Bonding of hot dip galvanised reinforcement in concrete

Esko Sistonen
Lic.Sc. (Tech.), Senior Research Scientist
Helsinki University of Technology
Laboratory of Structural Engineering and Building Physics
Rakentajanaukio 4
FIN-02150 ESPOO, Finland
esko.sistonen@tkk.fi

Pekka Tukiainen
M.Sc. (Tech.), Research Scientist
Helsinki University of Technology
Laboratory of Structural Engineering and Building Physics
Rakentajanaukio 4
FIN-02150 ESPOO, Finland
pekka.tukiainen@tkk.fi

Seppo Huovinen
Dr. Sc. (Tech.), Professor
Helsinki University of Technology
Laboratory of Structural Engineering and Building Physics
Rakentajanaukio 4
FIN-02150 ESPOO, Finland
seppo.huovinen@tkk.fi

ABSTRACT

The use of galvanised steel reinforcement bar increase the service life of concrete structures that normally suffers from carbonation induced reinforcement corrosion. The chloride threshold value of zinc is higher than black steel, so galvanised reinforcement also lengthens the service life of structures that are exposed to chlorides. However the galvanising changes the geometry of ribbed reinforcement bar by smoothing the ribs and decreasing their height and thereby affects the bonding between reinforcement bar and concrete. According to the pullout tests, which performed in this research project, ribbed black steel reinforcement bars had better bonding compared to galvanised reinforcement bars. The result is probably due to non-uniform zinc coating. The addition of nickel, restricting the silicon content of steel rebar to the target value of 0.15 % and the phosphor content of steel rebar to the target value of 0.020 % may improve the quality of the coating and thus have a positive affect on bonding of hot-dip galvanised rebar.

Keywords: Galvanised rebar, service life, hot-dip galvanised concrete reinforcement, passivate, hydrogen evolution, bonding, relative rib area.

1. BONDING BETWEEN REINFORCEMENT BAR AND CONCRETE

Bonding is formed with adhesion, friction and mechanical bond. Adhesion is based on capillary and adhesion forces between the concrete and steel. Friction bond is based on the friction and shear resistance between the roughness of the steel surface and the cement stone. Since the reinforcement most commonly used is ribbed, adhesion and friction play minor roles, and they affect only lighter loads and smaller slips. Mechanical bond is based on the ribbed geometry of the reinforcement bar, which is evaluated by considering the relative rib area, f_R, and the angle of slope of transversal ribs, α. The relative rib area f_R is a parameter which takes account of height and frequency, or the distance of transversal ribs. It is the ratio between the projected rib area and the cylindrical surface area of one rib space.

Relative rib area increases if rib height increases or the number on ribs per unit of length increases. Relative rib area, f_R, is calculated as follows

$$f_R = \frac{\sum S_{PR}}{\pi \cdot d \cdot a}, \qquad (1.1)$$

where d is the nominal bar diameter,
a is the length between transversal ribs and
S_{PR} is the projective area of transversal ribs (Figure 1).

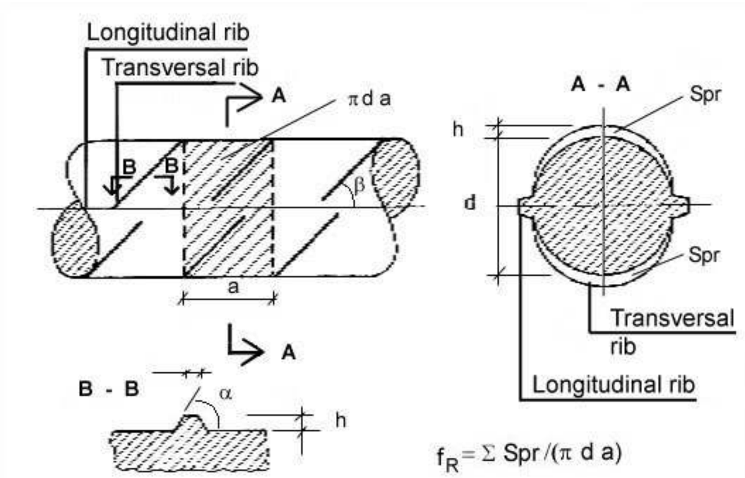

Figure 1 Definition of relative rib area, f_R. (Jokela 1979)

Slipping and fracturing can occur in two ways, depending on the properties of concrete and the geometry of the reinforcement bar. If the ribs are high and situated close to one another, breaking takes place on the cylindrical plane at the outermost edges of the ribs. If the ribs are lower or apart from one another, breaking occurs behind the ribs, where the hardened cement paste will be pulverised and the concrete broken in a wedge-shaped formation.

