



EXPERIMENTAL AND NUMERICAL ANALYSIS OF FLEXURAL COMPOSITE BEAMS WITH PARTIAL USE OF HIGH STRENGTH/HIGH PERFORMANCE CONCRETE

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Abstract. The paper summarises the experimental and numerical analysis of flexural capacity and deformability of structural concrete beams prepared as composite members consisting of two concrete layers made of reinforced normal concrete and high-performance concrete (HPC).

The reinforced concrete composite beams used in the tests were prepared in full scale with the cross-section of 120 x 200 mm and the effective span of 2950 mm. The basic samples were composed in two layers consisting of high-performance concrete as the top layer, and normal strength concrete. The results of the analyses confirm a significant improvement of structural properties of composite beams in comparison to the beams prepared totally of normal concrete, and in some cases also in comparison with the beam totally made of HPC.

Keywords: composite beam, high-performance concrete, flexural capacity, deformability, full-scale beam tests.

1. Introduction

In the last decade HPC-HSC are more widely used in practice parallel with growing interest of researchers to precisely describe mechanical properties and methods of design of structural members [1-4]. Simultaneously some new conceptions in this field have been presented, for example, in composite structures, where HPC-HSC are partially used [5].

As reported by Yamada [6, 7], the structural reinforced concrete and prestressed composite beams with the HSC layer tested in Japan under short-time load, may have improved sectional parameters, eg a higher flexural stiffness and greater bending capacity in comparison to homogenous members, made of normal strength concrete. Hybrid reinforced concrete composite beams show intermediate behaviour between reinforced concrete beams made of high-strength concrete and beams of normal strength concrete.

Our previous studies conducted on models of reinforced concrete composed with a partial use of HPC beams under short-time loading revealed the significant increase of beam stiffness and ultimate capacity in bending, compared to control RC beams made of normal concrete [8-10]. In this paper the selected results of experimental and numerical analysis of such composite beams in natural scale are presented and discussed.

2. Experimental investigations

The reinforced concrete composite beams were prepared with the cross-section of 120 × 200 mm and the effective span of 2950 mm. The composite beams were cast, as follows:

- Normal concrete as the bottom layer
- Adhesive layer
- HPC layer on the top of the beam with the thickness of 40 mm.

The HPC-HSC composition was elaborated [11] based on the cement type CEM I-42,5, natural fine aggregate 0-2 mm, and the fine basalt aggregate with fractions 2-8 mm together with the silica fume and superplasticising admixture Dynamon SX-N from Rescon Mapei AS. In normal concrete composition the same type of cement and natural fine aggregate of 0-2 mm, 2-8 mm has been used. The surface contact between normal and HPC concrete layers in composite beams was improved by a liquid adhesive agent from Ombran System; at the top of the normal concrete a hardened layer before the HPC layer was cast. Typical characteristics of concrete mixes and mechanical properties in hardened state of concrete used in the experimental beams are given in Table 1.

After 28 days curing of samples in air-dry environment, the tests were performed, including the observations and measurement of selected physical properties:

Table 1. Data composition and properties of concrete used in tests

Concrete	Concrete classes	Properties of concrete mix per 1 m ³			Mean strength of concrete	
		w/c	k/c	s/c	f _{cm cube} [MPa]	f _{ctm,sp} [MPa]
HPC	B105	0,25	2,42	0,10	115,40	6,2
N	B25	0,50	4,13	---	25,35	2,1

