International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:6, No:3, 2012

Long-term Flexural Behavior of HSC beams

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Abstract**—**This article presents the analysis of experimental values regarding cracking pattern, specific strains and deformability for reinforced high strength concrete beams. The beams have the concrete class C80/95 and a longitudinal reinforcement ratio of 2.01%, respectively 3.39%. The elements were subjected to flexure under static short-term and long-term loading. The experimental values are compared with calculation values using the design relationships according to Eurocode 2.

Keywords**—**High strength concrete, beams, flexure

I. Introduction

A worldwide use of high strength concrete during the last two or three decades and an expansion in the material technology developments has made it possible to design concrete having superior properties, regarding the material and structural behavior [1], [2], [3]. The use of HSC is preferred not only for economical design, but also for its serviceability and durability [4] which are the main concerns of material engineering, especially when long-term service life and sustainability are required. Load history and environmental conditions, as well as the non-linear and time-behavior modeling of concrete create difficulties in deflection prediction. Cracking, tension stiffening, creep and shrinkage of the concrete complicate the serviceability calculations [5]. Therefore an experimental study regarding flexural behavior was conducted on four beams, two of them subjected to short term loading and the other two at long-term loading. Long-term loading step represents 40% from the ultimate value of short-term bending moment. Short-term and long-term effects were evaluated considering the longitudinal reinforcement ratio as a variable parameter.

II. Experimental Program

A. Concrete Composition and Physical Mechanical Characteristics

High strength concrete composition for design class C80/95 is presented in Table I. The physical-mechanical caracteristics of the concrete were determined for each beam at 28 days as well as at the testing age of beams.

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TABLE I
HIGH-STRENGTH CONCRETE COMPOSITION

Components	Quantity
cement CEM I52,5R (C)	520 kg/m^3
silica fume (SF)	52 kg/m^3
coarse aggregates 8/16	686.40 kg/m^3
coarse aggregates4 /8	343.20 kg/m^3
river sand 0/4	686.40 kg/m^3
water (W)	135.20 l/m^3
superplasticiserz (Glenium ACE 30)	15.60 l/m^3
W/C	0.26
W/B (B=C+SF)	0.29

The experimental values of physical and mechanical characteristics obtained at the testing age of the beams are presented in Table II. Specimens were cast from the same batch as the reinforced elements. The geometrical dimensions for the tested specimens are as follows: cubes of 150mm×150mm×150mm to determine the compresion strength (f_{cm}), prisms of 100mm×100mm×300mm for the modulus of elasticity (E_{cm}), prisms of 100×100×550mm for the flexural tensile strength ($f_{ct,fl}$) and cubes of 141mm×141mm×141mm for the tensile splitting strength ($f_{ct,sp}$). Tests were performed acording to RILEM [6] procedure.

TABLE II
PHYSICAL – MECHANICAL CHARACTERISTICS

Characteristics	Beams			
	AD 1-1	AD 1-2	AD 2-1	AD 2-2
f_{cm} (MPa)	107.26	115.20	106.94	106.45
E_{cm} (MPa)	45411	43708	44588	45108
$f_{ct,sp}$ (MPa)	-	4.94	6.06	8.04
$f_{ct,fl}$ (MPa)	12.10	10.34	11.72	11.07

B. Elements design

The beams had the cross-section of b×h=120mm×240mm, length l=3200mm, effective span of 3000mm and concrete cover c=25mm. The reinforcement and test set-up of beams are presented in Table III and Fig. 1 and Fig. 2. The longitudinal reinforcement and stirrups were made of Bst500S steel type, with characteristic yielding strength f_{yk}=500MPa and experimental yielding strain ε_{sy}=2.720‰ [2]. Table III presents the longitudinal reinforcement ratio and mechanical longitudinal coefficient for each beam.

TABLE III
BEAMS REINFORCEMENT

Beams	AD 1-1, AD 1-2	AD 2-1, AD 2-2
Longitudinal reinforcement (A_s)	3Ø14	3Ø18
Reinforcement ratio for longitudinal reinforcement [7] $\rho_l = \frac{A_s \cdot 100}{b \cdot d}$ (1)	ρ_l =2.01 %	ρ_l =3.39 %
Mechanical longitudinal reinforcement coefficient [7] $\omega_s = \frac{A_s \cdot f_{yd}}{b \cdot d \cdot f_{cd}}$ (2)	ω_s=0.164	ω_s=0.276