2. THE EFFECT OF GALVANISING ON THE GEOMETRY OF RIBBED REINFORCEMENT BAR

Six types of steel bars with different geometries and relative rib areas were used. In this study testing was performed in 1999 and in 2001. In testing year 1999 all steel rebars were ordinary steel reinforcements. Half of steel bars in testing year 2001 were hot dip galvanised and chromated (27.10.2000) and the other half was left as references. Nickel was not added any into a zinc bath. The galvanised reinforcement bars were 6 metre long. The nominal diameter of all reinforcement bars were 12 mm. Four reinforcement bar types were hot rolled and two were cold deformed. Because of the dipping process the one end of the bar were at the zinc bath longer than the other. After galvanisation the bars were cut to 500 mm long specimens.

The galvanising reduced the α-angle in all reinforcement bar types with zinc gathering between the ribs, at the corners. The effect of galvanising on the relative rib area is not as straight forward, which can also be seen from the test results. Obviously the ribs became wider. On the other hand, the relative rib area is reduced with the rib height possibly becoming lower if there's a thicker coating between the ribs, than on top of them. Used specimens, both galvanised and ungalvanised reinforcement bars are presented in Table 1 and Table 2.

Table 1 Rebar information of the specimens (testing year 1999).

Reinforcement bar type		Remark
A500HW	Finnish weldable hot rolled ribbed steel bar	Decoiler were used for pulling reinforcement bar out of coil
A700HW	Finnish weldable hot rolled ribbed steel bar	
KS600ST	Swedish weldable hot rolled ribbed steel bar	
B500K	Finnish cold worked ribbed steel bar	
B500K/M	Finnish cold worked ribbed steel bar	Modified, every other transversal rib removed

The relative rib area (f_R) and the α-angle of the ribs were measured from each steel type, both from the galvanised bars and the references. Example of the relative rib area measurement specimens are presented in Figure 3. The relative rib area, the length between transversal ribs and the α- and β-angle of the ribs both galvanised and ungalvanised reinforcement bars are presented in Table 4 and Table 5. The thickness of zinc layer measured by microscopy is presented in Figure 2. The thickness of zinc layer varied from 100 μm to 420 μm. Mean thickness of zinc layer was 220 μm. When galvanised, the ribs became rounder and the slope α-angle, the length between transversal ribs and the relative rib area changed.

The degree of these changes depends on the original geometry of the bar, the silicon and phosphor content of the steel and the galvanising process. The geometry of some ribbed reinforcement bars is such that zinc is easily gathered in thick layers between the ribs. Such is the case, for example, with the v-shaped ribs of the Finnish hot rolled steel bar, A500HW.

Table 2 Rebar information of the specimens. The difference between A500HW Mep and A500HW Rotorcut is that Mep and Rotorcut decoilers were used for pulling them out of coil (testing year 2001).

Reinforcement bar type		Remark
A500HW Mep, Zn	Finnish weldable hot rolled ribbed steel bar	Hot-dip galvanised
A700HW, Zn	Finnish weldable hot rolled ribbed steel bar	Hot-dip galvanised
KS600ST, Zn	Swedish weldable hot rolled ribbed steel bar	Hot-dip galvanised
B500K, Zn	Finnish cold worked ribbed steel bar	Hot-dip galvanised
B500K mod., Zn	Finnish cold worked ribbed steel bar	Modified, every other transversal rib removed and hot-dip galvanised
A500HW Rotorcut, Zn	Finnish weldable hot rolled ribbed steel bar	Hot-dip galvanised
A500HW Mep, ref.	Finnish weldable hot rolled ribbed steel bar	
A700HW, ref.	Finnish weldable hot rolled ribbed steel bar	
KS600ST, ref.	Swedish weldable hot rolled ribbed steel bar	
B500K, ref.	Finnish cold worked ribbed steel bar	
B500K mod., ref.	Finnish cold worked ribbed steel bar	Modified, every other transversal rib removed
A500HW Rotorcut, ref.	Finnish weldable hot rolled ribbed steel bar	

