MODELS OF CONCRETE CONFINED BY FRP USED FOR CONCRETE CONFINED BY STEEL SPIRALS

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Abstract

This paper is about possibilities of using different models of confined concrete for concrete confined by steel spirals. Most models are prepared for concrete confined by FRP. There are some models prepared before 1990. The compared value is the confined concrete compressive strength. Some calculation examples of models comparison are presented. The comparison is also made to results of some experimental tests.

Keywords

Confined concrete, steel spirals for confinement, strength of confined concrete

1 INTRODUCTION

Concrete is a material which is very commonly used nowadays. Reinforced concrete structures next to steel structures are the most popular type of structures. One of the most important feature of concrete is its compressive strength. Its value is usually more than 10 times higher than tensile strength. Experimental tests of compressive strenght are usually conducted on cylinders of 150 mm diameter and the height of 300 mm. During these studies it occurs that specimens are destroyed by tensile stresses, which exceed the tensile strength of concrete. After the failure, two cones with common vertex and factions/blocks of concrete in the middle of height are formed. Observation of that fact gave researchers an idea to prevent concrete from deformation in lateral direction. Application of different means to reduce these deformations is called the confinement.

The confinement can be applied by steel tubes, reinforced concrete coating, reinforcing steel stirrups, grids or spirals. Now the most popular mean of doing this are the fibre reinforced polymers wraps. The first research on confined concrete was done by Richart et al. [1] in 1928. In the 20th century until 1990, some experimental tests [2], [3], [4] were conducted especially on steel confinement. Some models were prepared.

Confined concrete due to lateral constrains works under multiaxial stresses state. For instance FRP wraps on circular columns, after uniaxial compressive loads, deform and begin to extend. It causes tensile stresses in FRP bands. Because bands are fixed around the column, some perpendicular stresses appear and confine concrete. These stresses can be calculated by the following formula (1):

$$s_2 = \frac{2 \cdot t_f \cdot s_f}{D} \tag{1}$$

where:

t_f – thickness of the FRP wrap,

σ_f – stresses in the FRP wrap,

D – diameter of column or specimen.

After the year 1990 there was a very fast development on FRP. Because of that ,FRP bands were used for strengthening the concrete columns. Until now it is one of the most popular and effective method of the strengthening. This development caused numerous researches on concrete columns confined by FRP. Researchers from all around the world have started to develop new models of confined concrete or they have adopted some models from models of concrete confined by steel. There are more than 50 models. These models allow to determine compressive strength of confined concrete and usually they give equations for calculating ultimate axial strain of FRP-confined concrete. A review of many of them can be found in [5] and [6].

At the turn of the 20th and 21st centuries there has been also a quite large development of high strength concrete. There were some works (for example [7], [8]) on that concrete and impact of confinement on it. In most of this researches the FRP confinement was used.

The confiment of concrete is not used only in columns. Concrete also works in multiaxial stress state in anchorages zones of prestressed structures and areas where high compressive forces are applied and where confinement as spirals, stirrups or grids are used.

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The usage of FRP wraps in these areas is usually not possible. The main aim of this article is to show if it is possible to adopt and use new models of FRP-confined concrete for concrete confine by steel spirals.

2 WORK OF SPIRAL IN CONFINED CONCRETE

The work of spiral in confined concrete is quite similar to the work of FRP wraps (2)(see Fig. 1). The spiral bar has its diameter φ and area A_{st} The whole hoop of spiral has its diameter d_{core}. The centerline of the hoop forms the core area A_{core}. The pitch of hoops is called s_n. It is said that in the moment of failure due to lateral deformation steel of spiral yields (achives stresses f_y). This assumption can be true if ribbed bars are used for spiral. The compressive strength of unconfined concrete is f'_c and of confined concrete is f'_{cc}. Tests presented in [9] show that plain steel may not increase compressive strength of concrete effectively.

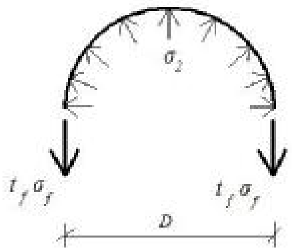

***Fig. 1** Confinement by a FRP wrap*

$$p = \frac{2 \cdot A_{st} \cdot f_y}{d_{core}} \tag{2}$$

To obtain effective stresses on confined concrete, the fact of distance of between hoops must be taken into account. Concrete between hoops is not so well confined near the concrete edge. It is not easy to give an exact factor of reduction. There are several methods of including that influance. They are presented in formulas (3, 4a, 4b, 4c). It is difficult to give the final value.

$$c = (1 - \frac{s_n}{d_{core}}) \tag{3}$$

$$c = (1 - \frac{s_n}{2 \cdot d_{core}} \cdot ctg(a))^2 \tag{4a}$$

$$c = (1 - \frac{s_n}{2 \cdot d_{core}} \cdot ctg(45\deg))^2 \tag{4b}$$

$$c = (1 - \frac{s_n}{2 \cdot d_{core}} \cdot ctg(26.5\deg))^2 \tag{4c}$$

Where α is a half of angle of the effective area with vertex in the hoop.

