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EXPERIMENTAL INVESTIGATION ON LONG-TERM DEFORMATIONS OF TENSILE RC MEMBERS

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ABSTRACT

Modelling of cracking behaviour and the tension-stiffening effect is considered to be one of the most complex and challenging issues in the constitutive modelling of reinforced concrete structures. Based on various assumptions, a number of tension-stiffening models have been proposed for the case of short-term loading. However, a very limited number of studies have been devoted to the investigation of tension-stiffening for the case of long-term loading. Current study aims at assessment of long-term degradation of tensile stiffness in RC elements. Four similar RC ties have been tested under sustained loading with load duration varying from 18 to 126 days. The experiments reveal that the early-age degradation of the tension-stiffening effect under sustained loading may reach 40-80% of the observed value at the end of loading. Comparison of experimental results with analytical predictions by the Eurocode 2 is also presented. The predicted decay of long-term tension-stiffening has occurred instantly just after the load sustaining. Such reduction might be considered as a supreme value since further deformation increment (due to concrete creep and shrinkage effects) was found insignificant.

1 INTRODUCTION

As cement-based materials have a relatively low tensile strength, cracking is a major concern at service conditions of such structures. Structural engineers for the analysis of concrete structures most often choose design code methods. Although the design code methods are simple and ensure safe design, they have significant shortcomings. These methods cannot include all important material and geometrical parameters and, therefore, are not accurate enough. Numerical techniques, as an alternative to the design code methods, are based on universal mechanical principles, but their adequacy depends on the correct assumption of constitutive laws.

Before cracking, concrete in tension can be modelled using the principals of elasticity. After cracking, due to bond with reinforcement, concrete between cracks carries a certain amount of tension stresses normal to the cracked plane. The concrete adheres to the reinforcement bars and contributes to the overall stiffness of the structure. The phenomenon is called tension-stiffening. Based on various assumptions, a number of tension-stiffening models have been proposed for the case of short-term loading [1-3].

Most of the proposed material laws take into account degradation of tension-stiffening with increasing load. Although the experience has shown that the degradation of tension-stiffening also takes place under sustained loading, a limited number of studies have been devoted to investigate tension-stiffening in the elements subjected to long-term load. In this respect, the experimental study conducted by Beeby and Scott [4] should be mentioned. The reported rapid decay of tension-stiffening (almost 50% reduction during the first 10–30 days of loading) was contradicted with the common view on this issue and allowed to relate such degradation to cumulative damage of the bond [5]. It was also found that concrete creep, load history and concrete strength have little effect on the reduction of tension-stiffening with time. Wu and Gilbert [6] have achieved similar results. It was demonstrated that depending on the load level the average tensile stress in concrete and the tension-stiffening strain reduced from 59 to 81% of their initial value in the first 50 days under sustained load.

Wenkenbach [7] investigated the tension-stiffening effect in RC members with large diameter of reinforcement bars obtaining significant scatter in the tension-stiffening decay. The latter was found decreasing with increased diameter of the bars. Beeby et al. [8], Zanuy [9], and Bacinskas et al. [10] have conducted theoretical studies on the long-term tension-stiffening effect.

Using deformation measurements of four RC ties loaded during 18 and 126 days, current study investigates time-dependent degradation of tension-stiffening. Sudden decrease in tension-stiffening in a period of few days after loading was observed. Comparison of the test results with predictions by the Eurocode 2 is also performed.

2 EXPERIMENTAL PROGRAM

Experimental tests were made in the Laboratory of Building Constructions at Vilnius Gediminas Technical University. The experimental program includes tensile tests of four RC ties. For the purpose of comparative analysis, all the test specimens had identical cross-section with similar concrete strength f_{cm} and reinforcement ratio p (about 1.6%) with notches to control crack pattern in the element.

