported that the effectiveness of transverse reinforcement in increasing shear strength is greater in the case of flexure-shear failure occurring in general in beams with higher a/d values than in shear-compression failure which occurs typically in beams having smaller a/d values and containing transverse reinforcement as recorded in the present tests (beams A86-1.5W, B86-1.5W). From this analysis, it can be deduced that any shear design approach based on the yielding of the transverse reinforcement such as the Ritter-Morsch truss analogy may not be safe for beams with smaller shear-span to depth ratios (a/d) since failure will occur before the yielding of the transverse stirrups; the transverse reinforcement contribution to the shear strength would be overestimated when based on the yielding hypothesis of this transverse reinforcing steel. The present tests showed, however, that the contribution of the transverse reinforcement to the shear strength, particularly that of high performances concrete, is greatly dependent on the quantity of the longitudinal reinforcement as shown in Figure 6.

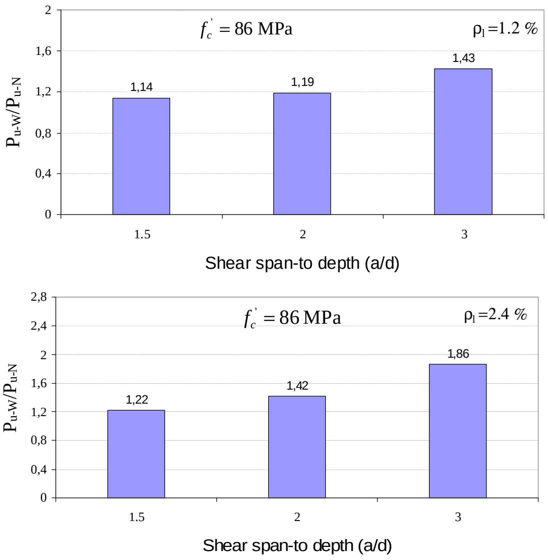


Figure 6: Transverse reinforcement contribution as a function of the shear-span/depth ratio

3.3. Effects of the transverse reinforcement on the ductility

The ductility was appreciated in the present tests through the deflection measurements up to just prior to ultimate. Figure 7 shows the effects of transverse reinforcement on the mid-span deflections for beams made of high performances concrete. For comparison purposes, the effects of transverse reinforcement on the deflections of the corresponding beams made of normal strength concrete are also shown in the same Figures. The examination of these Figures shows that the presence of transverse reinforcement has induced a long plastic range after the peak strength before ultimate failure occurred for both types of concrete (group W beams). When no transverse reinforcement was present (group N beams), failure was very abrupt and occurred just on reaching the peak strength at a load less than that where transverse reinforcement was used as argued previously. When comparing the plastic ranges of high performances concrete beams with those of normal strength concrete beams, it can be clearly seen from Figures 7 that those of high performances concrete were relatively longer, particularly for higher values of shear-span to depth ratios (a/d). When the beam exhibited a typical flexural behavior at ultimate such as in beams with higher a/d ratios, the deflection reached 19 mm prior to ultimate, representing L/70 in beam A86-3W and 23.7 mm prior to ultimate, representing L/55 in beam B86-3W. For the sake of comparison, the deflections of the corresponding normal concrete beams reached 16.5 mm, representing L/80 in beam A44-3W, and 13 mm, representing L/100 in beam B44-3W. This trend is also exhibited by the other beams with smaller a/d ratios (see Figure 7) though their behavior was rather a shear one and the deflections were relatively lesser prior to ultimate.