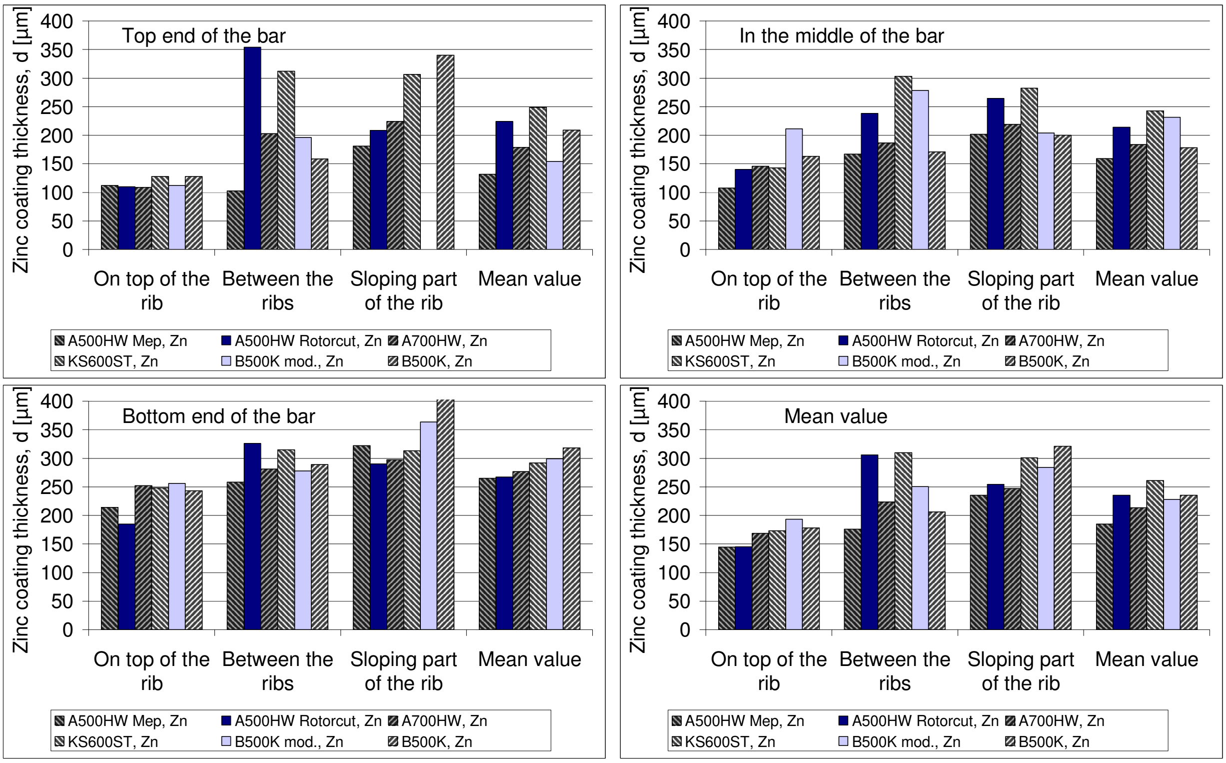

Figure 2 The thickness of zinc layer (testing year 2001).

In addition, due to dipping time, the coating thickness may vary enormously from one end of the bar to the other. On the 6 metre bars used, the coating was 120 µm thicker in bottom end of the bar. Mean zinc coating thickness was 220 µm.

Silicon and phosphor content of the specimens are presented in Table 3. According to the Finnish standards the silicon content in the normal reinforcing steels can be up to 0.55 – 0.60 % and the phosphor content in the normal reinforcing steels can be up to 0.06 %. The steel to be galvanised must therefore be chosen carefully, paying attention on the silicon content and the phosphor content. It seems that addition of nickel eliminates some of the unevenness caused by silicon content and dipping time, but only at the lower silicon values.

Table 3 Silicon and phosphor content of the specimens (testing year 2001).

Reinforcement bar type	Silicon content [Si-%]	Phospor content [P-%]	Si + 2.5P [%]
A500HW Mep, ref.	0.20	0.008	0.22
A700HW, ref.	0.20	0.008	0.22
KS600ST, ref.	0.21	0.017	0.25
B500K, ref.	0.19	0.016	0.23
B500K mod., ref.	0.19	0.021	0.24
A500HW Rotorcut, ref.	0.21	0.23	0.27

Table 4 The mean values of relative rib area, length between transversal ribs, the angle of slope of transversal ribs, and the angle of slope longitudinal ribs of the specimens (testing year 1999).

Reinforcement bar type	Relative rib area, f_R [-]	Minimum allowed relative rib area, f_R [-]	Length between transversal ribs, a [mm]	The angle of slope of transversal ribs, α [°]	The angle of slope of longitudinal ribs, β [°]
A500HW	0.077	0.063	15.1 / 7.5	45	69 / 62
A700HW	0.097	0.063	6.2 / 6.2	51	68 / 69
KS600ST	0.183	-	5.0 / 5.0	45	73 / 73
B500K	0.077	0.064	7.4	52	55
B500K/M	0.034	0.064	14.9	61	58