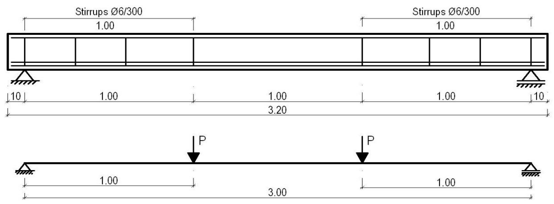

Fig. 1 Longitudinal reinforcement and test set-up

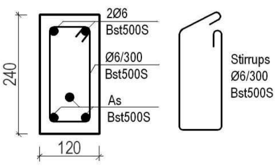

Fig. 2 Cross section

C. Equipments and testing of elements

The experimental study was conducted in two directions as presented in Table IV.

TABLE IV
TESTING TYPE

Beams	Loading type
AD 1-1 AD 2-1	Elements subjected to short-term loading to failure, in the ultimate limit state (ULS)
AD 1-2 AD 2-2	Elements subjected to flexure up to a service loading limit, with cracks in the serviceability limit state (SLS), unloaded and then subjected to long-term loading

1. Short-term loading

All beams were subjected to four-point flexure loading as shown in figure 1. Beams AD 1-1 and AD 2-1 subjected to short-term static loads were tested and cracks patterns, elements deformability and the ultimate bending moment (M_u) were followed. At each load increment, of 1/10 of bending design capacity, the concrete strains were measured with mechanical gauges (precision of 0.01mm) and digital microcomparator gauges (0.001mm precision), with 200mm measurement base, applied on the same side of the beam. The cracks widths were determined with a measuring loupe of 0.1mm precision. The deflections along the reinforced concrete beam were measured not only with mechanical gauges (0.1mm precision), but also with HBM type displacements transducers (0.001mm precision), WA/500mm and WA/200mm models. The data acquisition given by the digital transducers was made by a HBM type data logger system, Spider 8 model.

2. Long-term loading

AD 1-2 and AD 2-2 elements were subjected to flexure with long-term loading, having been previously loaded to the serviceability limit state (SLS), up to a maximum crack width of w_{cr}^{max}=0.1mm. Several loading steps were applied, each step of 1/5 of the final value of long-term loading, set at 40% of the ultimate bending moment of the pair beam subjected to short-term loading. The test set-up was made after the static scheme used at short-term loading, that of simply supported beam with two concentrated forces in the middle third. In the symmetry axis of the beams, sectional strains and deflections were measured. Along the beam the crack widths evolution within time were studied. After loading at 40%·M_u, the beams were kept in a climatic chamber at T=20°C±2°C temperature and RH=60%±5% relative humidity (Fig. 3). The experimental program regarding the beams subjected to long-term loading was conducted considering both concrete class and environmental conditions as constant parameters.

Fig. 3 Aspects regarding beams subjected to long–term loading

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Short-term loading

AD 1-1 and AD 2-1 beams were tested aiming the values associated at the appearance of maximum cracks width of w_{cr}^{max}=0.1 mm, respectively 0.2 mm and elements failure moment.

A comparative study between beams with different longitudinal reinforcement ratio ρ_l=2.01% si ρ_l=3.39% was conducted considering the experimental values of ultimate bending moment (M_u) and specific strains in concrete and reinforcement for loading step of M_{SLS}/M_u≈0.40. The experimental characteristics values of the beams subjected to short-term loading to failure are presented in Table V and Table VI.

The deflection was calculated according to Eurocode 2 [7] on the elements subjected to pure bending using the bending moments values obtained at M/M_u≈0.40 loading step. Equation (1) was used to determine the design deflections by summering the crack and uncracked states effect.

TABLE V
EXPERIMENTAL AND DESIGN VALUES AT LOADING STEP $M/M_U \approx 0.40$

Beams	AD 1-2	AD 2-1
ρ_l (%)	2.01	3.39
Failure M_u (kN·m)	53.10	76.65
Experimental values at ≈ 40%·M_u		
M_{SLS} (kN·m)	20	25
Δ^{exp} (mm)	8.63	11.13
l/x	l/348	l/270
ε_c^{max} (‰)	0.611	0.960
ε_s (‰)	1.684	1.660
M_{SLS}/M_u	0.38	0.33
Design values according to Eurocode 2 [7]		
Δ^{design} (mm)	6.93	4.20
$\Delta^{design}/\Delta^{exp}$	0.80	0.38

TABLE VI
CRACK PATTERN IN SERVICEABILITY LIMIT STATE (SLS)