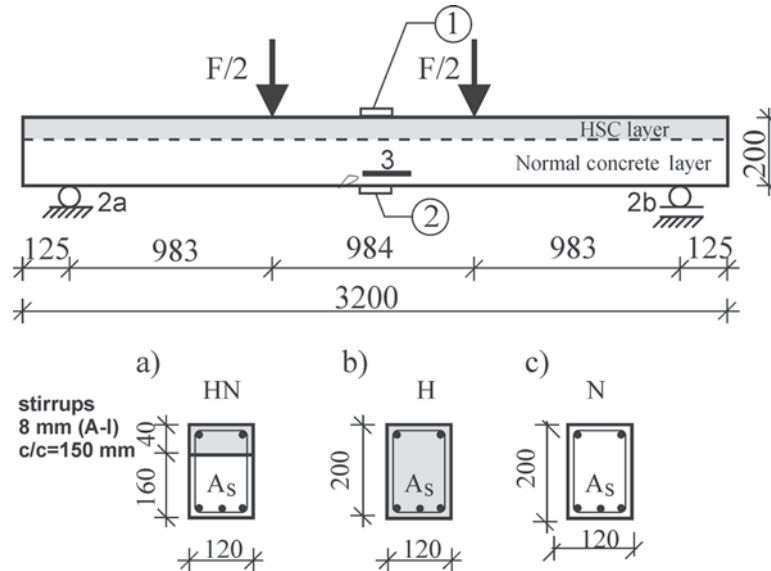


Fig 1. Loading scheme, cross-sections and zones of measurements in the tested beams:

a) composite beam, b) control homogeneous beam made of HPC, c) control normal concrete beam, 1 – zone of compressive strain measurement, 2, 2a, 2b – zones of deflection registration, 3 – tensile steel strain measurement

- Short-time concrete compressive strains on the top of beams.
- The beam deflections measured at a half span of each beam and near to the bearings.
- The analysis of crack pattern during loading.
- Bending capacity for basic and control beams.
- Concrete strains at the cross-section height on the side surface of the beam.

Based on preliminary model beam analyses, the tested beams were singly reinforced by the ribbed steel bars class A-III ($f_{yd} = 455$ MPa, $E_s = 200$ GPa) according to Polish Code PN-B-03264:2002 [12] with 3 % reinforcement ratio.

The characteristics of main and control beams and reinforcement in respective series are given in Table 2.

Table 2. Main characteristics of tested composite beams

Type of the beam	h_{HPC} / h_{tot} layer depth ratio*	Tension steel of the beam	Reinforcement ratio
Composite HN	0,20	3 ϕ 16	3 %
Control H	1,00		
Control N	0,00		

* h_{HPC} and h_{tot} – the depth of the layer made of HPC and the total depth of the beam

Each series consists of three beams. Cross-sections of the specimens and loading conditions during testing are shown in Fig 1.

The view of the composite beam is presented in Fig 2. The HPC layer at the top is shown by grey colour.

The concrete strains and beam deflections were measured using a computerised system of registration

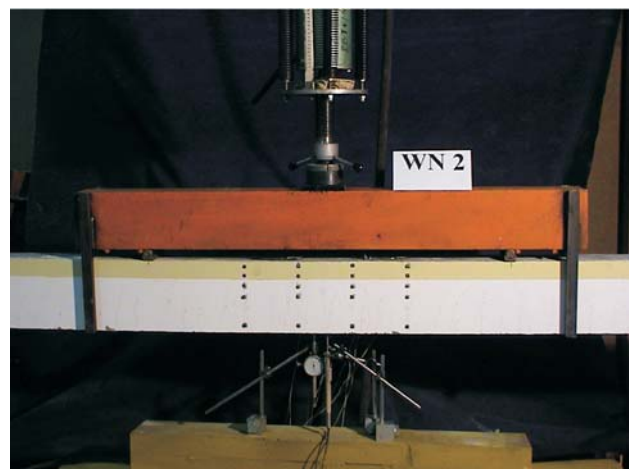


Fig 2. The composite beam on the test stand in the testing machine

DaqBook made in USA equipped by inductive sensors of Peltron type with the reading accuracy of 0,001 mm. The concentrated load subjected to the tested beams was registered with the accuracy of 100 N.

3. Analysis of short-time effects under bending

The measured values of compressive strains and beam deflections are related to the mean values for all the samples tested in each series for the chosen force level. Selected results of investigations, describing experimental relationships between loading force F and deflection a and compressive strains ϵ_c for composite beams and also for homogeneous control beams are presented in Fig 3a, 3b.

