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LONG-TERM BEHAVIOR OF RC BEAMS SUBJECTED TO SUSTAINED LOAD: COMPARISON BETWEEN EXPERIMENTAL AND ANALYTICAL RESULTS ACCORDING TO EUROCODE 2

The influence of concrete creep and shrinkage on the behavior of reinforced concrete elements is most often checked through the serviceability limit states: limitation of stresses, cracking and deflections. Under sustained load, the deformations of the element gradually increase with time and may be many times greater than the initial value. If the temperature remains constant, the gradual development of strain with time is caused by the shrinkage and creep of concrete. In order to determine the influence of different intensity of long–term sustained load on the behavior of reinforced concrete elements during the time, an experimental program has been realized. Eight reinforced concrete beams and an appropriate number of test concrete samples were made and monitored in a laboratory environment with constant ambient temperature and humidity. Seven beams are loaded with different load intensity, whilst six beams are loaded with a sustained load with intensity in which cracks appear in the considered time period. No load was applied to one of the beams and only the shrinkage strains of concrete were observed. Through the experimental analysis was obtained a picture of the long–term behavior of reinforced concrete elements subjected to different intensity of sustained load, as well as its influence on the serviceability limit states. A comparison was also made with the results obtained with modern analytical models in the codes.

Keywords: creep, shrinkage, sustained load, deflections

1. INTRODUCTION

In order to be able to ensure the desired behavior of the structure or part of it in service, it is necessary to control the serviceability limit states: deflection control, crack control, limiting stresses in concrete and reinforcement, vibrations, etc. Their control is proof that in the most unfavorable combination of the service loads, the predicted values will not be exceeded, taking into account the duration of the load.

The long–term influence of the load causes a significant increase in the deflections and the crack width, which leads to a decrease in the tensile stiffness, increased stresses in the reinforcement at the place of the cracks and increased curvature of the section. All this leads to endangering the load-bearing capacity and serviceability of the structure.

During calculating the long-term behavior of structural elements there are three factors we should consider: creep, shrinkage and reduction of tensile strength in the tensile zone of the cracked cross-section due to the formation of cracks during the time and local loss of bond between the concrete and reinforcement [1].

The process of the loading of reinforced concrete elements is accompanied by the process of crack formation. As the load increases, the initially rapid changes in the crack pattern decrease and the pattern gradually stabilizes. Under sustained service load, cracks frequently form with time between the most widely spaced cracks in a cracked tensile region, thereby reducing the average crack spacing with time. In addition, cracks usually form with time in previously uncracked regions thereby increasing the extent of cracking.

Shrinkage and creep as time-dependent deformations have a great influence on the overall behavior of reinforced concrete sections, elements and structures. Many structures have suffered unintended consequences due to inaccurate determination of their influence. In statically indeterminate structural systems that are composed of elements with different deformable properties, there is a redistribution of static influences [2]. Therefore, these impacts must not be neglected and should be properly considered at the design stage. Particularly, the precise assumptions should be made in extremely tall buildings, in segmented bridges, those that have quite large spans as well as pre-stressed structures where cracks may occur in critical sections. Due to all this time spent in the design process on defining the properties of the material should be similar to the time spent on the analysis of the structure.

There is still no precise model for predicting the behavior of concrete during the time, which is primarily due to its highly elastic properties and heterogeneous structure. Most models are based on empirical expressions, so to obtain a model for the practical application it is necessary to improve it with the results of experimental tests.

2. CALCULATION OF DEFLECTIONS ACCORDING TO EUROCODE 2

Deflection control is usually determined using simple rules for limiting the span/depth ratio, which is an adequate approach for common situations.