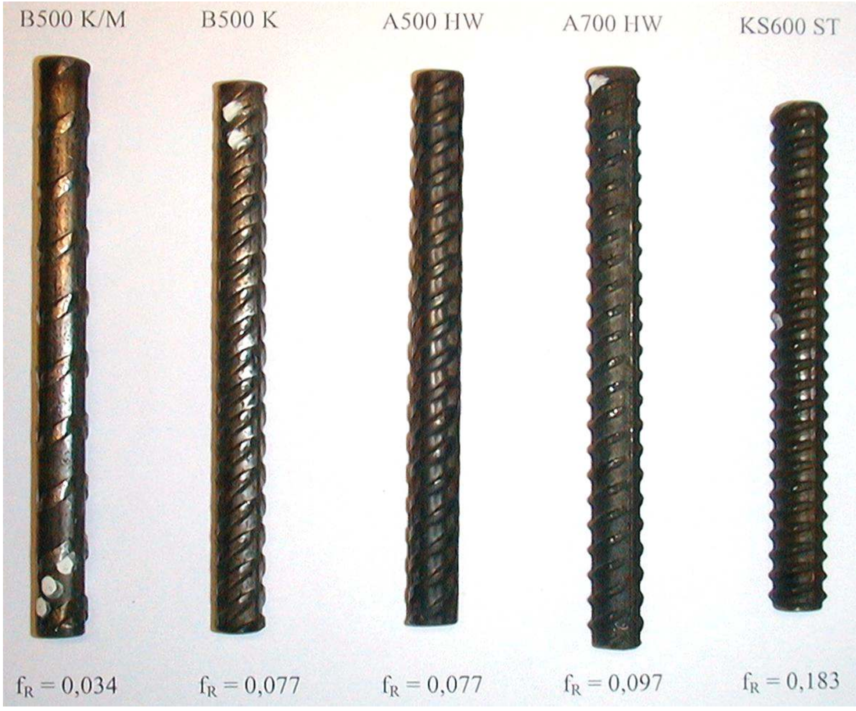

Figure 3 Specimens used in relative rib area measurement (testing year 1999).

Table 5 The mean values of relative rib area, length between transversal ribs, the angle of slope of transversal ribs, and the angle of slope longitudinal ribs, of the specimens (testing year 2001).

Reinforcement bar type	Relative rib area, f_R [-]	Minimum allowed relative rib area, $f_{R,min}$ [-]	Length between transversal ribs, a [mm]	The angle of slope of transversal ribs, α [°]	The angle of slope of longitudinal ribs, β [°]
A500HW Mep, Zn	0.074	0.063	14.6 / 7.3	34	69/63
A700HW, Zn	0.101	0.063	6.3 / 6.2	41	70/70
KS600ST, Zn	0.126	-	5.1 / 5.1	34	62/62
B500K, Zn	0.032	0.064	7.5	34	60
B500K mod., Zn	0.071	0.064	15.0	33	57
A500HW Rotorcut, Zn	0.089	0.063	14.7 / 7.2	34	70/61
A500HW Mep, ref.	0.071	0.063	14.7 / 7.2	39	69/63
A700HW, ref.	0.087	0.063	6.1 / 6.1	46	70/69
KS600ST, ref.	0.149	-	5.1 / 5.1	45	62/62
B500K, ref.	0.032	0.064	7.4	39	60
B500K mod., ref.	0.073	0.064	14.9	42	57
A500HW Rotorcut, ref.	0.090	0.063	14.6 / 7.2	43	70/61

Galvanising reduced the α-angle and length between transversal ribs in all the types. The relative rib area, however, either increased or decreased. Minimum allowed α-angle for hot rolled and cold worked steel bars is 40°. Only one galvanised rebar, Finnish weldable hot rolled ribbed steel bar, had the allowed α-angle.

3. REACTION OF ZINC WITH FRESH CONCRETE

Another drawback of bonding of galvanised reinforcement bar with concrete is the reaction of zinc with fresh concrete resulting in hydrogen gas. Hydrogen pores and zincates reduce the adhesion forces of initial bonding. Hydrogen pores also affect reducing friction bond in the contact area of the hardened cement paste near the surface of the bars. In addition, with the reduced strength the hardened cement paste will be pulverised more easily. Chromates are used to passivate zinc and to prevent hydrogen formation, but unfortunately the durability of the chromating during storage is very uncertain. Furthermore, chromates may cause allergic reactions to workers, and therefore other means of passivating zinc are being researched. In this study the treatment of the galvanised steel was chromation. After steel rebars were hot dip galvanised (27.10.2000), they were stor½ed 20 days at indoor conditions (T ≈ 20 °C, RH ≈ 30 %) before casting (16.11.2000).

4. THE PULLOUT TEST

The pullout test was used to evaluate the bonding between reinforcement bar and concrete. The concrete used in the pullout test is presented in Table 6.

Table 6 The properties of the concrete used in the pullout test (testing years 1999 and 2001).

Testing year	1999	2001	Unit
Cement, c	230	411	kg/m^3
Cement type	Mega (CEM I A 42,5 R)	Rapid (CEM II A 42,5 R)	-
Water, w	206	156	kg/m^3
w/c (w/b)	0,89 (0,80)	0,38 (0,38)	-
Fly ash	90	-	kg/m^3
Aggregates # 0 – 8 mm	1405	899	kg/m^3
Aggregates # 4 – 8 mm	374	-	kg/m^3
Aggregate, # 8 – 16 mm	-	830	kg/m^3
Super plasticizer (General Parmix)	0,8	1,2	%
Air-entraining agent (Micro-air)	-	0,2	%
Air content of fresh concrete	1,4	6,5	%
Consistency class	2 – 3	1 – 2	sVB
Concrete strength class	30	40	MPa
Compressive strength,	35,2	41,8	MPa
Testing age of the compressive strength after casting	27	28	d

At the pullout test a steel bar was pulled out from a concrete cube with increasing force – the rate was 4 kN /min – and the slip at the other end of the reinforcement bar was measured. The bonding between the steel and the concrete was limited by plastic tubes to 60 mm. Testing procedure is illustrated in Figure 4. At the time of the testing at year 1999 the specimens were 35 – 37 days old. At the time of the testing at year 2001 the specimens were 25 – 27 days old.

