ANALYSIS OF THE FAILURE MODE OF FRC BEAMS LOADED AXIALLY AND TRANSVERSALLY

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Abstract

Within the innovation process a prestressed pier of noise barrier was designed instead of conventional reinforced concrete one. Results of full-scale tests of piers are analysed in the paper. Arrangement of the test set-up is discussed and its consequences on the failure mode of tested element. Values of load at cracking and ultimate loads are compared for reinforced concrete piers, prestressed piers from SFRC (steel fibre reinforced concrete) and from fibre reinforced concrete with synthetic fibres and prestressed piers from common concrete without fibres. Full scale tests and their analysis showed that prestressed piers have higher load-bearing capacity, enhanced durability and they are more economic than common reinforced concrete pier..

Keywords: Fibre-Reinforced-Concrete, full-scale testing, prestressed element, pier of noise barrier

1. Introduction

Cooperation of research institutes and industrial sphere can bring innovatory businesslike results. Our department used to cooperate with production firms on development of new technologies and products from fibre reinforced concrete.

One of such cooperation regarded change of production technology and design of a noise-barrier supporting pier.

2. Design of a new product

The original pier of a noise-barrier has I-shaped profile; it's made from concrete with common rebar reinforcement in longitudinal direction and shear reinforcement (fig. 1).

The enhanced pier was designed as a pre-stressed element from fibre reinforced concrete. Pre-stressing is provided as pre-tensioning by two strands. There is no other rebar reinforcement in the element (fig. 2). Fibre reinforced concrete was provided in two variants – with synthetic fibres and with steel fibres.

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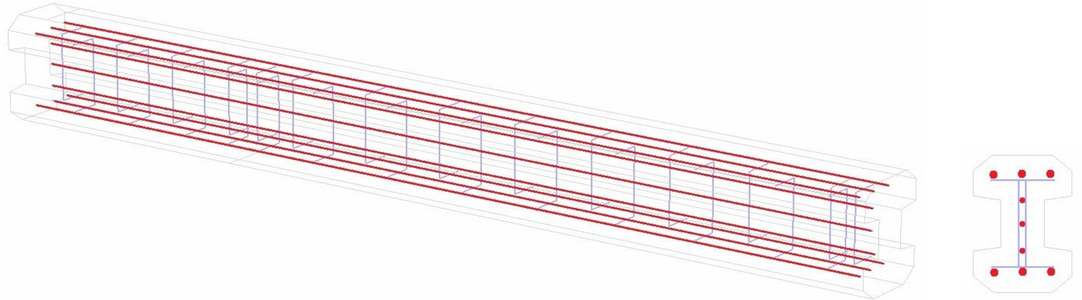

Fig. 1: Line model of the original RC pier (longitudinal reinforcement in red, shear reinforcement in blue)

Fig. 2: End section of a prestressed precast pier

3. Testing program

The testing program included testing of the SFRC (steel fibre reinforced concrete) material properties and full-scale tests. The full-scale tests were required to verify behaviour of the pier for the certification approval and they were carried out in Klokner Institute of the CTU in Prague.

Mean and characteristic resistance and load-bearing capacity at hair crack (width 0.2 mm) were followed parameters. The comparative basis for testing was RC pier from common production (fig. 1).

In the first stage precast piers without anchorage block were tested. The piers were loaded as cantilevers by transversal force F applied at one end; fixed support was represented by couple of forces on lever arm z ≈ 0,4 m. The supporting lead to shear failure at formation of crack at the level of loading force $F_{cr,m}$ = 4,0 kN. The shear crack formed between two fixing steel ribbon stays that represented real supporting conditions of the pier. Such shear crack would not happen in real foundation of the pier. That's why this type of laboratory supporting was declared incorrect and a new set-up of test was proposed.

In the subsequent stage of testing program supporting of test piers was constituted by rigid concrete body. The length of anchoring of the pier in the concrete anchorage block was varied – three different heights of the block were tested: 600 mm, 800 mm and 1 000 mm.

The investigated types of piers were:

Type A – piers from concrete with common rebar longitudinal and shear reinforcement

Type B – concrete, pre-tensioned

Type C – fibre reinforced concrete (synthetic fibres), pre-tensioned

Type DF – steel fibre reinforced concrete, pre-tensioned

Non-prestressed pier is manufactured from concrete class C 35/45. All prestressed piers B, DF a C are made from concrete class C 55/67. The higher concrete class was chosen to limit the losses of prestress and enhancing of bond of strands and quality concrete. Survey of tested specimens is in a table 1.