As we can see, the composite beams reveal distinctly lower concrete compressive strains, in comparison not only with normal concrete control beams but also with control beams made totally of HPC.

The quantitative effects of the use of HPC layer on the composite beam behaviour has been defined as the coefficient k_α computed by the general formula [9]:

$$k_\alpha = \alpha_N / \alpha_{HPC}, \tag{1}$$

where:

α_N – effects (strains, deflection, crack width) measured on homogenous control beams made of normal strength concrete;

α_{HPC} – respective effects measured on the beams made with the use of HPC layer.

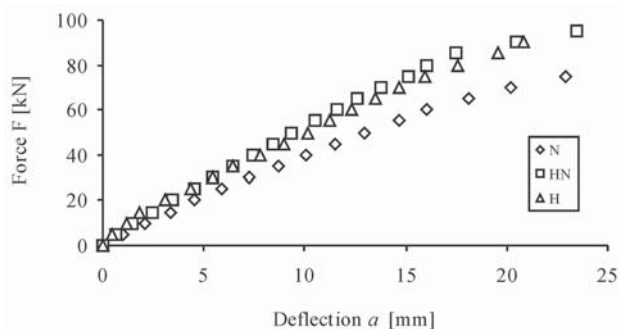


Fig 3a. Experimental relationships obtained from an experimental analysis of loading force F deflection

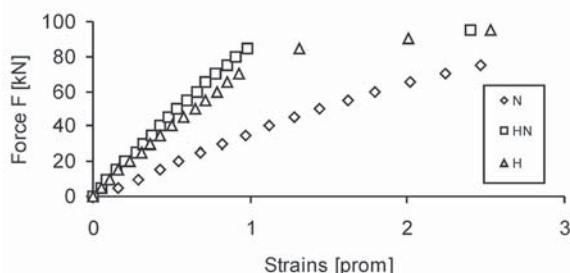


Fig 3b. Experimental relationships obtained from an experimental analysis of loading force F compressive strains

The selected values of coefficient k_a computed for measured deflections from the above formula for chosen three levels of the load are presented in Table 3.

Table 3. Quantitative effects of the use of HPC layer on beam deflection

Beam type	Deflection a [mm] of the beam					
	$F = 45$ kN		$F = 55$ kN		$F = 65$ kN	
	a	k_a	a	k_a	a	k_a
Control N	11,536	1,00	14,643	1,00	18,114	1,00
Composite HN	8,450	1,36	10,469	1,40	12,592	1,44
Control H	9,004	1,28	11,222	1,30	13,492	1,34

The results of investigations in Table 3 indicate that the tested reinforced concrete composite beams made with a partial use of HPC have a relatively higher stiffness in comparison to stiffness of homogenous control beams made of normal concrete. For the load level 50 kN (equal to about 60 % of carrying capacity) the composite beam revealed the stiffness equal or even a little larger than the beam totally made of HPC.

This effects are due to stress and strain state redistribution in the zone of contact between HPC and normal concrete.

4. Flexural capacity of composite beam

The tested beams have been statically loaded to failure. The failure mechanism of composite beams was without splitting on the contact surface between HPC and normal concrete layers. The mean values of flexural capacities of the beams of destructive tests for three series are compared in Table 4.

For the considered beams series, the quantitative effect of strengthening by HPC layer on the bending capacity of the beams was evaluated as the experimental coefficient m :

$$m = M_{b,HPC} / M_{b,N}, \tag{2}$$

where:

$M_{b,HPC}$ – measured mean carrying capacity of the beam made with the use of HPC;

$M_{b,N}$ – measured mean carrying capacity of the normal concrete control beam.

Table 4. Carrying capacity of beams and the effect of HPC use

Beam type	Mean carrying capacity [kNm]		HPC effect on beam capacity coefficient m according to formula (2)	
	Experimental	Computer analysis	Experimental	Computer analysis
Composite HN	47,37	43,27	1,31	1,23
Control H	46,05	42,60	1,27	1,21

5. Numerical analysis

Numerical analysis of given composite beams are performed using the discretisation of the cross-section for α layers and taking into account the non-linear behaviour of concrete in compression and Bernoulli principle.