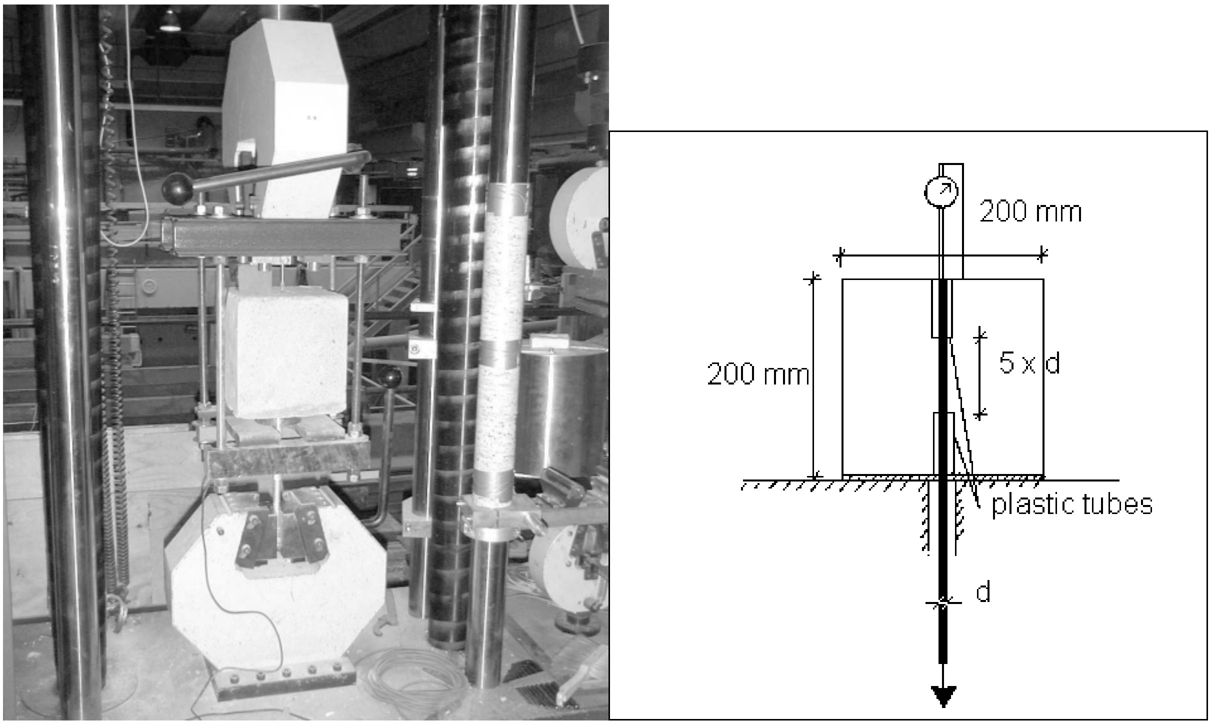

Figure 4 Testing procedure for pullout test. At the time of the testing at year 1999 the specimens were 35 – 37 days old. At the time of the testing at year 2001 the specimens were 25 – 27 days old.

5. TEST RESULTS OF PULLOUT TEST

The slip at 160, 200, 235 and 265 MPa was measured. Because of measurement difficulties, no slip values could be obtained for certain steel rebars, but to give some indication of the magnitude, the closest possible values with the respective stresses are given. In most cases the reference bar had clearly smaller values for slips, and therefore bonding was better (Figure 6, Table 7 and Table 8). Two steel reinforcement bars made an exception: weldable hot rolled ribbed steel bar, A500HW Rotorcut, and cold worked rolled steel bar, B500K, had slightly smaller slips with the galvanised bars. Also, concrete strength had effect on embedment, in hot dip galvanised rebar with higher concrete strength bonding was often better than in reference rebar with lower concrete strength (Figure 6).

In the pullout tests obtained failure mode was pullout failure. Any splitting cracks were not mentioned due to testing method, rebars were totally pulled out from concrete specimen. However, in testing year 2001, concrete cracked in four specimens of Swedish weldable hot rolled ribbed steel bar KS600ST. After testing concrete specimens were sawn (testing year 2001) and the real length of embedment of specimens were measured. Mean deviation of the length was low in all specimens, except in those four cracked specimens, which were left out from testing results. Little amount of hydrogen evaluation was visually observed from sawn concrete specimens.

In the literature the results obtained for the bond of galvanised bars are very contradictory (Proverbio et al. 1998; Concrete Institute of Australia 1984; Sarja et al. 1984; Andrade et al. 1995). The prevailing tendency however is that galvanising does not reduce a bond, and in the case of passivated zinc the results can be even better than with uncoated steel. The results do not merely depend on the quality of the coating and the geometry of the bars: the properties of concrete play a significant role as well.

Table 7. Result of the pullout tests (testing year 1999).