2.1 Specimens details and testing

Experimental ties were 1500 mm long with 100×100 mm nominal cross-section in place without notch and 100×70 mm – in place with notches. Each member was reinforced with a single 12 mm diameter steel bar. Reinforcement was axially placed in the specimens. Geometrical and loading details of the experimental members are summarized in Table 1 and Fig. 1. The specimens were divided into two series of two elements in each (Table 1). The notches have divided entire length of each of the elements into n sections with a uniform length s (Fig. 1). Ties of the first set had nine notches with $s = 167$ mm, whereas elements of the second set had eight notches with $s = 188$ mm.

The ties were demolded in 2 days after casting and further were moist cured until the time of loading t_0 (Table 1). Ambient conditions during long-term testing were: average relative humidity (RH) 57% and average temperature 20 C.

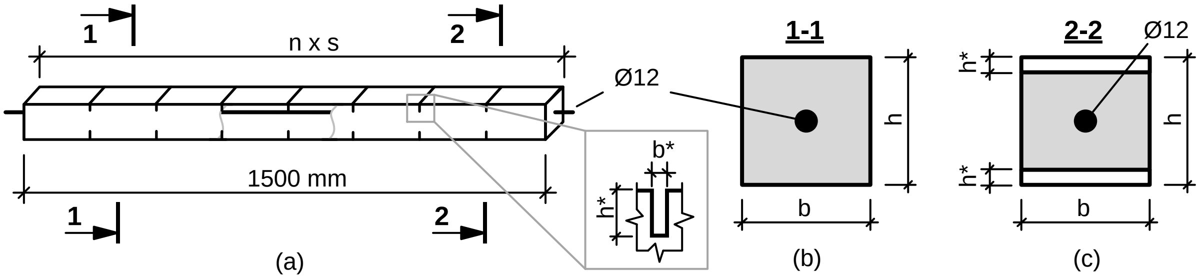

Figure 1. Geometrical parameters of the specimen (a), cross-section (b) and cross-section with notches (c).

Table 1. Details of tension specimens

Series	Specimen	Cross-section parameters, mm		Notch parameters, mm		Loading parameters		
		h	b	h^*	b^*	t_0	t	N/N_{ult}
I	TS1	101	104	18	4	50	68	0.5
	TS2	102	103	18				
II	TS3	104	105	17		69	195	
	TS4	100	101	15				

2.2 Material properties

All specimens were made using the same concrete mixture. The ordinary Portland cement and crushed aggregate (16 mm maximum nominal size) were used. Water/cement and aggregate/cement ratio by weight were taken as 0.32 and 1.98, respectively. Mechanical properties of the concrete were determined using ∅150×300 mm cylinders. Mean compressive strength was found to be $f_{cm} = 53.1$ MPa at 28 day, and $f'_c = 57.6$ MPa and $f'_c = 59.2$ MPa at the age of loading t_0 (i.e. 50 and 69 day, see Table 1). Elasticity modulus at the age of loading was $E_{cm} = 39.8$ GPa and $E_{cm} = 40.0$ GPa for the I and II series, respectively.

Deformed bars (∅12 mm) of mild steel were used for reinforcing the specimens. In order to determine the actual characteristics of steel reinforcement, four samples of the bars were tested. The average values of yielding stress f_y and modulus of elasticity E_s were obtained equal to 545 MPa and 179 GPa, respectively (these parameters are based on the nominal diameter).

2.3 Test set up

In order to apply a sustained load to the test specimen, four test frames, were specially designed (based on a double lever system). The experimental setup is shown in Fig. 2. The test rigs applied load using a weight and double lever system achieved a 16:1 load ratio – each 5 kg weight applied a force of 0.8 kN to the test specimen. The load was gradually applied using 1.5 kg or 5 kg weights reaching the half of ultimate capacity of the element (Table 1). The latter load was determined ($N_{ult} = f_y \pi \varnothing^2 / 4$) on a basis of the nominal diameter and yielding strength f_y of the reinforcement. To define accurately the crack initiation phase, the reduced loading increments were applied approaching the cracking load. The tests were paused for short periods to take readings at each load step. On average, it took 30 load increments with 1 hour duration of short-term test stage. The maximum short-term load was sustained for the period (t-t_0) = 18 or 126 days (respectively, for I or II series, see Table 1).