Concrete relationship σ - ϵ has been described by the relationship in EC2 [11].

$$\sigma_\alpha = f_{cm} \frac{k\eta_\alpha + \eta_\alpha^2}{1 - (k-2)\eta_\alpha}, \quad \eta_\alpha = \frac{\epsilon_\alpha}{\epsilon_{c1}}, \quad (3)$$

where the positive values of σ_α and ϵ_α denote tensile stresses and strains in the respective layer α .

For the tension in steel reinforcement, the linear relationship has been assumed:

$$\sigma_\alpha = \begin{cases} E_s \epsilon_\alpha, & \epsilon_\alpha \leq f_{yd} / E_s, \\ f_{yd}, & \epsilon_\alpha > f_{yd} / E_s. \end{cases} \quad (4)$$

The numerical algorithm is based on solving the system consisting of two non-linear equations and two unknowns: z (the neutral axis depth) and κ (curvature of section)

$$\begin{cases} f(z, \kappa) = \sum_{\alpha=0}^n A_\alpha \sigma_\alpha = 0 \\ g(z, \kappa) = \sum_{\alpha=0}^n A_\alpha \sigma_\alpha (z - z_\alpha) - M = 0. \end{cases} \quad (5)$$

For the numerical solution of this problem, the commonly used iteration method of Newton has been applied. As the initial approximation for the Newton process, the general formulas are used:

$$z^0 = \frac{\sum_{\alpha=0}^n E_\alpha A_\alpha z_\alpha}{\sum_{\alpha=0}^n E_\alpha A_\alpha}, \quad \kappa^0 = \frac{M}{\sum_{\alpha=0}^n E_\alpha A_\alpha (z - z_\alpha)^2}, \quad (6)$$

where:

- σ_α – tensile stresses in the layer α ,
- A_α – cross-sectional area for layer α ,
- z_α – distance of layer α from the bottom,
- E_α – coefficient of elasticity for layer α .

The cracking effects are modelled by the iteration process in which at any step of design one consecutive layer after cracking, was eliminated.

The condition of elimination of cracking concrete layer i was assumed to be:

$$\sigma_\alpha > f_{ctm}, \quad (7)$$

where f_{ctm} – mean tensile strength.

The layers made of steel (modelled steel bars) have been not eliminated.

For concrete, according to prEN [13], basing on mean compressive strength f_{cm} the following properties, have been evaluated:

$$\begin{aligned} E_{cm} &= 22[(f_{cm})/10]^{-3} \quad \epsilon_{c1} = 0,7 \cdot f_{cm}^{0,31}, \\ f_{ctm} &= \{0,30(f_{cm} - 8)\}^{2/3}, f_{cm} < 58MPa, \\ f_{ctm} &= \{2,12 \ln[1 + (f_{cm}/10)]\}, f_{cm} \geq 58MPa. \end{aligned} \quad (8)$$

6. Numerical simulation of composite beams in full scale

Based on the given relationships, the computer procedures were elaborated and the numerical simulation of the same composite beams used in experimental investigations were analysed. In the analysis, the respective HPC layer depths were differentiated assuming values equal to $w = 20, 30, 40$ and 50 mm (giving the non-dimensional ratios equal to $0,10; 0,15; 0,20$ and $0,25$ of total beam depth).

The numerical analyses of maximum concrete compressive strains, curvature and carrying capacities of the beams were performed. The selected results of respective composite beams for different thickness of HPC layer are shown below in diagrams and tables.