In addition, another approach is given in Eurocode 2 [3] which involves calculating the curvature of the corresponding cross-section and integrating it along the element to obtain the deflection. Especially in cracked sections, due to the change in curvature that occurs in the area between the cracks and due to the adhesion that still exists between the concrete and the reinforcement, it is necessary to determine the mean curvature. The product of the mean curvature $k_s(t)$, obtained by applying the Simpson rule of numerical integration and the fictitious bending moment M along the element gives the deflection a in the desired cross-section.

$$a = \int_0^l k_s(t)\overline{M}(x)dx \qquad (1)$$

During calculating the deflection from long-term loads, three factors should be taken into account: creep, shrinkage and reduction of tensile stress in tensile concrete as a result of increasing the number and width of cracks during the time, as well as local disturbances of the connection between concrete and reinforcement. The mean curvature is determined for the considered time at the moment t, as the sum of the initial curvature of the intersection and its increase due to time-dependent deflections. It is obtained by interpolation between the smallest value for the curve $k^I(t)$ calculated for the cross-section without cracks (state I) and the largest value for the curve $k^{II}(t)$ calculated for the cross-section with cracks (state II) [4].

$$k_s(t) = (1-\varsigma)k^I(t) + \varsigma k^{II}(t) \qquad (2)$$

The effect of the tensile concrete between the cracks is included through the coefficient ς.

$$\varsigma = 1 - \beta_1 \beta_2 \left(\frac{M_{cr}}{M}\right)^2 \qquad (3)$$

where the coefficient β_1 includes the degree of adhesion between the concrete and the reinforcement (β_1 = 0.5 for smooth reinforcement; β_1 = 1.0 for ribbed reinforcement); the coefficient β_2 includes the influence of the time-dependent properties of the concrete during the time (β_2 = 1.0 for short-term loads; β_2 = 0.5 for long-term and repeated loads); M_{cr} is the cracking moment; M is the considered moment [5].

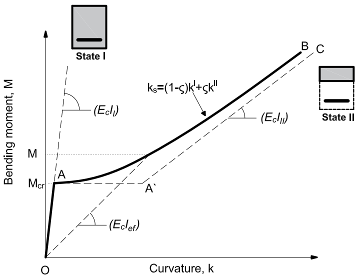


Figure 1. Moment versus curvature relationship [6]

3. EXPERIMENTAL PROGRAM

Having in mind the importance of the long-term effects of concrete structures, in the past years at the Faculty of Civil Engineering in Skopje, experimental investigations have been conducted that they include different types of concrete, as well as different load intensity and duration [7,8,9,10].

In order to determine the influence of long-term sustained loads on the behavior of reinforced concrete elements during the time, an experimental program has been realized in the laboratory of the Faculty of Civil Engineering in Skopje.

Figure 2. Test setup of RC test beams (left) and test setup for creep (right)

The experimental program consists of eight test elements-reinforced concrete beams made of concrete class C35/45, with a 15/28cm rectangular cross-section and 300cm in length. They were monitored in a laboratory environment with constant ambient temperature and humidity. In order to determine the material and time-dependent properties of the concrete, a suitable number of test specimens with different shapes and dimensions were tested. The selected dimensions of the beams allow the use of real concrete and reinforcement. The geometry, required reinforcement and the applied load given in relation to the in-service moment at mid-span (M_e=12.9kNm) are shown in Figure 3.

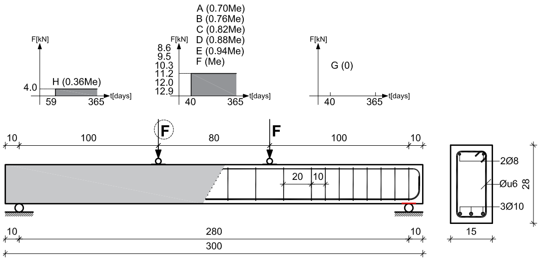


Figure 3. Geometry, load scheme of RC test beams

They are divided into eight groups: A, B, C, D, E, F, G, H. Seven beams are loaded with different load intensity, which are applied to the beam in the form of two concentrated forces. Six beams are loaded with a sustained load with intensity in which cracks appear in the considered period. One beam is not loaded in order to monitor shrinkage strains and any changes in ambient conditions during the same monitoring period.

At the age of 40 days, when the load on the reinforced concrete beams is applied, tests of the specimens were performed to determine the properties of the concrete, as follows: compressive strength, flexural and splitting tensile strength, modulus of elasticity, creep and shrinkage. The test results are shown in Table 1.