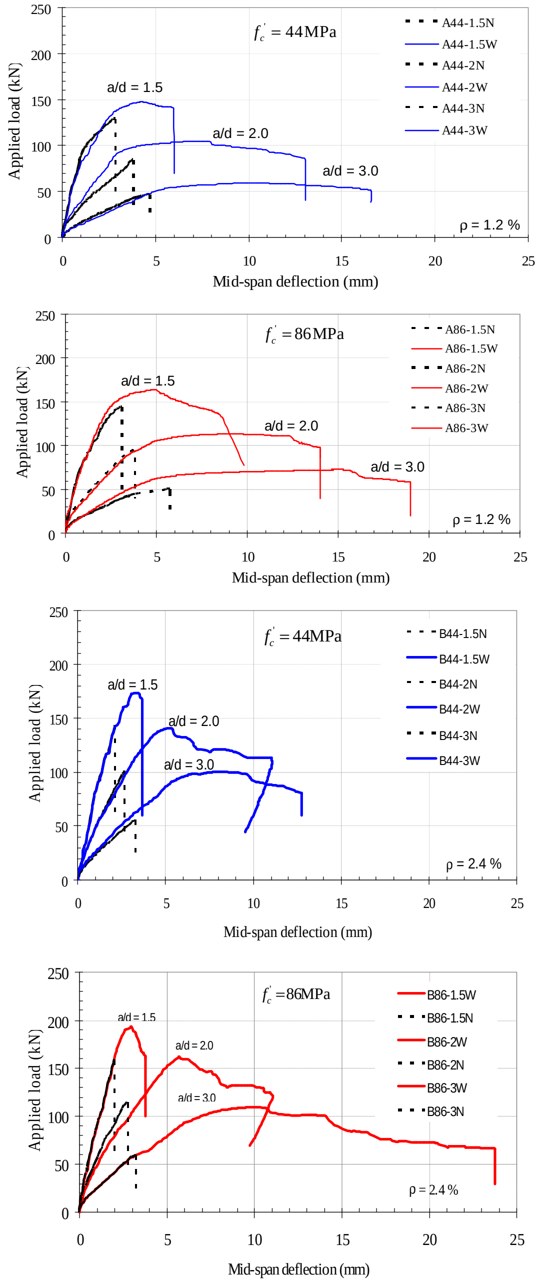


Figure 7: Mid-span deflection against applied load for beams with and without stirrups

It can be concluded from the test results presented in Figures 7 that, with the presence of transverse reinforcement, high performances concrete becomes more ductile, even more than ordinary concrete. This could, once again, be explained by the better steel-concrete composition with perfect bonding between the two materials minimizing greatly the risk of any slipping movement of one material in relation to the other. This would ensure a better transmission of internal forces from one material to the other and hence a better redistribution of internal forces.

In terms of ductility defined as deflection at ultimate over deflection at yield point (δ_u/δ_y), for beams made of high performances concrete, it varied from 3.0 to 5.0 (Table 4). The deflection and ductility results clearly illustrate that, though high performances concrete is a brittle material when not reinforced, it becomes a relatively more ductile material than ordianry concrete when adequately reinforced with a spreaded transverse reinforcement pattern (Figure 8, Table 4).

Table 4: Ductility factor for the tested beams containing transverse reinforcement

Beams	$\delta_{y\text{-}w}$ (mm)	$\delta_{u\text{-}w}$ (mm)	f = $\delta_{u\text{-}w}/\delta_{y\text{-}w}$
A44-1.5W	2.61	5.95	2.28
B44-1.5W	2.59	3.68	1.42
A44-2W	3.23	12.95	4.03
B44-2W	3.52	11.01	3.13
A44-3W	3.90	16.54	4.19
B44-3W	4.30	12.90	3.00
A65-2W	3.22	13.35	4.15
A86-1.5W	2.55	8.45	3.31
B86-1.5W	2.16	3.77	1.75
A86-2W	3.10	14.03	4.53
B86-2W	3.32	11.05	3.34
A86-3W	3.80	19.00	5.00
B86-3W	5.94	23.73	3.99

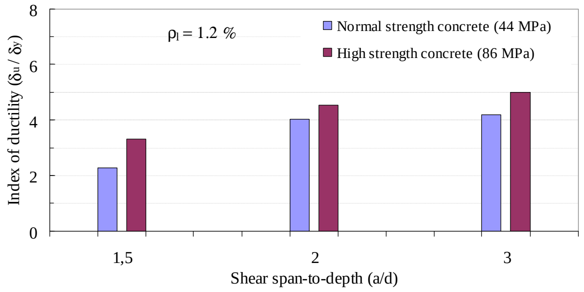


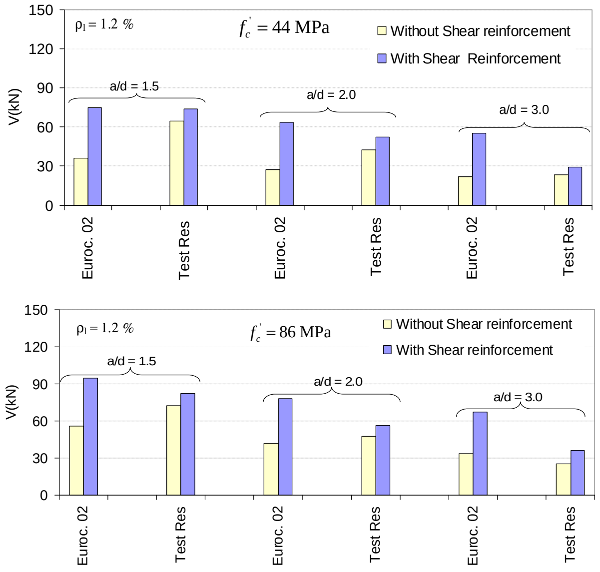
Figure 8: Effect of the shear span-to-depth ratio on the ductility factor