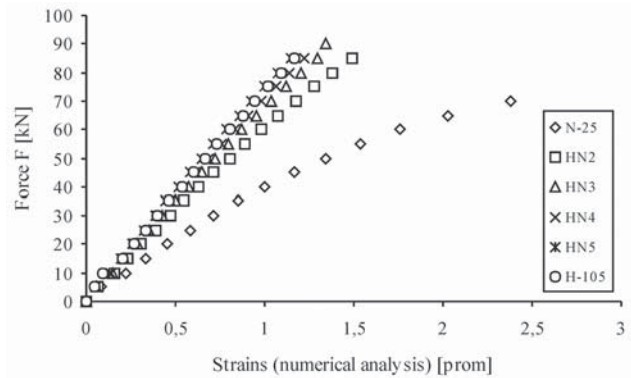


Fig 4. Numerical relationships between load F and compressive strains ϵ_c [%] on the top of beams (HN2, HN3, HN4 and HN5) and control beams made totally of normal strength concrete (B-25) and HPC (B-105)

Table 5. Concrete compressive strains ϵ_c [%] on the top of beams (numerical analysis)

Type of beam	$\delta = \frac{w}{h}$	Concrete compressive strains ϵ_c [%]				
		$F= 25$ [kN]	$F= 35$ [kN]	$F= 45$ [kN]	$F=55$ [kN]	$F= 65$ [kN]
Control N	---	0,578	0,852	1,164	1,537	2,027
Composite HN 2	0,10	0,390	0,545	0,734	0,891	1,077
Composite HN 3	0,15	0,351	0,497	0,648	0,793	0,953
Composite HN 4	0,20	0,339	0,471	0,613	0,750	0,900
Composite HN 5	0,25	0,321	0,447	0,581	0,717	0,857
Control H	1,00	0,337	0,467	0,605	0,735	0,878

Table 6. The quantitative comparison of strains ϵ_c [%] in composite beams and control beams (H, N)

	$F= 25$ [kN]		$F= 35$ [kN]		$F= 45$ [kN]		$F=55$ [kN]		$F= 65$ [kN]	
HN 2	<u>0,578</u>	1,48	<u>0,852</u>	1,56	<u>1,164</u>	1,59	<u>1,537</u>	1,73	<u>2,027</u>	1,88
N	0,390		0,545		0,734		0,891		1,077	
HN 3	<u>0,578</u>	1,65	<u>0,852</u>	1,71	<u>1,164</u>	1,80	<u>1,537</u>	1,94	<u>2,027</u>	2,13
N	0,351		0,497		0,648		0,793		0,953	
HN 4	<u>0,578</u>	1,70	<u>0,852</u>	1,81	<u>1,164</u>	1,90	<u>1,537</u>	2,05	<u>2,027</u>	2,25
N	0,339		0,471		0,613		0,750		0,900	
HN 5	<u>0,578</u>	1,80	<u>0,852</u>	1,91	<u>1,164</u>	2,00	<u>1,537</u>	2,14	<u>2,027</u>	2,36
N	0,321		0,447		0,581		0,717		0,857	

Table 7. Flexural curvatures χ [1/m] of the composite beams with the ratio $\delta = 0,10; 0,15; 0,20; 0,25$

Force F [kN]	Control N	Composite $HN 2$	Composite $HN 3$	Composite $HN 4$	Composite $HN 5$	Control H
20	0,00548	0,00450	0,0043	0,00424	0,0042	0,00418
30	0,00846	0,00681	0,0066	0,00644	0,0064	0,00634
40	0,0117	0,00919	0,0088	0,00863	0,0086	0,00853
50	0,0152	0,0116	0,0111	0,01084	0,0107	0,0107
60	0,0193	0,0140	0,0134	0,0131	0,0130	0,0129

The respective quantitative comparison of strains is presented in Table 6.

Comparative analysis of maximal compressive concrete strains of beams HN2, HN3, HN4, HN5 and homogeneous control beams showed that the strains of the beam HN5 are about two times smaller than the control beams made of normal concrete.

In Table 7 the numerical values of beam curvatures χ for the beams of types HN2, HN3, HN4 and HN5 for the chosen values of loading forces are presented. The respective relationships F - χ are shown in Fig 5.

Comparison of composite flexural beam curvatures χ with the respective control beam curvatures revealed that the smallest value of curvature was for the beam HN5 ($\delta = 0,25$). For this case the curvature were about 42 % smaller in comparison with the control beam made of normal concrete and almost equal to the curvature of control beam made totally of HPC.