Beams	AD 1-2	AD 2-1
ρ_l (%)	2.01	3.39
Failure M_u (kN·m)	53.10	76.65
Experimental values at ≈ 40%·M_u		
M_{SLS} (kN·m)	20	25
w_{cr}^{max} (mm)	0.12	0.15
w_{cr}^{mean} (mm)	0.07	0.07
Cracks number	21	22
M_{SLS}/M_u	0.38	0.33

$$\Delta = \zeta \cdot \Delta_{II} + (1-\zeta) \cdot \Delta_{I} \tag{3}$$

Where: $$\zeta = 1 - \beta \cdot \left(\frac{M_{cr}}{M}\right) \tag{4}$$

M_{cr} – Cracking design moment,
M – Bending moment,
β – Coefficient regarding the loading duration (β=0.5 for short-term loading, β=1.0 for long-term loading).

AD 1-2 beam (ρ_l=2.01%) was loaded to long-term bending at a loading value corresponding to AD 1-1 serviceability limit state; this value was obtained at the achievement of the following values of AD 1-1 beam: loading step of M_{SLS}/M_u=0.38, maximum crack width of w_{cr}^{max}=0.12mm and mean cracks width of w_{cr}^{mean}=0.07mm. The experimentally measured short-term deflection represents l/348, with approximately 25% above the design value. The maximum experimental concrete strains ε_c^{max} represents 17.5% of the ultimate compressive strain in the concrete ε_{cu}=3.5‰ and the ratio between the specific strain in the reinforcement and yield value is $\varepsilon_s/\varepsilon_{sy}$=0.62.

AD 2-1 beam (ρ_l=3.39%) presents an experimental deflection of l/270, exceeding up to 2.65 times the design value calculated for a loading value corresponding to SLS. The maximum crack width recorded was w_{cr}^{max}=0.15mm. The concrete maximum strains achieve approximately 27.5% of ε_{cu}=3.5‰ and in the reinforcement the ratio between the specific strains and yield value is $\varepsilon_s/\varepsilon_{sy}$=0.61. AD 2-2 beam was subjected to long-term loading at M_{SLS}/M_u= 0.33 loading step.

B. Long-term loading

Long-term behavior was conducted in terms of mid span deflection, evolution of crack pattern within time, as also regarding the specific strains in concrete and reinforcement. Experimental values recorded when service loading was applied are presented in Table VII.

Cracking pattern regarding the maximum and mean values of cracks widths within time is presented in Fig. 4 and Fig. 5

TABLE VII
EXPERIMENTAL VALUES AT LOADING

Beams	AD 1-2	AD 2-1
ρ_l (%)	2.01	3.39
ω_s	0.164	0.276
M_{SLS}/M_u	0.38	0.33
$w_{cr,i}^{max}$ (mm)	0.06	0.11
number of cracks	24	25
s^{med} (mm)	125	120
Δ^i (mm)	39.80	44.30
ε_c^i (‰)	0.360	0.410
ε_s (‰)	0.788	0.375

Immediately after long-term load application of M_{SLS}=0.38·M_u, AD 1-2 beam (ω_s=0.164) presents a maximum crack width of w_{cr}^{max}=0.06mm and the mean value achieves w_{cr}^{mean}=0.03mm. After 90 days of monitoring the mean cracks width values attenuation occurs (Fig. 5).

AD 2-2 beam (ω_s=0.276) presents for a ratio of M_{SLS}/M_u=0.33 a maximum crack width of w_{cr}^{max}=0.11mm and mean value of w_{cr}^{mean}=0.05mm. These crack width values were measured immediately after load was applied. Fig. 5 shows that similar to beam AD 1-2 the mean cracks width stabilizes after the age of 90 days.