4. COMPARISONS OF TEST RESULTS WITH CURRENT DESIGN CODES

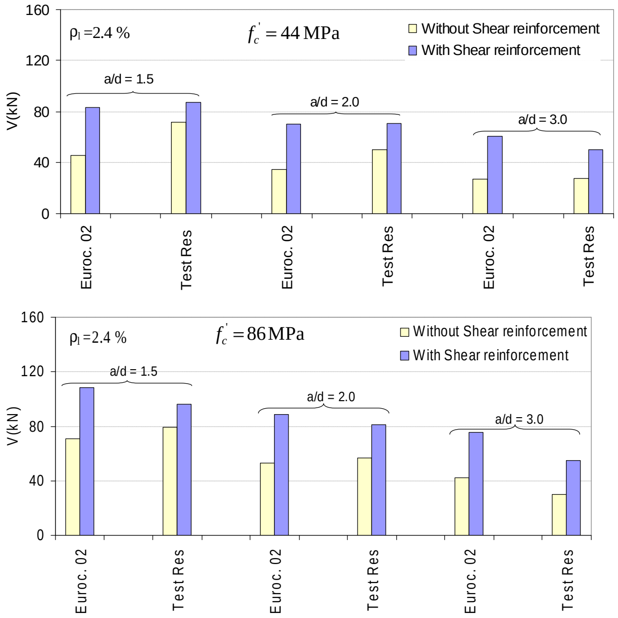
Table 5 gives the shear strength contribution provided by the transverse reinforcement in the tested beams. This is calculated as the difference between the shear strength of a beam containing transverse reinforcement and that of a corresponding one without transverse reinforcement. For comparison purposes, the model used in Eurocode 2 is used to compute the shear strength contribution provided by the transverse reinforcement, after having taken the safety factor considered by the considered model as equal to one for ease of comparison with the test results. The Eurocode 2 model predictions are also shown in Table 5. The test results and the model predictions are represented in histograms as shown in Figure 9. It can be clearly seen from Figure 9 that the theoretical predictions of Eurocode 2 overestimate the transverse reinforcement contribution to the shear strength. In this sense, it is wise to note that even the beams, which failed in flexure did develop distinctive and wide diagonal cracking as A65-2W, A86-2W, B86-3W of Figure 3 and were not very far from a shear failure. Indeed, according to most major codes, wide open diagonal cracking is in itself a sign of failure. The ultimate loads of these beams are in effect considered as approximately the ultimate shear capacity in this argumentation. In general, the shear strength for all the tested beams is not much increased by the presence of transverse reinforcement. Their contributions to the shear strength of the beams in the present tests varied from 14% to 86%. The higher transverse steel contribution to shear occurred in beam with higher a/d ratios where the diagonal cracks are less inclined to the vertical and hence are efficiently restrained by the transverse vertical stirrups. The higher transverse steel shear contribution occurred in beam B86-3W made of high performance concrete and having 2.4% of main longitudinal steel, reaching 86%. As a comparison, when 1.2% of longitudinal reinforcement was used as in sub-group A beams, the average contribution was a little over 25% for high performances concrete beams and a little over 20% for normal concrete beams. This transverse reinforcement contribution to shear strength increased when higher amount of longitudinal reinforcement was used as in sub-group B beams (ρ_l =2.4%) where the average increase was 50% for high performances concrete beams and lesser for normal strength concrete ones.

Table 5: Transverse reinforcement contribution: comparison of test results with Eurocode 2

Beam	V_u test (kN)	V_C test (kN)	V_S test (kN)	V_S EC2 (kN)	$V_{S\ test}/V_{S\ EC2}$
			ρ_l = 1.2 %		
A44-1.5W	74,1	64,7	9,4	36,4	0,26
A44-2W	52,3	42,6	9,7	36,4	0,27
A44-3W	29,6	23,7	5,9	36,4	0,16
A86-1.5W	82,1	72,1	10,0	36,4	0,27
A86-2W	56,7	47,8	8,9	36,4	0,24
A86-3W	36,3	25,4	10,9	36,4	0,30
average					0,25
			ρ_l = 2.4 %		
B44-1.5W	86,9	71,8	15,1	35,8	0,42
B44-2W	70,5	50,3	20,2	35,8	0,56
B44-3W	50,5	27,5	23,0	35,8	0,64
B86-1.5W	96,5	79,2	17,3	35,8	0,48
B86-2W	80,8	56,8	24,0	35,8	0,67
B86-3W	54,9	29,5	25,4	35,8	0,71
average					0,58
Average for 12 beams					0,42