Tab.1: Required design resistance of piers

Type	Materials – concrete and reinforcement	max [kN]
A	Pier from concrete C 35/45 with common reinforcement (6ø 12 + 3 ø 10)	22
B	Prestressed pier; concrete C 55/67, pretensioned by two strands ø15,7 mm, σ_p = 1375 MPa without fibres and without mild reinforcement and shear reinforcement	32
C	Prestressed pier; concrete C 55/67, pretensioned by two strands ø15,7 mm, σ_p = 1375 MPa with synthetic fibres 3M and without mild reinforcement and shear reinforcement	32
DF	Prestressed pier; concrete C 55/67, pretensioned by two strands ø15,7 mm, σ_p = 1375 MPa with steel fibres Fibrex and without mild reinforcement and shear reinforcement	32

3.1 Results of experiments

The resistance and durability of piers was analysed in terms of load at creation of the hair crack (width 0.2 mm) – average loading $F_{cr,m}$ and characteristic loading $F_{cr,k}$ – and at ultimate loading – average load $F_{u,m}$ and characteristic load $F_{u,k}$.

Tab.2: List of tests

Indication of set	Typ of pier	Concrete class	Type of reinforcement	Fibres	Height of anchorage block	Indication of specimen
SL11	"A"	C 35/45 XF4	Mild reinforcement B505B	Without fibres	600	779/11
						780/11
						781/11
SL12	"B"	C 55/67 XF4	Prestressing two strands σ_p=1375 MPa	Without fibres	600	782/11
						783/11
						784/11
SL13	"B"	C 55/67 XF4	Prestressing two strands σ_p=1375 MPa	Without fibres	800	785/11
						786/11
						787/11
SL14	"B"	C 55/67 XF4	Prestressing two strands σ_p=1375 MPa	Without fibres	1000	788/11
						789/11
						790/11
SL15	"DF"	C 55/67 XF4	Prestressing two strands σ_p=1375 MPa	Steel fibres	800	791/11
						792/11
						793/11
SL16	"DF"	C 55/67 XF4	Prestressing two strands σ_p=1375 MPa	Steel fibres	600	1040/11
						1041/11
						1042/11
SL17	"C"	C 55/67 XF4	Prestressing two strands σ_p=1375 MPa	Synthetic fibres	800	1145/11
						1146/11
						1147/11

Fig. 3: Full-scale test; pier is fixed in anchoring block with height h_p = 600mm

Tab.3: Loads at cracking

Indication of set	Typ of pier	Type of reinforcement	Fibres	Height of anchorage block	Load at cracking > 0,2mm [KN]	
SL11	"A"	Mild reinforcement B505B	Without fibres	600	9,8 12,8 14,5	$F_{cr,m}$ = 12,4 $F_{cr,k}$ = 7,85
SL12	"B"	Prestressing two strands σ_p=1375 MPa	Without fibres	600	30,0 24,0 30,0	$F_{cr,m}$ = 28,0 $F_{cr,k}$ = 21,5
SL13	"B"	Prestressing two strands σ_p=1375 MPa	Without fibres	800	30,0 32,5 28,0	$F_{cr,m}$ = 30,2 $F_{cr,k}$ = 25,9
SL14	"B"	Prestressing two strands σ_p=1375 MPa	Without fibres	1000	28,5 30,3 30,0	$F_{cr,m}$ = 29,6 $F_{cr,k}$ = 27,8
SL15	"DF"	Prestressing two strands σ_p=1375 MPa	Steel fibres	800	34,0 33,0 34,0	$F_{cr,m}$ = 33,7 $F_{cr,k}$ = 32,6
SL16	"DF"	Prestressing two strands σ_p=1375 MPa	Steel fibres	600	36,5 32,4 30,0	$F_{cr,m}$ = 33,0 $F_{cr,k}$ = 26,8
SL17	"C"	Prestressing two strands σ_p=1375 MPa	Synthetic fibres	800	34,7 33,7 36,5	$F_{cr,m}$ = 35,0 $F_{cr,k}$ = 32,3