Steel grade			Stress at slip			Slip at stress x				
	f_R	α-angle	0.1 mm	1 mm	Maximum bonding strenght	x = maximum	x = 160 MPa	x = 200 MPa	x = 235 MPa	x = 265 MPa
	-	°	MPa	MPa	MPa	mm	mm	mm	mm	mm
A500HW	0.077	45	172.2	246.9	254.3	0.7	0.08	0.18	0.33	
A700HW	0.097	51	179.3	234.9	254.1	0.6	0.07	0.16	0.30	
KS600ST	0.183	45	207.5	229.0	269.1	0.4	0.03	0.09	0.17	0.35
B500K/M	0.034	61	119.9	279.4	359.8	3	0.22	0.39	0.61	0.86
B500K	0.077	52	160.2	251.7	259.1	0.8	0.10	0.19	0.34	

Table 8. Result of the pullout tests. (1) The upper end of the galvanised reinforcement bar. The shortest dipping time. (2) The middle of the reinforcement bar. (3) The lover end of the galvanised reinforcement bar. The longest dipping time. (4) Average of the galvanised reinforcement bar. (5) Reference reinforcement bar (testing year 2001).

Steel grade					Stress at slip			Slip at stress x				
		f_R	α-angle	Average thickness of zinc layer	0.1 mm	1 mm	Maximum bonding strenght	x = maximum	x = 160 MPa	x = 200 MPa	x = 235 MPa	x = 265 MPa
		-	°	µm	MPa	MPa	MPa	mm	mm	mm	mm	mm
A500HW Mep	1	0.070	36	132	189.4	280.3	280.3	1	0.05	0.13	0.27	0.54
	2	0.078	32	159	190.4	270.9	270.9	1	0.06	0.13	0.28	0.69
	3			265	174.2	222.0	222.1	0.9	0.06	0.25		
	4				184.7	257.7	257.7	1	0.06	0.15	0.37	
	5	0.071	39	0	219.9	310.1	310.1	1	0.01	0.06	0.15	0.26
A700HW	1	0.101	38	179	230.5	304.5	304.5	1	0.03	0.05	0.11	0.22
	2	0.100	44	184	217.6	305.7	305.7	1	0.03	0.07	0.15	0.28
	3			277	205.4	289.0	289.0	1	0.03	0.09	0.19	0.37
	4				217.8	299.7	299.7	1	0.03	0.07	0.15	0.29
	5	0.087	46	0	282.1	355.2	355.2	1				0.06
KS600ST	1	0.127	33	249	209.6	245.8	248.0	0.7	0.02	0.08	0.25	
	2	0.125	34	243	202.6	231.4	236.5	0.6	0.03	0.09	0.46	
	3			292	179.6	220.8	223.7	0.7	0.05	0.17		
	4				197.3	232.6	235.9	0.7	0.03	0.11	0.53	
	5	0.149	45	0	259.6	304.1	305.4	0.7				0.13
B500K mod.	1	0.031	29	154	114.7	251.2	344.3	3	0.30	0.56	0.85	1.20
	2	0.033	37	231	110.1	226.5	302.6	3	0.33	0.70	1.14	1.65
	3			299	102.0	230.5	317.6	4	0.42	0.71	1.07	1.54
	4				109.0	236.1	320.6	3	0.35	0.65	0.99	1.45
	5	0.032	42	0	127.9	262.8	389.5	4	0.24	0.47	0.74	1.03
B500K	1	0.074	32	209	189.6	293.4	301.6	2	0.05	0.13	0.25	0.46
	2	0.068	36	178	176.9	269.4	274.7	2	0.07	0.17	0.37	0.82
	3			319	172.1	293.0	293.0	1	0.08	0.16	0.28	0.48
	4				179.6	285.3	289.7	2	0.07	0.15	0.29	0.54
	5	0.073	39	0	163.6	262.5	269.4	2	0.09	0.18	0.38	1.36
A500HW Rotorcut	1	0.086	35	224	244.7	327.3	327.3	1	0.03	0.05	0.08	0.16
	2	0.092	33	214	242.6	325.9	325.9	1	0.02	0.04	0.09	0.16
	3			267	212.3	288.2	288.8	0.9	0.03	0.08	0.16	0.29
	4				233.2	313.8	313.8	0.9	0.02	0.05	0.11	0.19
	5	0.090	43	0	215.9	275.8	275.8	1			0.18	0.48