The most conservative approach is to use formula (4c). In this article α was declared as 35˚.

3 MODELS OF CONFINED CONCRETE [7][8]

In the table 1 some models of confined concrete are presented. Author has chosen the most popular or those which he suppose will give the right approximation and the formulas were much different than others. Most of these models are prepared for FRP-confined concrete. In the table 1 the formulas for the ultimate compressive strength are given.

Author	Ultimate compressive strength of confined concrete	General / FRP model
Richart et al. (1928) [1]	$f'_{cc} = f'_c + 4{,}1 \cdot s_{eff}$	general

Fardis and Khalili (1982) [10]	$f'_{cc} = f'_c \cdot \left(1 + 3{,}7 \cdot \left(\frac{s_{eff}}{f'_c}\right)^{0,86}\right)$	FRP
Mander et al. (1988) [2]	$f'_{cc} = f'_c \cdot (2.254 \cdot \sqrt{1 + 7{,}94 \frac{s_{eff}}{f'_c}} - 2 \cdot \frac{s_{eff}}{f'_c} - 1{,}254)$	general
Cusson and Paultre (1995) [11]	$f'_{cc} = f'_c \cdot \left(1 + 2{,}1 \cdot \left(\frac{s_{eff}}{f'_c}\right)^{0,70}\right)$	general
Mirmiran (1996) [12]	$f'_{cc} = f'_c + 4{,}269 \cdot s_{eff}^{\;0,587}$	FRP
Karbhari and Gao (1997) [13]	$f'_{cc} = f'_c \cdot \left(1 + 2{,}1 \cdot \left(\frac{s_{eff}}{f'_c}\right)^{0,87}\right)$	FRP
Pilakotas and Mortazavi (1997) [14] (this formula is used in EN 1992-1-1)	$f'_{cc} = f'_c \cdot \left(1{,}125 + 2{,}5 \cdot \frac{s_{eff}}{f'_c}\right) \text{for } 2 \cdot \frac{s_{eff}}{f'_c} \geq 0{,}10$ $f'_{cc} = f'_c \cdot \left(1{,}0 + 5{,}0 \cdot \frac{s_{eff}}{f'_c}\right) \text{for } 2 \cdot \frac{s_{eff}}{f'_c} < 0{,}10$	FRP (adopted to general in EC2)
Spoelstra and Monti (1999) [15]	$f'_{cc} = f'_c + 6{,}0 \cdot s_{eff}^{\;0,70}$	FRP
Lam and Teng (2002) [16]	$f'_{cc} = f'_c \cdot \left(1 + 2 \cdot \frac{s_{eff}}{f'_c}\right)$	FRP
Guralnick and Gunawan (2006)	$f'_{cc} = f'_c \cdot \left(0{,}616 + \left(\frac{s_{eff}}{f'_c}\right) + 1{,}57 \cdot \left(\frac{s_{eff}}{f'_c} + 0{,}06\right)^{0,5}\right)$	FRP
Youssef et al. (2007) [17]	$f'_{cc} = f'_c \cdot \left(1 + 2{,}25 \cdot \left(\frac{s_{eff}}{f'_c}\right)^{1,25}\right)$	FRP
Girgin (2009)	$f'_{cc} = f'_c + 2{,}109 \cdot f'_c \cdot \left(\frac{s_{eff}}{f'_c}\right)^{0,783}$ - based on the Mohr-Coulomb model $f'_{cc} = s_{eff} + \sqrt{f'^{\,2}_c + 3{,}5 \cdot f'_c \cdot s_{eff}}$ - based on the Hoek-Brown model	FRP
Wu and Zhou (2010) [18]	$f'_{cc} = s_{eff} + \sqrt{\left(\frac{16{,}7}{f'^{\,0,42}_c} - \frac{f'^{\,0,42}_c}{16{,}7}\right)\frac{s_{eff}}{f'_c} + 1} \cdot f'_c$	FRP
Cevik (2011) [19]	$f'_{cc} = s_{eff}^{\;1,5} + (\ln(f'_c))^3 + 2 \cdot \ln(s_{eff}) - 13{,}65 \cdot \left(\frac{s_{eff}}{f'_c}\right) + \left(\frac{s_{eff}}{f'_c}\right)^{1,5}$	FRP