Tab.4: Ultimate load

Indication of set	Typ of pier	Type of reinforcement	Fibres	Height of anchorage block	Ultimate load [kN]		Charekteristic load F_{uk}[kN] standard deviation s_k [kN]
SL11	"A"	Mild reinforcement B505B	Without fibres	600	36,1	F_{um} = 36,3	F_{uk} = 35,6 s_k = 0,7
					36,7		
					36,1		
SL12	"B"	Prestressing two strands σ_p=1375 MPa	Without fibres	600	44,2	F_{um} = 42,7	F_{uk} = 40,0 s_k = 2,7
					41,3		
					42,6		
SL13	"B"	Prestressing two strands σ_p=1375 MPa	Without fibres	800	42,0	F_{um} = 41,7	F_{uk} = 39,1 s_k = 2,6
					42,9		
					40,2		
SL14	"B"	Prestressing two strands σ_p=1375 MPa	Without fibres	1000	44,5	F_{um} = 43,5	F_{uk} = 41,5 s_k = 2,00
					43,6		
					42,4		
SL15	"DF"	Prestressing two strands σ_p=1375 MPa	Steel fibres	800	43,5	F_{um} = 43,5	F_{uk} = 43,3 s_k = 0,10
					43,4		
					43,5		
SL16	"DF"	Prestressing two strands σ_p=1375 MPa	Steel fibres	600	44,0	F_{um} = 42,4	F_{uk} = 38,7 s_{uk} = 3,70
					43,0		
					40,2		
SL17	"C"	Prestressing two strands σ_p=1375 MPa	Synthetic fibres	800	42,2	F_{um} = 42,4	F_{uk} = 41,4 s_k = 0,90
					42,0		
					42,9		

Comparison of behaviour of the piers anchored in a block with 600 mm height is depicted in the figure 4. Characteristic values $F_{cr,k}$ and $F_{u,k}$ are compared as they represent also the variance of the loads.

Notes to figure 4:

The related types of piers are:

- A (reinforced concrete pier; concrete C35/45, without fibres)
- B (pre-tensioned piers, concrete C55/67, without fibres)
- DF (pre-tensioned piers, concrete C55/67, with steel fibres)
- C (pre-tensioned piers, concrete C55/67, with synthetic fibres)