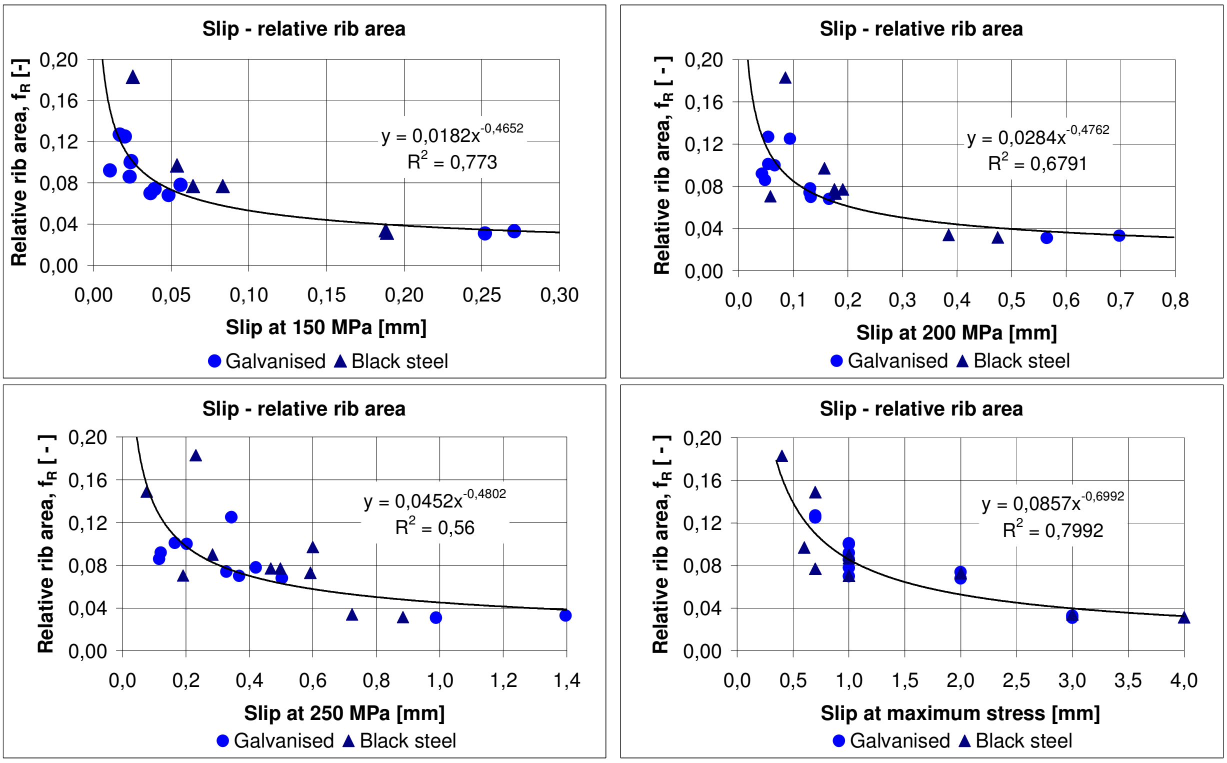

Figure 5 *Slip at 150, 200, 200 MPa and maximum stress – relative rib area, average (testing years 1999 and 2001).*

The poor results for the galvanised bars may be partly attributed to the fact that the chromating was almost three weeks old in a casting day, and in consequence some hydrogen pores have resulted. However the result is probably mainly due to non-uniform zinc coating, which smoothed the reinforcement bar geometry.

The difference between the reference and the galvanised bar was smallest with the cold worked ribbed steel bars B500K.

The slips of different reinforcing steel types at 150 MPa, 200 MPa, 250 MPa and maximum stress are presented in Figure 5. The slips of black steel bar are both from studies of the testing year 1999 and partly from studies of the testing year 2001. There is slight correlation between slip and relative rib area.