Applying 0.001 mm mechanical gauges, reinforcement strains were measured along the 1520 mm gauge length as shown in Fig. 2. Deformation response of ties was assessed using the force and strain measurements.

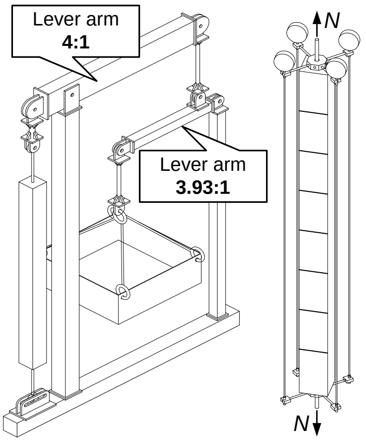

Figure 2. Test setup of RC tie.

3 RESULTS AND DISCUSSION

Axial force-average strain diagrams for test specimens under short-term and long-term loading are presented in Fig. 3. To quantify the tension-stiffening effect, this figure also presents the bare bar response. It can be observed that a bilinear curve quite adequately represents the experimental response of the member subjected to short-term loading (ascending part of the diagram). Further strain increment (under constant axial force $N \approx 31$ kN) corresponds to the response of the member under sustained loading. In comparison purposes, Fig. 3 shows the theoretical curves obtained according to Eurocode 2 technique. The diagram named ‘EC2’ corresponds to the case of short-term deformation analysis. It is evident that the deformations are underestimated (by 45-75%) using the tensile strength of concrete calculated by Eurocode 2 on a base of the average compressive strength f_{cm} from Table 1. This can be explained by the reduction of the cracking resistance due to concrete shrinkage strain restrained by the reinforcement [11]. This effect is not included in the Eurocode short-term deformation prediction model.

Curve named ‘EC2*’ (Fig. 3) corresponds to the force-average strain diagram calculated by Eurocode 2 assuming experimental value of the cracking force N_{cr}. In this case, the prediction results are adequate to the experimental measurements. Minor differences between the diagrams can be attributed to variation of cracked concrete (tension-stiffening) strain distribution along the element length [12].

The curve ‘EC2**’, shown in Fig. 3, corresponds to load-average strain relationship of the tensile member subjected to the loading sustained for the period (t-t_0). The curve was obtained taking into account concrete creep and shrinkage effects. The effect of concrete creep was evaluated using effective modulus of concrete:

$$E_{cm,eff} = E_{cm} / [1+\varphi(t,t_0)]. \tag{1}$$

The shrinkage effect was assessed by means of fictitious axial force calculated by the following equation:

$$N_{sc}(t,t_0) = \varepsilon_{sc}(t,t_0) A_c E_{cm,eff}. \tag{2}$$

In above equations, $\varphi(t,t_0)$ is a creep factor; $\varepsilon_{sc}(t,t_0)$ is the free shrinkage strain, A_c is the concrete area of the un-notched section. As shown in Fig. 3, the influence of concrete creep and shrinkage before element cracking is not significant. Whereas, a sudden increase of the predicted strains in ‘EC2**’ diagram occurs immediately after cracking that is related to the long-term tension-stiffening model accepted in the Eurocode.