Load at crack width 0,2 mm average value $F_{cr,\,0,2,\,m}$

characteristic $F_{cr,\,0,2,\,k}$

Ultimate load average value $F_{u,\,m}$

characteristic $F_{u,\,k}$

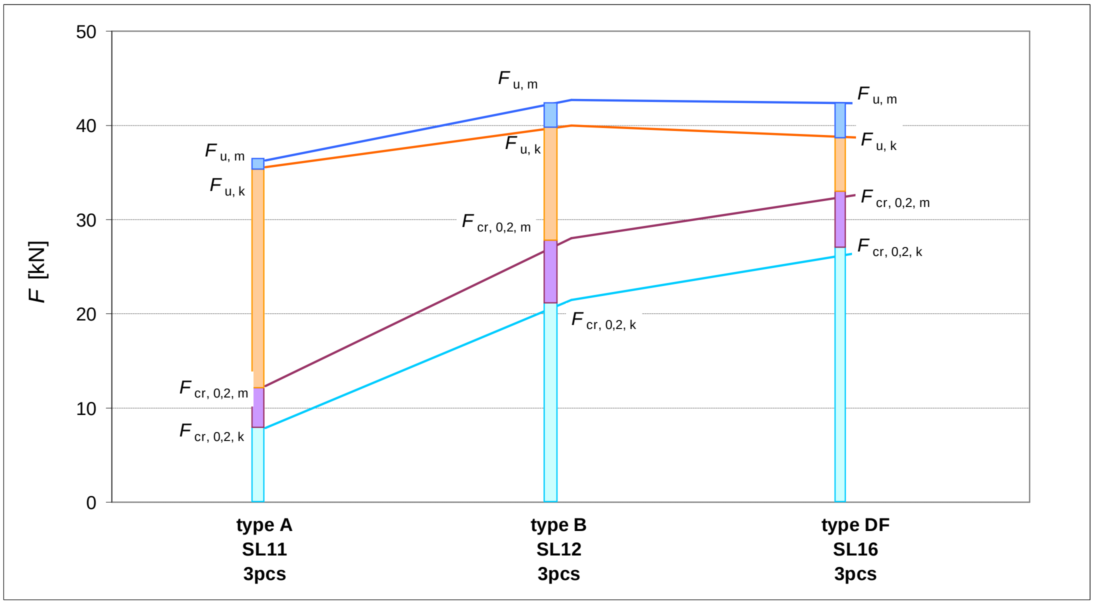

Fig. 4: Comparison of resistance of piers with anchorage block h_p = 600 mm

Tab.5: Tab 5: Summary of load values from figure 4

	SL 11 type A	SL 12 type B	SL 16 type DF
$F_{u,\ m}$	36,3	42,7	42,4
$F_{u,\ k}$	35,6	40,0	38,7
$F_{cr,\ 0,2,\ m}$	12,4	28,0	33,0
$F_{cr,\ 0,2,\ k}$	7,85	21,5	26,8

3.2 Discussion of the results

The efficiency of the newly designed pre-tensioned pier is evident from table 6. Results of the tests of prestressed piers (type B and type DF) with anchorage lock of height h_p = 600 mm are related to the common pier reinforced with mild rebar reinforcement.

Tab.6: Comparison of load at cracking and resistance load related to RC pier

		Type A	**Type B**	**Type DF**
Hair crack	$F_{cr,m}$	100%	226%	266%
	$F_{cr,k}$		274%	341%
Resistance	$F_{u,m}$		118%	117%
	$F_{u,k}$		112%	109%

Prestressing and utilisation of FRC (fibre reinforced concrete) substantially enhance service life of piers and durability of concrete.

From table 2 follows that for pier type B prestressing increases limit state of cracking; it is higher by 126% at average and for decisive characteristic value the increase is even by 174%.

Increase of the resistance is not so high for both prestressed types of piers (DF and C). Average value increased by 18%; characteristic by 10%.

3.3 Analysis of anchor length of pre-tensioned piers related to height of anchorage block h_p

As described above the piers in real conditions are cantilevers fixed in the basement. That signifies that the peak moment is at the bottom of piers and safe anchoring of reinforcement in the basement can be decisive for reliability of the structure.

Effect of anchor length of prestressing strands was also investigated in the full-scale tests. Values of ultimate loads were followed for three tested lengths of anchoring e.g. threes heights h_p of anchoring blocks.

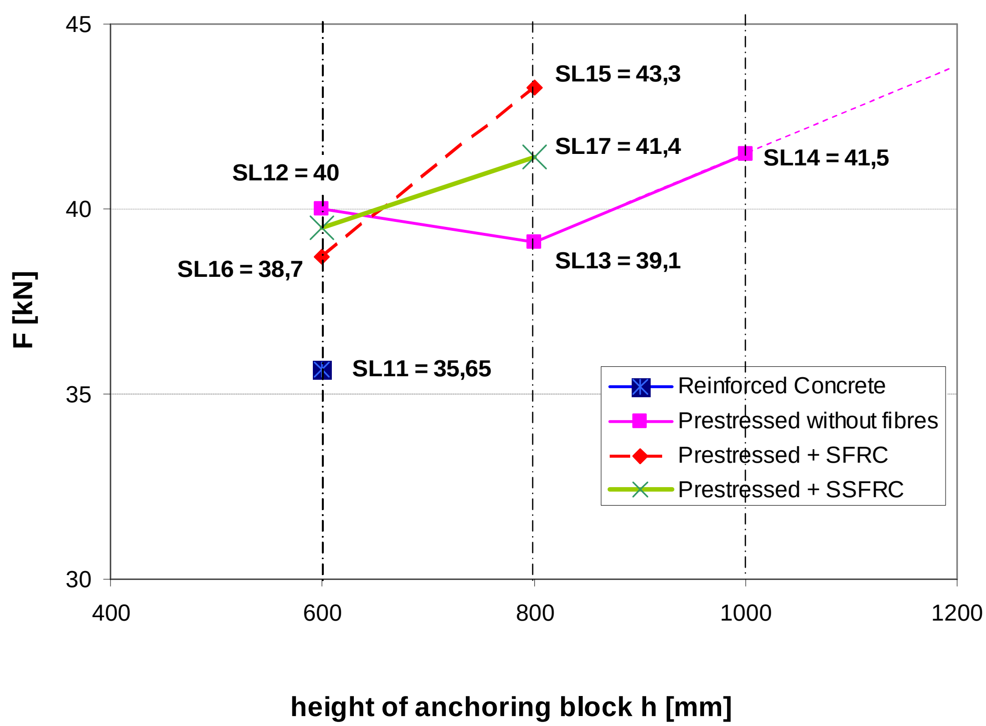

Fig. 5: Comparison of characteristic load-bearing capacities F_{uk} of all tested sets of piers related to height of anchoring block h_p

The effect of fibres on the anchoring of prestressed piers in terms of ultimate resistance $F_{uk,i}$ / $F_{uk,i}$ (fibre reinforced concrete / concrete) is discussed in this clause.