Numerically and experimentally predicted flexural capacities for respective composite and control beams are presented in Table 8. The discrepancies between experimental and numerical results are not significant – not larger than 10 %.

Table 8. Carrying capacity M_{Rd} [kNm] (experimental and numerical analysis)

Type of beams	Carrying capacity (numerical analysis) [kNm]	Carrying capacity (experimental analysis) [kNm]
Control N	35,20	36,23
Composite HN 2	43,00	----
Composite HN 3	43,27	----
Composite HN 4	43,27	47,37
Composite HN 5	42,90	----
Control H	42,60	46,05

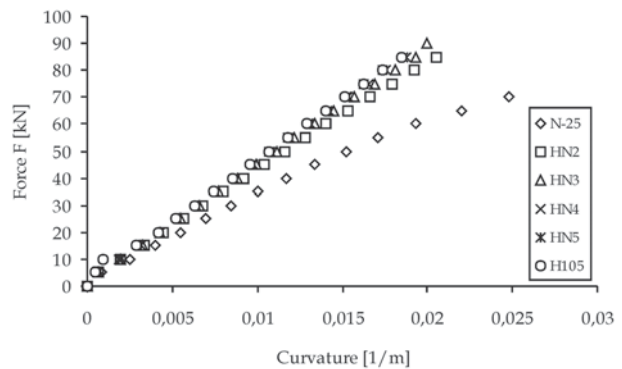


Fig 5. Numerical relationships between load F and curvature χ [1/m] for composite beams (HN2, HN3, HN4, HN5) and control beams made totally of normal strength concrete (B-25) and HPC (B-105)

The numerical analysis revealed that the composite beams with different depth of HPC layers have the carrying capacity almost equal to the control beam totally made of HPC. Composite beams revealed about 22 % of flexural larger capacity in comparison with normal concrete control beam.

7. Conclusions

The experimental and numerical analyses conducted on reinforced concrete composite beams made of normal concrete within HPC layer revealed various positive effects of strengthening the composed beams compared to homogenous, normal strength concrete beams.

Bending tests conformed to significantly reduced compressive strains and deflections measured in composite beams in comparison with the strains and deflections measured in control beams made of normal concrete. This positive static effects can be explained by the redistribution of stresses and strains in the composite beams.

The influence of HPC layer on flexural carrying capacity of the composite beams with HPC layer depends on reinforcement ratio of beam section. For tested beams with ratio $\rho = 3\%$, the predicted experimentally bending capacity was about 31% higher, compared to the capacity of homogeneous beams of normal strength concrete.

The analyses showed the possibility of applications of such composite flexural structures in strengthening the structural concrete members in rehabilitation and reconstruction works.

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STIPRIOJO LABAI FUNKCIONALAUS BETONO LANKSČIŲ KOMPOZITINIŲ SIJŲ EKSPERIMENTINIS IR TEORINIS TYRIMAS

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Santrauka

Pateikiami iš normalaus stiprio bei labai funkcionalių betonų pagamintų kompozitinių sijų eksperimentinės bei teorinės analizės rezultatai. Bandymai buvo atlikti su 120×200 mm skerspjūvio ir 2 950 mm tarpatramio gelžbetoninėmis kompozitinėmis sijomis. Pagrindiniai bandiniai buvo pagaminti iš dviejų sluoksnių: iš labai funkcionalaus betono (viršutinėje skerspjūvio dalyje) bei normalaus stiprio betono. Analizės rezultatai parodė kompozitinių sijų ir sijų, pagamintų vien tik iš normalaus stiprio betono, esminius savybių bei elgsenos skirtumus. Palyginti rezultatai, gauti išbandant sijas, pagamintas vien tik iš labai funkcionalaus betono.

Raktažodžiai: kompozitinė sija, labai funkcionalus betonas, laikomoji galia, deformavimas, natūralaus dydžio sijos bandymai.

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