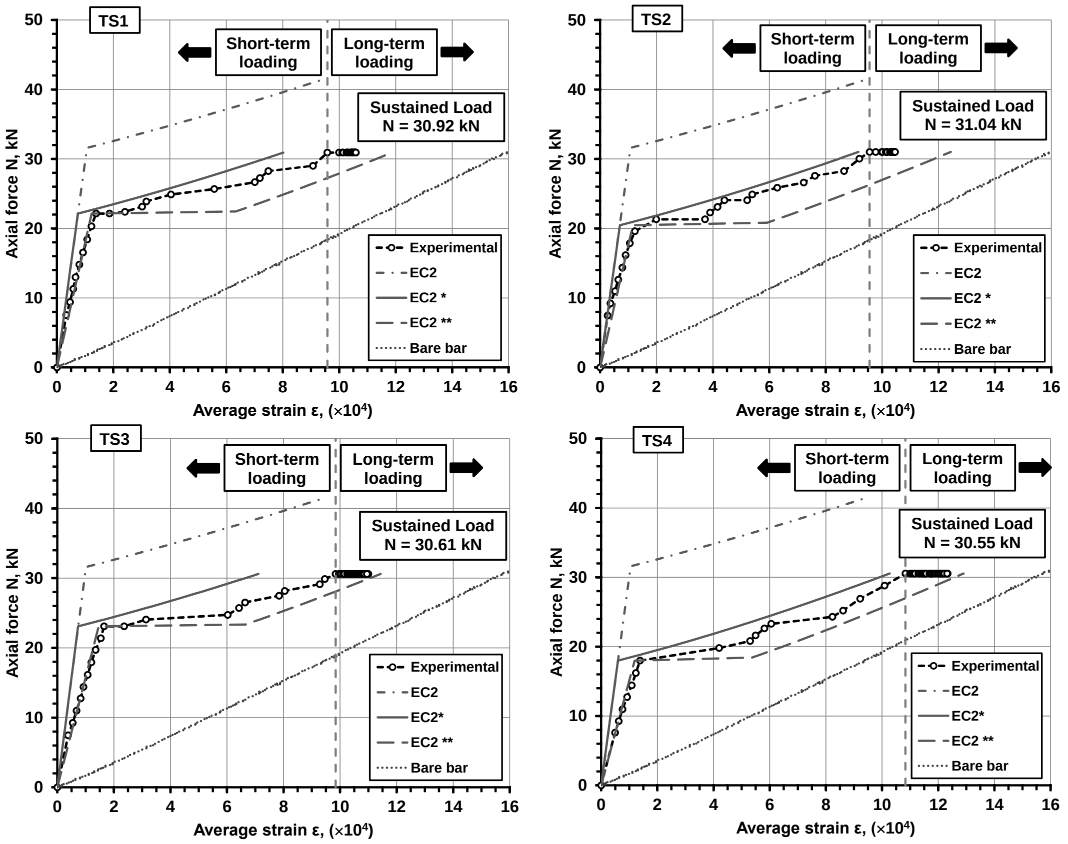

Figure 3. Load–average strain diagrams of test specimens

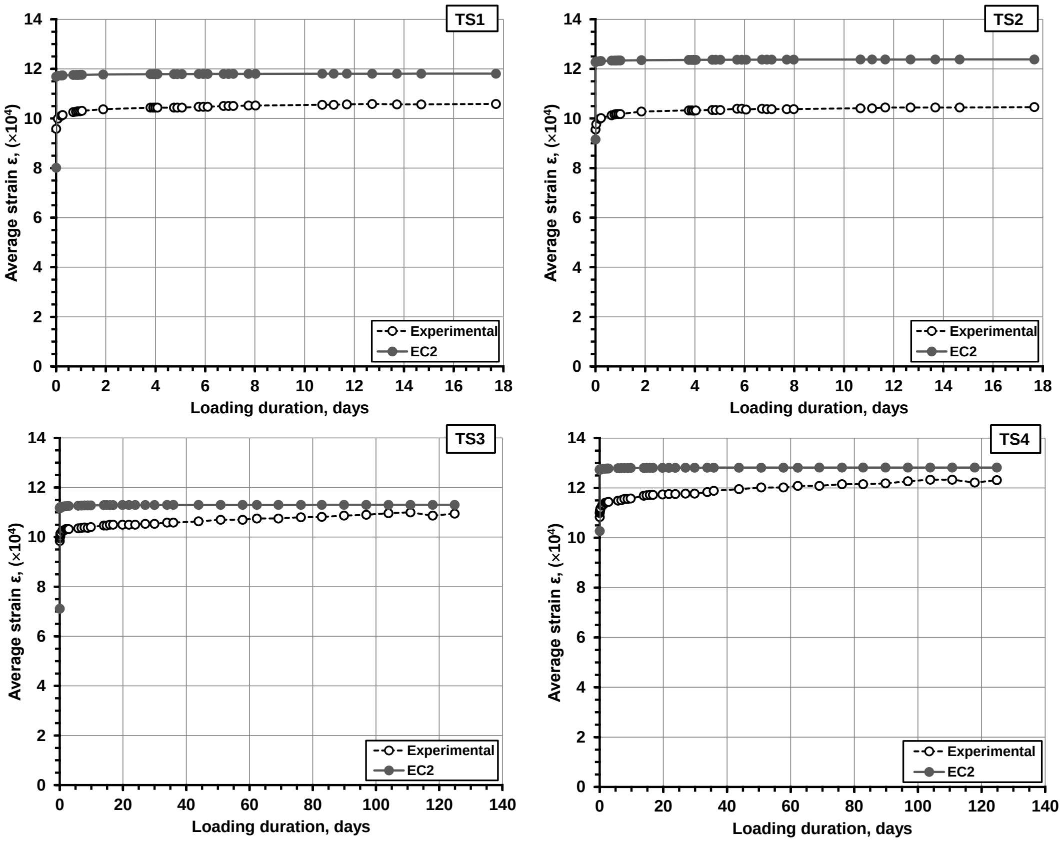

Figure 4. Variation of average strains of test specimens under sustained load

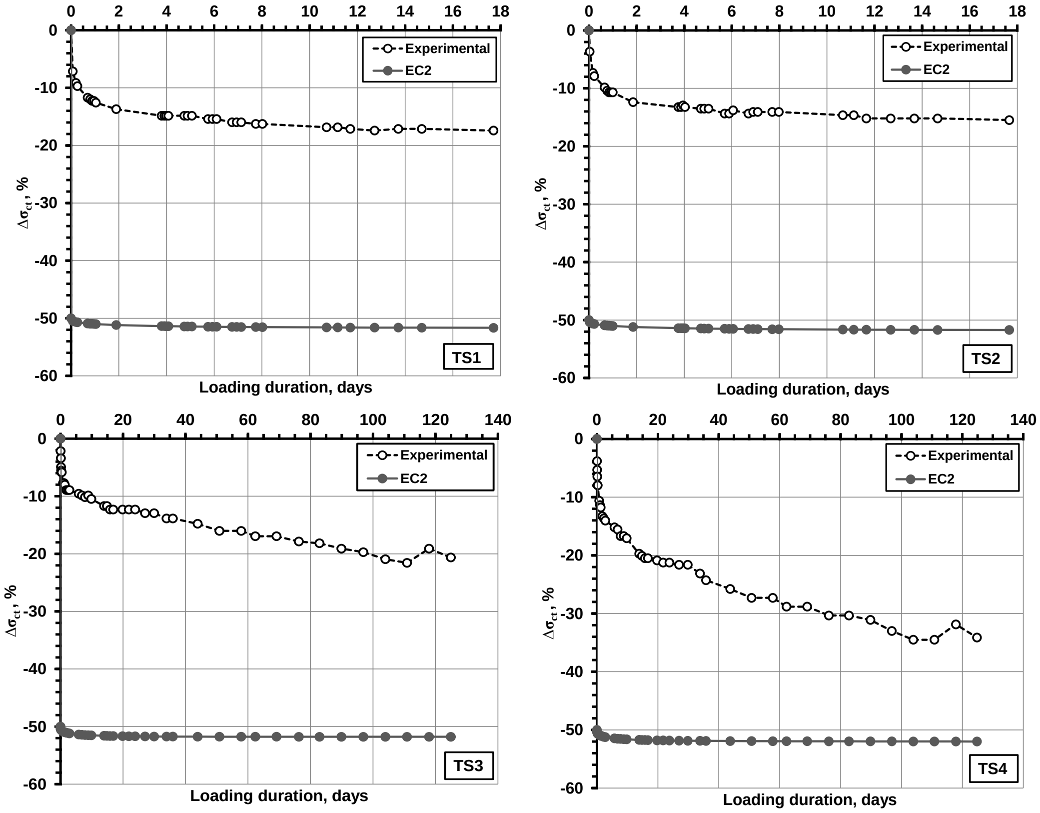

Figure 5. Variation of long-term tension stiffening stresses long-term test

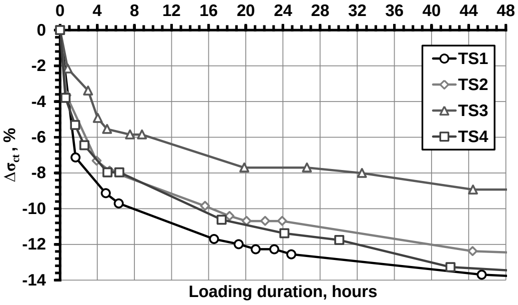

Figure 6. Variation of long-term tension stiffening stresses during 48 hours after loading

Figure 4 presents variation of the total average strain of test specimens under sustained loading. The experimental strains increase during the first two days of loading. Further strain increment is less significant. Similar tendencies are obtained by the Eurocode method. The theoretical curves (‘EC2’) correspond to the long-term strain increment. It was obtained as the difference between ‘EC2**’ and ‘EC2*’ diagrams (Fig. 3) at the sustained load level with increased load duration $t_0 < t_i \leq t$. The prediction difference has increase instantly after the load sustaining; further increment due to concrete creep and shrinkage effects is insignificant. It is important that the observed strains of elements TS3 and TS4, at the end of sustained loading (126 day), approach the predicted values, which can be considered as the upper limit value of the long-term deformations.