Table 1. Experimentally obtained values for the material and time-dependent properties of concrete for t=40 days and t=365 days

C35/45				
Time [days]	$f_{ck,cube}$ [MPa]	f_{ck} [MPa]	$f_{ct,f}$ [MPa]	$f_{ct,sp}$ [MPa]
t=40	48.27	40.82	6.82	3.84
t=365	/	/	/	/
Time [days]	E_c [MPa]	ε_{cs} [‰]	ε_c [‰]	φ
t=40	34100	0.204	/	/
t=365	/	0.460	0.903	1.755

4. RESULTS OF EXPERIMENTAL ANALYSIS

The influence of the long–term sustained load on the behavior and the maximum value of the deflections of the reinforced concrete elements is determined by monitoring the eight test elements over a period of 365 days. The beams are loaded on the 40th day after casting, except for beam H witch is loaded on the 59th day. They are unloaded at 365th day and monitored until the 465th day after casting.

The development of deflection during the time in the middle of the span is shown through the deflection-time diagram in Figure 4, while Figure 5 shows the force-deflection diagram. Table 2 shows the values of the deflection at the moment of loading (a_0) at the age of the concrete t = 40 days, at the moment of unloading (t=365 days) and the final value of the measured deflection (a_t) at the age of the concrete of t = 365 days and t = 465 days. The same table shows the increase in deflection because of the creep (Δa_t).

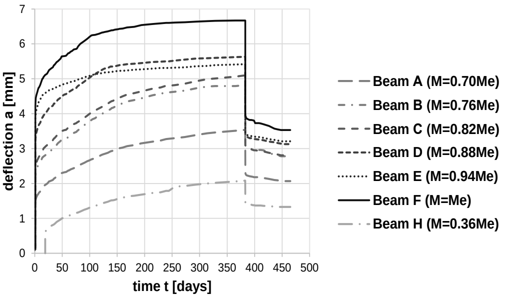


Figure 4. Deflection development during the time for all beams

It can be concluded that the increase of deflections under the influence of long-term loads due to the creep and shrinkage of concrete depends on the level of load, so it is more pronounced for elements that do not have cracks or are in the phase of crack formation, than elements that are in a phase of stabilized picture of cracks.

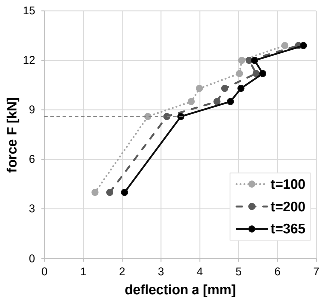


Figure 5. Diagram: force – deflection

Table 2. Measured deflection values at t=40 days, t=365 days and t=465 days

Beam	**loading** / unloading		
	a_0 (**40,59**/365) [mm]	a_t (**365**/465) [mm]	Δa_t (**365**/465) [mm]
A	**1.01**/1.17	**3.51**/2.07	**2.50**/0.90
B	**1.43**/1.62	**4.79**/2.78	**3.36**/1.16
C	**1.76**/1.91	**5.06**/2.81	**3.30**/0.90
D	**2.20**/2.09	**5.62**/3.13	**3.42**/1.04
E	**2.80**/1.86	**5.41**/3.21	**2.61**/1.35
F	**3.14**/2.60	**6.67**/3.53	**3.53**/0.93
H	**0.55**/0.61	**2.06**/1.33	**1.51**/0.72

Figure 6 shows the increase of the instantaneous deflection from the long-term effect of the load in relation to the current during the time.

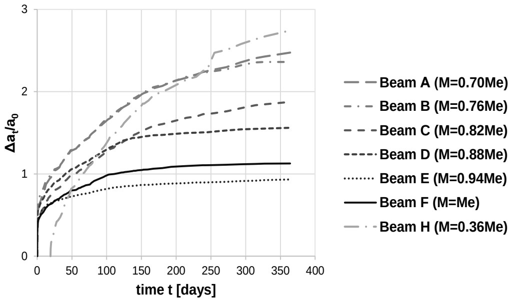


Figure 6. Deflection increase of long-term sustained load / instantaneous deflection during the time

From the comparison shown in Figure 6, it can be seen that in the whole monitoring period there is a more pronounced increase of deflections from the long-term load on the less loaded beams, despite the fact that with increasing load the total deflection is greater.