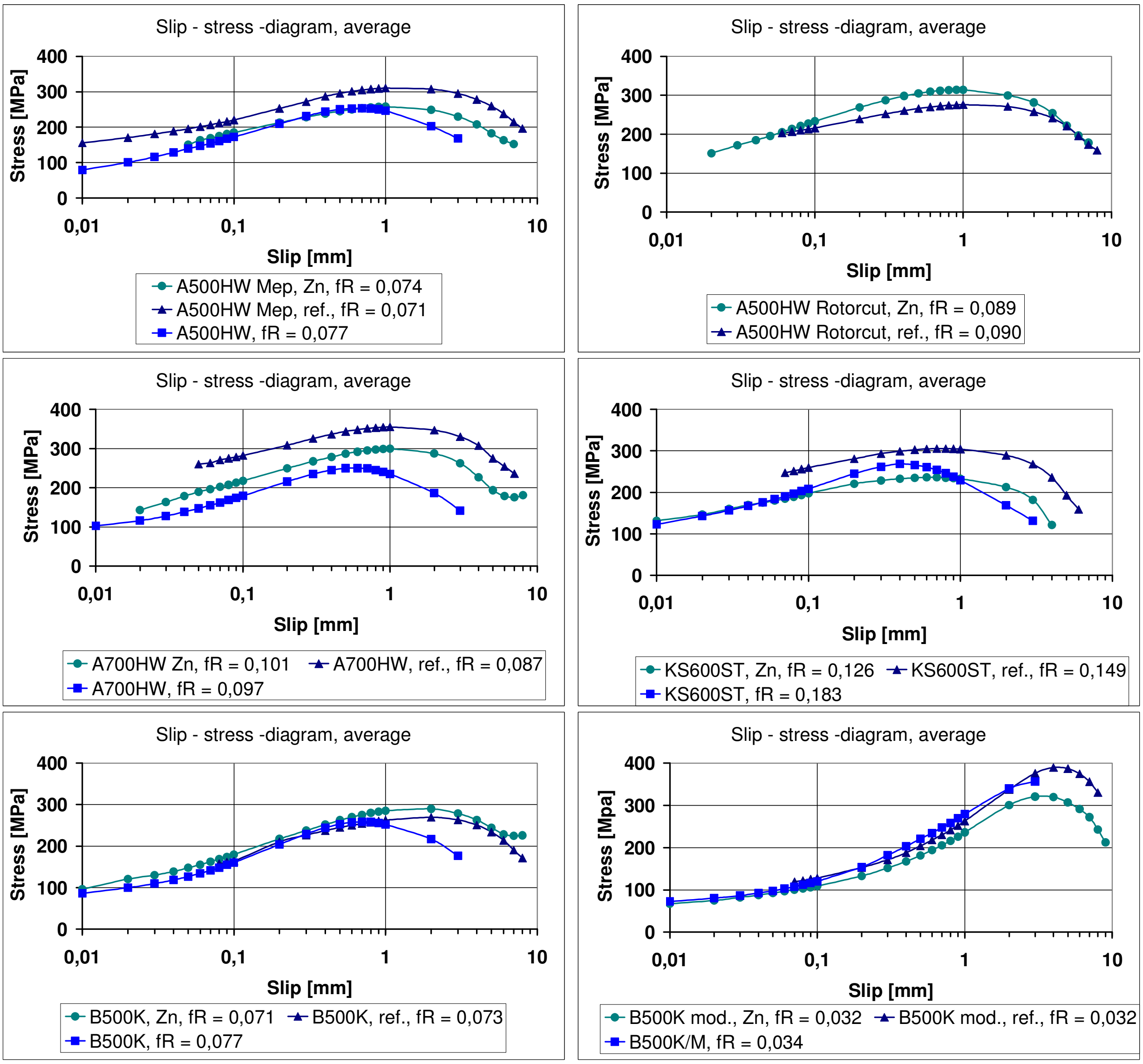

Figure 6 Slip – stress –diagrams (testing years 1999 and 2001).

6. CONCLUSIONS

The experimental part consisted of several tests. The thickness and structure of the coating, and the bonding properties of hot-dip galvanised reinforcement were tested on ribbed reinforcement steels of various types. Hot-dip galvanising changed the geometry of reinforcement bars, by smoothing the ribs and decreasing their height, thus affecting the bonding between reinforcement bar and concrete. In most cases galvanising did have adverse effect on bonding between reinforcement bar and concrete.

When galvanised, the ribs became rounded and the slope angle and the relative rib area changed. The angle of slope diminishes with zinc drops gathering between the ribs at the corners. The effect of galvanising on the relative rib area is not as straightforward, which can be seen from the test results. Obviously, the ribs become wider. If the projected rib area becomes larger, the relative rib area will enlarge as well. On the other hand, the relative rib area is reduced with the growing diameter, and the rib height possibly becomes lower (the coating is thicker between the ribs than on top of them).

The emphasis should be on the quality of the coating. It should be uniform, regardless of the diameter, length, shape (whether bent or straight) or silicon content of the bars. The coating thickness should be equal between the ribs and on the top of the ribs as well as at both ends of the bar, so the smoothing and the decreasing of the height of ribs could be avoided.

In the literature it is obtained that the galvanised coating affects the porous structure of the interfacial transition zone (ITZ) with the surrounding cement paste (Belaid et al. 2001). However, in this study it was observed that the main parameters for bonding were concrete and zinc coating quality.

With a right concrete mix one could decrease the amount of hydrogen evolution. Quality specifications for the concrete mix are for instance lower pH value of used cement type, use of quickly hardening concrete, lower water-binder-ratio and use of low alcality binders. The exact pH value does not have a straight correlation with hydrogen evaluation because the critical pH value depends also on cement type (C_3A/C_3S, w/c) (Arliguie. 2001).

Quality specifications for zinc coating are for instance target silicon content of rebar Si = 0,15 %, target phosphor content of rebar P = 0,020 % (target value for [Si-% + 2,5×P-%] content of rebar is 0,20 %), the properties of galvanising method and the formation and structure of the zinc coating. The galvanising method used during the tests was not suitable for achieving a uniform coating. Care should be taken when placing the bars into the rack. There should be a sufficient support for the bars with smaller diameters. The dimensions should be taken into account in the dipping time. A visual estimation of the quality of the coating, in particular of the profile, is suggested. For example, the sharpness of the ribs can be seen with eye, especially when compared with uncoated steel rebar. The quality of the zinc coating is usually better with higher bar diameters.

It is possible to choose the rebar and the concrete so, that bonding of hot dip galvanised reinforcement in concrete is as good as the bonding with ordinary steel reinforcement.

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