The experimental results were used for identification of tension-stiffening degradation under long-term loading. The assessment has been done by means of decrement of concrete tensile stress $\Delta\sigma_{ct}(t,t_0)$ with time. The following equation was applied for calculation of the stress reduction:

$$\Delta\sigma_{ct}(t,t_0)=\left(1-\frac{\sigma_{ct}(t,t_0)}{\sigma_{ct}(t_0)}\right)\cdot 100\% = \left\{1-\frac{N-[\varepsilon(t_0)+\Delta\varepsilon(t,t_0)]E_sA_s}{N-\varepsilon(t_0)E_sA_s}\right\}\cdot 100\% . \qquad (3)$$

In above equation, time intervals (t,t_0) and (t_0) are related to the case of long-term and short-term loading, respectively. It also ignores the concrete shrinkage effect. Figure 5 shows that the predicted degradation of the long-term tension-stiffening is constant throughout the considered loading period giving the two times reduction of the short-term value. This contradicts with the experimental diagrams, which indicate graduate degradation of tension-stiffening with time. The stresses $\Delta\sigma_{ct}(t,t_0)$ of elements TS1, TS2 and TS3 were decreased by 20%, whereas the element TS4 has possessed the 32% degradation.

Figure 6 presents the early-age degradation of tension-stiffening under sustained loading. During the first two days of loading, the tension-stiffening stresses decreased by 13.7 and 12.4% (or approximately 80% of the observed value at the end of loading) in elements TS1 and TS2, respectively. The stress reduction in elements TS3 and TS4, loaded during the period of 126 days, was of 8.9 and 13.3%, respectively (that is 39-43% of the final value).

4 CONCLUSIONS

Current study investigates degradation of tensile stiffness in RC elements under sustained loading. Four ties were tested with load duration varying from 18 to 126 days. The following conclusions can be drawn.

- The Eurocode 2 short-term deformation prediction model significantly overestimates cracking response of the RC ties – the cracking force was overestimated by 45-75%. Assuming experimental value of the cracking force, the prediction results become adequate to the experimental measurements. This effect can be attributed to the shrinkage-induced reduction of cracking resistance of the test specimens.
- The experiments reveal that the early-age degradation of the tension-stiffening effect under sustained loading may reach 40-80% of the observed value at the end of loading.
- According to Eurocode 2 the decay of long-term tension-stiffening has occurred instantly just after the load sustaining. Such reduction might be considered as a supreme value since further deformation increment (due to concrete creep and shrinkage effects) was found insignificant.

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