(a) Beams with ρ_l = 1.2 %



(b) Beams with ρ_l = 2.4 %

Figure 9: Transverse reinforcement contribution to the shear strength - Comparison of test results with Eurocode 2

In contrast, the theoretical transverse reinforcement contributions to the shear strength predicted by the Eurocode 2 model are independent of the shear-span to depth ratio and independent of the amount of main longitudinal reinforcement, two factors found to be very influencing on the efficiency of the transverse stirrups in contributing to the shear strength of high performances concrete and to a lesser extent to that of normal strength concrete. The Eurocode 2 Shear model seems to be based on the yielding of the transverse reinforcing steel, whatever is the span/depth ratio, and hence whatever is the angle between the stirrups and the diagonal crack, as clearly expressed by equations (3) and (4). The present tests show clearly that for smaller a/d values, the vertical stirrups do not yield since almost parallel to the diagonal cracks and shear failure is by a diagonal splitting and crushing of concrete within the inclined concrete strut. The second reason for this overestimation of the transverse steel shear contribution is related to the insignificant shear transfer from concrete to the transverse reinforcement after diagonal cracking has occurred because of inefficient transverse reinforcement patterns. Hence, any design approach based on a systematic yielding of transverse reinforcement will necessarily overestimate the contribution of shear reinforcement to the shear strength. In this sense, the Eurocode 2 model predicts transverse reinforcement contributions to shear strengths that are on average more than twice the real ones as obtained in the present tests, particularly where transverse stirrups are less efficient such as in smaller shear-span/depth ratios and in the presence of smaller amount of longitudinal reinforcement. When more main longitudinal steel is used, the confining action of the transverse stirrups tends to be more efficient in restraining diagonal cracking particularly with higher shear-span/depth ratios as in beam B86-3W and as a result the transverse reinforcement becomes more strained. In such a case, the theoretical predictions of the transverse reinforcement contribution to the shear strength, based on their yielding, relatively approaches the experimental ones; a ratio 0.71 was obtained for V_{Stest}/V_{SEC2} for beam B86-3W with a/d of 3,0 as in Table 5. For beams with smaller shear-span/depth ratios such as beam A86-1.5W, the Eurocode 2 predictions are overestimated, with V_{Stest}/V_{SEC2} around 0.25, expressing the need for more refinement of this design model. This overestimation of the transverse reinforcement contribution to the shear strength might lead to a lack of security towards shear, particularly for high performances concrete since the test results in Figure 9 clearly show that the resulting shear capacity of a beam, that is the concrete contribution (Table 5) plus the transverse steel contribution (V_c+V_s), might be overestimated by the code model, hence leading to unsafe shear design particularly in the presence of a lesser amount on main longitudinal reinforcement such as in sub-group A beams (Figure 9a). The present results in Table 5 and Figure 9 illustrate the complexity of shear in reinforced concrete in general, and in high performances concrete in particular, and call for a clearer understanding that may lead to the development of a rational design theory. In the absence of such rational theory, more important safety factors should be used in design to cover for this lack of understanding.

5. ADJUSTMENT OF THE MODEL OF EUROCODE2

On examining the Eurocode 2 shear design model for structural concrete, particularly for high performances concrete, the contribution of the transverse reinforcements to the shear strength is largely overestimated as shown in Table 5 and Figure 9. When summing up the concrete contribution [2] and that of the transverse steel contribution to the shear strength of high performances concrete beams, that is V_C + V_S, the Eurocode2 appears to overestimate the transverse steel contribution. From the test results obtained in the present work, an attempt to readjust the formula giving the shear contribution of the transverse reinforcement in Eurocode 2 is presented in this section.

This readjustment is based on the shearing behavior exhibited by all the beam specimens tested, even when the final collapse was by bending in some cases. Indeed, the wide diagonal cracks and the damaged shear zones of the specimens, which failed in flexure (Figures 3) represent clearer signs that ultimate shear was not very far and shear failures of these beam specimens were imminent. Moreover, the flexural failures that occurred were more by a flexure-shear interaction. The proposed adjustment of the Eurocode2 shear contribution V_s is based on the following principle of resistance:

$$V_{Stest} \geq K\ V_{SEurocode2} \qquad (5)$$

With K a correction factor deduced from the present experimental results to be tentatively taken as 0.5, representing an average value of V_{Stest}/V_{SEC2} for high performances concrete beam specimens. More work is, however, needed to set up definitely a value for K. The work should cover wider ranges of shear-span to depth ratios and amounts of main longitudinal reinforcement.