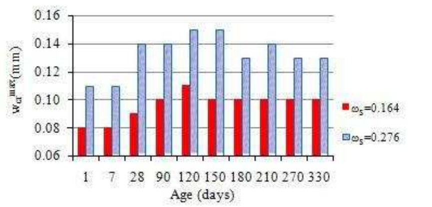

Fig. 4 Maximum experimental values of cracks widths

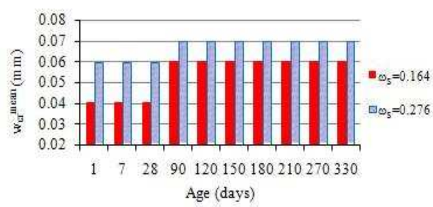

Fig. 5 Mean experimental values of cracks widths

The mean crack width is stabilized at w_{cr}^{mean}=0.04mm after 90 days of monitoring for 2.01% longitudinal reinforcement ratio, respectively at w_{cr}^{mean}=0.06 mm for ρ_l=3.39%. The experimental results show a good behavior regarding the cracking state, both at loading (w_{cr}^{max}=0.06mm for ρ_l=2.01%, respectively w_{cr}^{max}=0.11mm for ρ_l=3.39%), and also after approximately 1 year of observation (w_{cr}^{max}=0.10mm, respectively w_{cr}^{max}=0.13mm). The cracking pattern has a strong influence on the beams deformability. For the beams with the mechanical longitudinal coefficient of ω_s=0.164 approximately 50% of the total crack number have relatively equal values. Significant higher widths cracks were observed at beam with ω_s=0.276 for 1/3 from the total number of measured cracks.

Specific concrete strains and beams deformability were analyzed for all the beams subjected to long-term bending.

Fig. 6 shows the creep and shrinkage coefficient for concrete strains development in time.

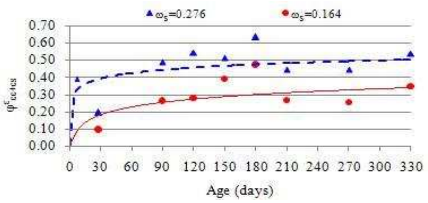

Fig. 6 Evolution in time of creep and shrinkage coefficient for concrete strains

For C80/95 high strength concrete class, the creep and shrinkage coefficient $\varphi^{\varepsilon}_{cc+cs} = \dfrac{\varepsilon^{t}_{cc+cs}}{\varepsilon^{i}}$ of the maximum croncrete strains at a higher longitudinal reinforcement coefficient (ω_s=0.276) presents a 50% increase compared to values obtained for ω_s=0.164.

The final long-term deflection is composed from the instantaneous deflection Δ^i obtained by load application and the additional time-dependent deflection Δ^t_{cc+cs}, which depends on cracking development and the reduction in stiffness over time, as well as the increase in curvature at each cross-section due to concrete creep. The creep and shrinkage coefficient value $\varphi^{\Delta}_{cc+cs} = \dfrac{\Delta^{t}_{cc+cs}}{\Delta^{i}}$ for the deflection calculated according to Eurocode 2 [7] (by using the equation (3)) presents values of approximately 8 times higher than the experimentally obtained values (Fig. 7).

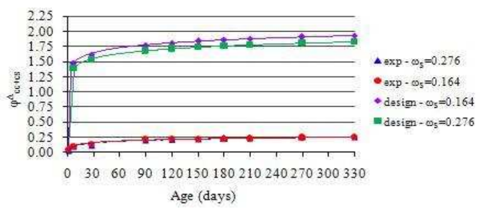

Fig. 7 Creep and shrinkage coefficient $\varphi^{\Delta}_{cc+cs} = \dfrac{\Delta^{t}_{cc+cs}}{\Delta^{i}}$ for experimental and design values of long-term deflections

IV. Conclusion

The experimental study presents a good behavior for beams subjected to flexure under long-term loadings during the 330 days of monitoring. Long-term deflections after t = 330 days are relatively small, around l/270, representing about 27% of the initial instantaneous deflection Δ^i. Attenuation of long-term deflections is observed around the age of 90 days when Δ^{90days}_{cc+cs} is approximately 80% of the final experimental value at 330 days. An overestimation of the design values calculated according to Eurocode 2 was observed towards the experimentally obtained values. The number of cracks did not increase in time in about 1 year of monitoring the beams under long-term loading. An attenuation of mean crack widths was observed after 90 days of loading. The long-term maximum crack width does not exceed w_{cr}^{max}=0.15mm, which is smaller than the design value given by Eurocode 2, respectively 0.4mm for XC exposure classes.

Acknowledgment

The present paper was supported by the project "Doctoral studies in engineering sciences for developing the knowledge based society-SIDOC” contract no. POSDRU/88/1.5/S/60078, project co-funded from The European Social Fund through Sectorial Operational Program Human Resources 2007-2013. Also, the authors would like to express their gratitude to CNCSIS for financing the research program within the type A Grant, code CNCSIS 1053: „Green concrete – Ecology, Sustainability”, grant director Cornelia Măgureanu, Professor, PhD. The authors of this paper have equal contributions and therefore are both considered main authors.

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