- SL 15/SL 14:

$F_{uk,15}$ / $F_{uk,14}$ = 43,3 kN / 41,5 kN = 1,045

Anchoring: h_{15} / h_{14} = 0,8 / 1,0 = 0,8

Characteristic deviation: $s_{k,15}$ / $s_{k,14}$ = 0,1 / 2,0 = 0,05

Findings: Load-bearing capacity of pier anchored in steel fibre reinforced concrete h_{15} = 800 mm is by 4,5% better than load-bearing capacity of pier anchored h_{14} = 1000 mm in concrete without fibres.

- SL 17/ SL 14:

$F_{uk,17}$ / $F_{uk,14}$ = 41,4/ 41,5 = 0,998 ≈ 1,0

Anchoring: h_{17} / h_{14} = 0,8 / 1,0 = 0,8

Characteristic deviation: $s_{k,17}$ / $s_{k,14}$ = 0,9 / 2,0 = 0,45

Findings: Load-bearing capacity of pier from fibre reinforced concrete with synthetic fibres anchored h_{17} = 800 mm is practically same as load-bearing capacity of pier from common concrete anchored one meter in anchoring block (h_{14} = 1000 mm). But the load bearing capacity of SFRC (steel fibre reinforced) pier is higher.

Higher anchoring length is required in piers without fibres as the piers are not provided with the transversal reinforcement.

Tab.7: Effect of the height of anchoring block and used fibres on characteristic ultimate load-bearing capacity F_{uk} of prestressed piers, sets 14, 15 and 17 (see tab. 4)

Type of element	Indication of set	$F_{uk,i}$	$s_{k,i}$	h_i	Fibres
Prestressed	SL 14	41,5 (100%)	2,0	1000	–
Prestressed	SL 15	43,3 (104%)	0,1	800	Steel fibres
	SL 17	41,4 (100%)	0,9	800	Synthetic fibres

3.4 Analysis of safety margin of the load-bearing capacity of prestressed piers

Prestressed piers have higher load-bearing capacity and resistance than reinforced concrete piers. For prestressed pier is important height of anchoring block. The tests showed that for smaller height h_p of anchoring block is important effect of fibres that prevent microcracking in anchoring zone of prestressing strands and sudden loss of bond after creation of macrocrack.

Tab.8: Safety margin γ_{Fj} of load-bearing capacity with respect to required resistance

$\gamma_{Fj} = F_{um} / F_{um, req}$		
Type j	Height of anchoring block h_p	
	600 mm	800 mm
B	42,7 / 32,0 = 1,33	41,7 / 32,0 = 1,30
DF	42,4 / 32,0 = 1,32	43,5 / 32,0 = 1,36
C	-	42,4 / 32,0 = 1,32

Safety $\gamma_{F,j} \geq 1{,}3$ is acceptable for fibre reinforced piers (type DF a C). For piers without fibres (type B) the safety should be increased to $\gamma_{F,B} \geq 1{,}5$.

4. Conclusions

Efficacious way to innovate production, to reduce and economize products can be utilisation of fibre reinforced concrete in structural elements. Such innovation was used for a pier of noise barriers; the pier was changed concerning material and technology of production.

Piers of noise barriers are extremely strained and their design is not elementary. They must resist wind pressure, vehicle crash, their position close to roadways implies incidence of de-icing salts. So the demands on durability are high. The change of production technology from conventionally reinforced element to prestressed one minimised cracking. Thus the durability was enhanced. The durability is also favourably affected by use of fibres. The increase of durability and minimising of maintenance and repairs is one source of cutting of price. Second aspect of price reduction is in decrease of workability during production.

Full scale test presented in the paper proved also higher load-bearing capacity of innovated, e.g. prestressed piers.

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