5. COMPARISON BETWEEN EXPERIMENTAL AND ANALYTICAL RESULTS

Using the method given in Eurocode 2 [3], it was made a comparison between the analytically and experimentally obtained deflections. They were analyzed in the middle of the span of the reinforced beams.

The deflections are calculated with numerical integration, by determining the curvature in multiple cross-sections along the element. Interpolation was performed between the calculated deflection assuming that the whole element is working without cracks and the calculated deflection when the cracks are fully developed, or when there is already a stabilized picture of cracks.

The analytically obtained deflections are calculated by including material and time-dependent properties for concrete class C35/45 (given in Eurocode 2 [3]), and then an improvement is made, which includes the experimentally determined material and time-dependent properties.

The cracking moment, which is used in the analytical calculation of the deflections, is determined theoretically because the total load is applied to the reinforced concrete beams at once. In the calculation where the material and time-dependent properties for concrete class C35/45 are included, it is $M_{cr,1} = 9.14$kNm, while where the experimentally obtained properties are included, it is $M_{cr,2} = 9.32$kNm.

Table 3 shows the initial and final values of the deflections for all beams that are monitored, the deflections in t=40 and t=365 days. The same table shows the percentage maximum and minimum deviations of the experimental from the analytically obtained.

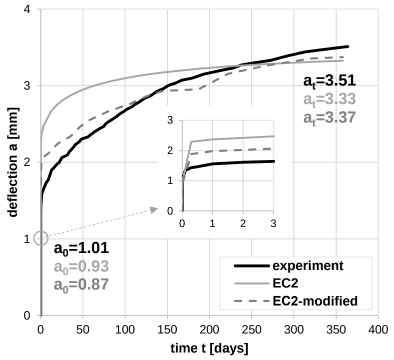
Table 3. Table showing the deflection measured experimentally and calculated analytically according to EC2

DEFLECTION [mm]						
Beam	t [days]	Exp.	EC2	%	EC2-mod.	%
A	t=40	1.01	0.93	8.6	0.87	16.09
	t=365	3.51	3.33	5.41	3.37	4.15
B	t=40	1.43	1.35	5.93	1.28	11.72
	t=365	4.79	4	19.75	4.06	17.98
C	t=40	1.76	1.73	1.73	1.65	6.67
	t=365	5.06	4.55	11.21	4.62	9.52
D	t=40	2.2	2.15	2.33	2.08	5.77
	t=365	5.62	5.2	8.08	5.16	8.91
E	t=40	2.8	2.54	10.24	2.46	13.82
	t=365	5.41	5.68	4.99	5.71	5.55
F	t=40	3.14	2.97	5.72	2.89	8.65
	t=365	6.67	6.15	8.46	6.24	6.89
H	t=40	0.55	0.4	37.5	0.4	37.5
	t=365	2.06	1.2	71.67	1.24	66.13

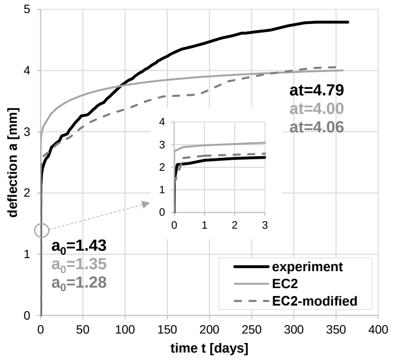
The following diagrams show the deflections obtained experimentally (black line), analytically with material and time-dependent properties of EC2 (gray solid line) and analytically - modified (gray dashed line).