Wang and Wu (2011) [20]	$$f'_{cc} = \frac{\left(1{,}0 - 5{,}54\frac{s_{eff}}{f'_c}\right)\cdot f'_c}{\left(1{,}0 - 1{,}49\frac{s_{eff}}{f'_c}\right)}$$	FRP

***Tab. 1** Models and formulas to calculate compressive strength of confined concrete*

4 COMPARISON OF MODELS ON SOME RESEARCHES

To show the differences between models a comparison of results of calculated compressive strength of confined concrete is prepared. Details of specimens are presented in table 2.

Specimen(s)	h	D	d_{core}	s_n	f_y	ϕ	A_{st}	σ_2	χ	σ_{eff}	f'_c
[-]	[mm]	[mm]	[mm]	[mm]	[MPa]	[mm]	[mm^2]	[MPa]	[-]	[MPa]	[MPa]
II-1 [3]	150	75	71,9	25,4	413	3,07	7,40	3,35	0,56	1,87	26,18
II-2 [3]	150	75	71,9	12,7	413	3,07	7,40	6,70	0,76	5,12	26,18
III-1 [3]	150	75	71,9	38,1	413	3,07	7,40	2,23	0,39	0,86	37,90
III-2 [3]	150	75	71,9	25,4	413	3,07	7,40	3,35	0,56	187	37,90
III-3 [3]	150	75	71,9	12,7	413	3,07	7,40	6,70	0,76	5,12	37,90
IV-1 [3]	150	75	71,9	38,1	413	3,07	7,40	2,23	0,39	0,86	51,68
IV-2 [3]	150	75	71,9	25,4	413	3,07	7,40	3,35	0,56	1,87	51,68
V-1 [3]	150	75	71,9	25,4	413	3,07	7,40	3,35	0,56	187	65,46
V-2 [3]	150	75	71,9	12,7	413	3,07	7,40	6,70	0,76	5,12	65,46
VI-1 [3]	150	75	73,4	38,1	1433	1,59	1,99	2,03	0,40	0,81	52,23
VI-2 [3]	150	75	72,6	12,7	1116	2,38	4,45	10,78	0,77	8,25	52,23
SR1 [4]	300	150	143,8	30	299	6,2	30,19	4,18	0,72	3,03	22,26
SR2 [4]	300	150	143,8	60	299	6,2	30,19	2,09	0,49	1,03	18,73
SR3 [4]	300	150	143,8	90	299	6,2	30,19	1,39	0,31	0,43	17,65
SR4 [4]	300	150	143,8	120	299	6,2	30,19	1,05	0,16	0,17	13,73
SR5 [4]	300	150	143,8	150	299	6,2	30,19	0,84	0,07	0,05	24,51
SR6 [4]	300	150	146,0	30	677	4,0	12,57	3,88	0,73	2,83	19,61
SR7 [4]	300	150	146,0	60	677	4,0	12,57	1,94	0,50	0,97	21,77
SR8 [4]	300	150	146,0	90	677	4,0	12,57	1,29	0,31	0,41	29,42
SR9 [4]	300	150	146,0	120	677	4,0	12,57	0,97	0,17	0,17	28,93
SR10 [4]	300	150	146,0	150	677	4,0	12,57	0,78	0,07	0,06	23,53
SR11 [4]	300	150	143,8	45	299	6,2	30,19	2,79	0,60	1,68	23,05
S4E0 [22]	300	150	130	40	1200	5,0	19,63	9,06	0,61	5,52	36,20
S2E0 [22]	300	150	130	20	1200	5,0	19,63	18,12	0,79	14,36	36,20

***Tab. 2** Details of specimens and confining stresses*

The calculated values of compressive strength of confined concrete according to models from Tab. 1. are presented (see Tab. 3a. and Tab. 3b).