After adjustment of the model of Eurocode2, the revised code predictions for the shear contribution of the transeverse reinforcement are as presented in Figure 10. They are more comparable with the experimental results obtained. A slight difference remains for the case of a/d = 3, since for such cases failure is usually by flexure just before reaching the ultimate shear and hence the predicted ultimate shear would be higher than the measured failure load.

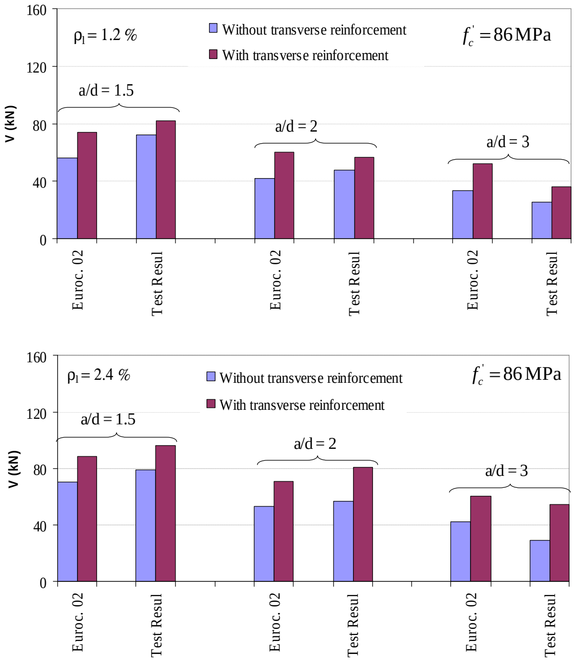


Figure 10: Transverse reinforcement contribution to the shear strength: comparison of test results with the adjusted Eurocode2 model

6. CONCLUSIONS

This paper studies the effects of transverse reinforcement on the shear behaviour of high performances concrete beams. The cracking behaviour and the crack patterns, the transverse reinforcement contribution to the shear strength and the ductility were investigated. The predictions of the major code models in use throughout the world are also assessed:

1- In the presence of transverse reinforcement, the number of cracks increased with an increase of the compressive strengths of concrete (from 44 MPa to 86 MPa), indicating a better restraint of cracking. This was thought to be due to the relatively better quality of the bonding between the reinforcing steel and concrete, resulting in a better transfer of the internal forces from concrete to steel and an enhanced redistribution of these internal forces in the beams made of high performances concrete (65 MPa and 86 MPa).

2- After cracking, transverse reinforcement controlled better the crack opening in high strength concrete than in normal strength concrete. Diagonal crack widths of high performances concrete beams were less open even at relatively higher loads than those of normal strength concrete beams. The serviceability limit of crack width is reached at relatively higher loads in high performances concrete, translating an improved service loading conditions for the material in the presence of transverse reinforcement.

3- The presence of transverse reinforcement improved the shear strength of high performances concrete beams and changed the failure mode from shear to flexure for beams with higher shear-span to depth ratios. However, such improvement is limited, and in general, transverse reinforcement did not seem to have yielded just prior to failure.

4- Transverse reinforcement improved considerably the anchorage of the main longitudinal reinforcement by clamping them and preventing any cracking to develop along them even at failure as observed in beams without transverse stirrups. In the presence of higher amounts of longitudinal reinforcement, the clamping and confining action proved to be very efficient in improving the structural behavior of high performances concrete beams.

5- The presence of transverse reinforcement improved considerably the ductility of high performances concrete beams by comparison to those without transverse reinforcement. From a brittle material when plain, high performances concrete exhibits a very ductile behavior when reinforced uniformly. The better bond between steel and concrete is though to be the key factor in this improvement of ductility.

6- The current European Eurocode 2 predict transverse steel contributions to the shear strengths that are excessively overstimated; the code predictions could exceed three times the experimental values for beams with smaller shear-span/depth ratios. This could have harmful consequences in terms of safety towards shear design. This is thought to be due to the fact that all of these prediction models use the Richter-Morsch truss model analogy, which is based on the yielding of the transverse reinforcement. Such yielding did not always occur in the present tests, particularly for the shorter shear spans where very few stirrups crossed the diagonal cracking at a very small angle. The Code needs a rational refinement in this sense.

7- An attempt is made in the present work to adjust the formula of the Eurocode2 model to take into consideration the reduced transverse reinforcement contribution to the shear strength of high performances concrete beams.

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