From the comparison, it can be noticed that in all beams the values calculated according to EC2 and the values calculated in the same model, but with included material and time-dependent properties from the experiment gave acceptable predictions in relation to the experimentally measured. This is due to the close values of the cracking moment. At beam H we have a complete overlap of the values for the deflections because the cross-section is without cracks, so the cracking moment does not affect the calculation. The values calculated according to EC2 give a closer value for the instantaneous deflection of all beams, which is not the case with deflection during the time.

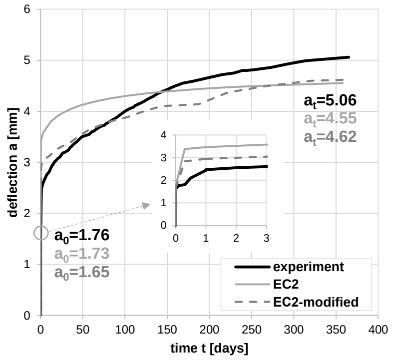
Beam A



Beam B



Beam C



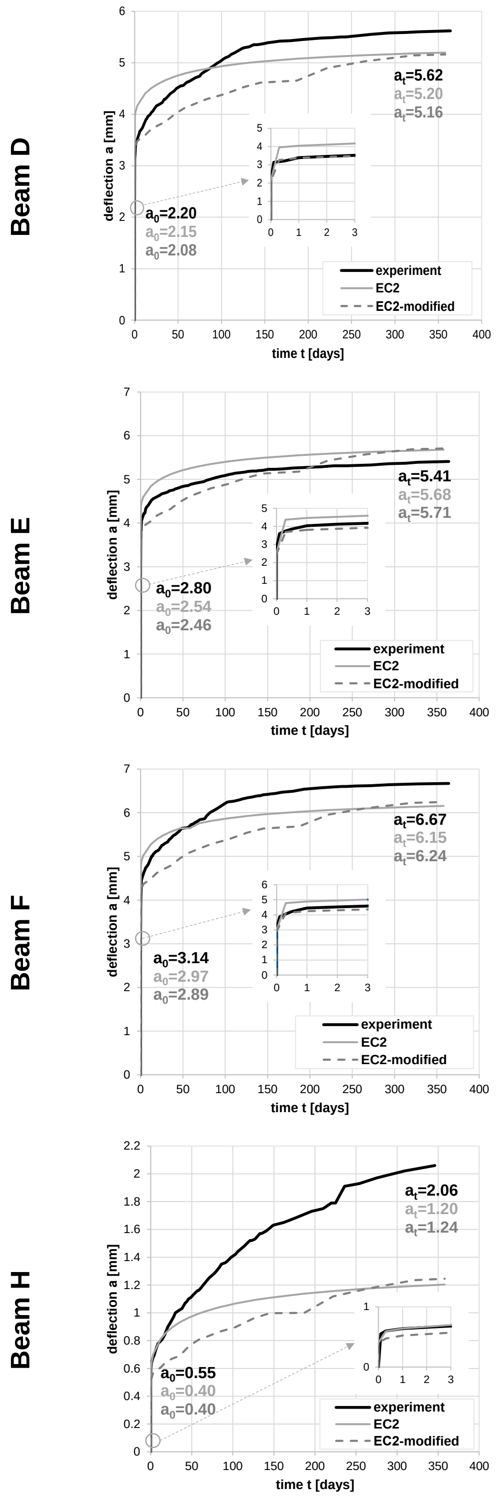


Figure 7. Comparison of analytically obtained deflection with experimentally measured ones

CONCLUSIONS

The following conclusions can be drawn from the experimental investigations of reinforced concrete elements exposed to long–term sustained loads of different intensity and the analysis carried out using analytical models:

- The intensity of sustained load has an influence on the behavior of reinforced concrete elements during the time.
- Higher total deflections are registered in the beams exposed to sustained load with higher intensity.
- A more expressive increase in time of instantaneous deformations is found in beams loaded with a lower load intensity.
- Changes resulting from the long-term effects are more pronounced in the immediate post-load period.
- The considered analytical models proposed in current standards with sufficient accuracy can predict the limit states of reinforced concrete elements exposed to long–term sustained load.

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