Specimen(s)	σ_{eff}	f'_c	f'_{cc}								
			experimental	Richart et al. [1]	Fardis and Khalili [11]	Mander et al. [2]	Cusson and Paultre [12]	Mirmiran [13]	Karbhari and Gao [14]	Pilakotas and Mortazavi [15] (EC2)	Spoelstra and Monti [16]
[-]	[MPa]										
II-1 [3]	1,87	26,18	31,56	33,86	36,21	37,32	34,86	32,35	31,72	34,14	35,49
II-2 [3]	5,12	26,18	38,93	47,17	49,98	51,21	43,72	37,31	39,47	42,25	45,00
III-1 [3]	0,86	37,90	39,62	41,44	43,32	43,58	43,54	41,82	40,86	42,22	43,31
III-2 [3]	187	37,90	42,03	45,58	48,46	49,53	47,60	44,07	43,72	47,27	47,21
III-3 [3]	5,12	37,90	47,54	58,89	62,96	65,21	57,50	49,03	51,84	55,43	56,72
IV-1 [3]	0,86	51,68	53,05	55,22	57,34	57,44	57,87	55,60	54,77	56,00	57,09
IV-2 [3]	1,87	51,68	55,12	59,36	62,71	63,64	62,32	57,85	57,74	61,05	60,99
V-1 [3]	187	65,46	68,97	73,14	76,86	77,62	76,89	71,63	71,71	75,83	74,77
V-2 [3]	5,12	65,46	73,03	86,45	92,52	95,52	88,55	76,59	80,43	86,44	84,28
VI-1 [3]	0,81	52,23	55,81	55,53	57,78	57,62	58,15	55,99	55,14	56,26	57,39
VI-2 [3]	8,25	52,23	59,94	86,07	91,77	94,77	82,38	66,97	74,26	79,39	78,52
SR1 [4]	3,03	22,26	40,69	34,69	37,09	38,41	33,84	30,44	30,51	32,62	35,30
SR2 [4]	1,03	18,73	23,05	22,96	24,46	25,06	24,90	24,08	21,89	23,65	24,86
SR3 [4]	0,43	17,65	21,38	19,40	20,31	20,45	20,39	20,24	19,10	19,78	20,96
SR4 [4]	0,17	13,73	15,00	14,43	14,90	14,88	15,07	15,24	14,36	14,58	15,47
SR5 [4]	0,05	24,51	24,03	24,73	24,98	24,89	25,23	25,28	24,76	24,78	25,29
SR6 [4]	2,83	19,61	31,09	31,21	33,33	34,49	30,23	27,47	27,25	29,13	32,03
SR7 [4]	0,97	21,77	25,40	25,75	27,32	27,85	26,95	25,96	24,82	26,62	27,64
SR8 [4]	0,41	29,42	33,34	31,08	32,16	32,15	32,50	31,93	30,91	31,45	32,61
SR9 [4]	0,17	28,93	30,59	29,61	30,19	30,07	30,57	30,42	29,61	29,76	30,63
SR10 [4]	0,06	23,53	24,03	23,76	24,01	23,91	24,24	24,31	23,78	23,81	24,32
SR11 [4]	1,68	23,05	36,48	29,95	32,03	33,03	30,80	28,84	28,02	30,14	31,69
S4E0 [22]	5,52	36,20	45,77	58,82	62,77	64,87	56,57	47,83	51,00	54,52	56,03
S2E0 [22]	14,36	36,20	61,50	95,08	96,68	92,10	76,00	56,60	70,21	76,63	74,94
average error of method [%]				12,11	15,31	16,40	11,21	5,89	7,84	10,25	10,38
average error of method for [3] [%]				13,24	19,68	22,11	14,85	4,61	5,93	11,70	13,17
average errof of method for [4] [%]				5,63	5,14	5,36	5,32	7,11	8,85	6,69	5,46
average $f'_{cc.exp}/f'_{cc.model}$ for [3]				1,13	1,20	1,22	1,15	1,04	1,06	1,12	1,13
average $f'_{cc.exp}/f'_{cc.model}$ for [4]				0,95	0,99	1,01	0,98	0,95	0,92	0,95	1,00

Tab. 3a *Values of the compressive strength of confined concrete according to the models (part 1)*

Specimen(s)	σ_{eff}	f'_c	f'_{cc}								
			experimental	Lam and Teng [17]	Guralnick and Gunawan	Youssef et al. [18]	Girgin (Mohr-Coulomb)	Girgin (Hoek-Brown)	Wu and Zhou [19]	Cevik [20]	Wang and Wu [21]
[-]	[MPa]										
II-1 [3]	1,87	26,18	31,56	29,93	32,91	28,36	33,18	31,15	31,57	37,67	17,69
II-2 [3]	5,12	26,18	38,93	36,42	42,02	33,84	41,56	39,09	40,07	47,07	-3,07
III-1 [3]	0,86	37,90	39,62	39,63	41,33	38,65	42,04	40,25	40,18	48,23	34,28
III-2 [3]	187	37,90	42,03	41,65	44,90	39,89	45,49	42,92	42,79	51,18	29,71
III-3 [3]	5,12	37,90	47,54	48,14	54,74	44,88	54,57	51,11	50,80	61,08	1195
IV-1 [3]	0,86	51,68	53,05	53,41	55,17	52,38	56,10	54,03	53,77	61,68	48,09
IV-2 [3]	1,87	51,68	55,12	55,43	58,88	53,52	59,80	56,73	56,18	64,73	43,66
V-1 [3]	187	65,46	68,97	69,21	72,79	67,19	74,00	70,53	69,67	76,54	57,53
V-2 [3]	5,12	65,46	73,03	75,70	83,65	71,55	84,23	78,99	76,78	86,91	42,00
VI-1 [3]	0,81	52,23	55,81	53,84	55,50	52,87	56,43	54,43	54,17	61,98	48,89
VI-2 [3]	8,25	52,23	59,94	68,74	78,72	63,94	78,21	73,35	71,17	87,74	8,51
SR1 [4]	3,03	22,26	40,69	28,32	32,22	26,40	32,11	30,08	31,08	35,56	6,86
SR2 [4]	1,03	18,73	23,05	20,79	22,54	19,85	22,81	21,49	22,03	25,53	14,18
SR3 [4]	0,43	17,65	21,38	18,50	19,34	18,03	19,67	18,81	19,07	21,91	15,86
SR4 [4]	0,17	13,73	1500	14,07	14,43	13,86	14,66	14,20	14,35	14,34	13,02
SR5 [4]	0,05	24,51	24,03	24,62	24,75	24,54	24,94	2466	24,68	26,90	24,29
SR6 [4]	2,83	19,61	31,09	25,27	28,82	24,53	28,69	26,88	28,09	31,28	5,02
SR7 [4]	0,97	21,77	25,40	23,71	25,43	22,77	24,79	24,38	23,76	29,53	17,56
SR8 [4]	0,41	29,42	33,34	30,23	31,08	29,73	31,59	30,53	30,58	36,94	27,74
SR9 [4]	0,17	28,93	30,59	29,26	29,63	29,03	30,00	29,38	29,41	34,49	28,25
SR10 [4]	0,06	23,53	24,03	23,64	23,77	23,56	23,96	23,68	23,70	25,69	23,31
SR11 [4]	1,68	23,05	36,48	26,41	29,08	25,02	29,31	27,51	28,06	33,14	15,40
S4E0 [21]	5,52	36,20	45,77	47,24	54,01	43,96	53,70	50,35	50,19	60,59	7,29
S2E0 [21]	14,36	36,20	61,50	64,92	75,07	61,84	73,22	70,31	69,97	100,82	-106,04
average error of method [%]				7,36	9,14	9,16	9,10	7,76	6,75	17,85	48,96
average error of method for [3] [%]				3,39	9,21	5,19	9,95	4,82	4,01	21,22	41,54
average errof of method for [4] [%]				11,87	7,10	14,39	6,59	9,89	8,59	8,97	32,87
average $f'_{cc.exp}/f'_{cc.model}$ for [3]				1,00	1,09	0,96	1,10	1,04	1,03	1,21	0,58
average $f'_{cc.exp}/f'_{cc.model}$ for [4]				0,89	0,93	0,85	0,94	0,91	0,92	1,04	0,67

Tab. 3b *Values of the compressive strength of confined concrete according to the models (part 2)*

5 CONCLUSION

In the table 1 some models of confined concrete are presented .After analysing result of calculations of the compressive strength of confined concrete there are some conclusions. First of all, the smallest average error gives the model of Mirmiran [12]. The best value of average $f'_{cc.exp}/f'_{cc.model}$ gives the model of Karbhari and Gao [13]. Some models work better for different specimens‘ sizes. Probably, the problem could be solved by using better estimation of χ. For The model of Wang and Wu's [20] and Cevik [19] do not work well in most of cases. General models work quite well for this researches. Some FRP models can be adopted for concrete confined by steel spirals.

One of the most important observation was the fact that specimens confined by higher strength steel do not suit well to most of models. The problem could appear because confining steel could be plain (not ribbed). This kind of steel does not confine concrete effectively. The results would be different if the value of angle α is different.

More test for high strength steel bar should be prepared. Most of this models should be checked with high strength concrete. Another researches could check how this models work for concrete in anchorage zones or in partial loaded areas with high compressive forces.

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