Long-Term Tests of Reinforced Concrete Beams Loaded by Temperature Gradient or Settlement of a Support

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ABSTRACT

In this research, the relaxation of the restraint effects, due to both sudden and slow settlement of a support, was examined as a function of time; the relaxation of the restraint effect due to a thermal gradient was also investigated. It was observed that the relaxation was fairly rapid in a heated beam in particular. Also the relaxation of restraint effects caused by the settlement of supports was considerable. This contribution continues the report in (Jokela and Huovinen, 1985).

INTRODUCTION

If deformations or displacements have been induced or restrained onto a structure, one must instead of creep speak about a relaxation phenomenon which means the continuing reduction of stress with time. An induced or restrained displacement in a structure can, in principle, be of short or long duration. When the time period of displacement formation is short, relaxation cannot take place in concrete and it cracks if the restrained strain becomes greater than the failure strain.

Restrained displacements with long-term effects consist of both rapidly and slowly developing displacements. If no cracking occurs in connection with a rapidly forming restrained displacement, the corresponding restraint action grows in relation to the stiffness of the structure. At the formation phase of cracks, the restraint action grows clearly more slowly than the restrained displacement since every new crack reduces the stiffness of the structure. The restraint action cannot be assumed to grow at the rate of the restrained displacement before the crack formation has stabilized. After having reached its greatest value the action effect due to restrained displacement starts to relax owing to creep. Since the rate of creep decreases with time the relaxation of the restraint effect is the greater the younger the concrete when the restrained displacement takes place.

As the rate of the displacement formation slows down, a partial relaxation of the restraint effect takes place. If the restrained displacement, which only increases at the formation phase of cracks, grows quicker than the deformation induced by creep, the structure will crack, but the restraint effect does not grow greater than the crack action effect. If, on the other hand, the restrained displacement grows more slowly than the creep, the structure will not crack at all.

In order to estimate relaxation by calculational means, the time dependency of restrained displacement and that of creep as well as the changes taking place in the structural properties, above all in stiffness, during the displacement formation must be known. If the temperature deviates from the normal, the temperature dependency of creep must also be known. The problem has been examined from the calculational point of view by e.g. in references (Chali, 1969 and Schaper, 1978).

EXPERIMENTAL STUDY OF CONCRETE RELAXATION

Structural Model

The structural system of the test beams corresponded to a double beam stiffened at one end, whose free end was subjected to various restrained displacement. A temperature difference of about 50 °C was effecting to one beam: a restraint moment was induced at the fixed support.

Test Beams

Two double beams were manufactured for the tests and they were marked with the following symbols: 1a, 1b, 2a and 2b. The amount of tension and compression reinforcement was 0.43 % in beams 1a and 1b and 1.29 % in beams 2a and 2b. The dimensions and structures of the beams are set out in Fig. 1 and material properties in Table I.

Long-term Tests

In long-term tests (total duration 8 months) a thermal gradient of about 100 °C/m (temperature difference of 40 - 50 °C) was directed to beam 1a in such a way that the temperature of the upper surface remained at about 35 - 40 °C and that of the lower surface at about 80 - 85 °C. The thermal gradient was produced by heating the lower surface of the beam using electrical resistance mats. In order to direct heat flow mainly in one direction and to ensure a maximum thermal gradient, the sides of the beams were provided with approximately 50 mm thick mineral wool insulation. The upper surface was not insulated. The measuring plugs were installed for deformation measurements along the upper and lower edges of the entire length of the beam. For displacement and rotation measurements inductive displacement transducers were installed. The support reactions of the free end of beams were measured by means of a load cell. The measurement results were registered throughout the test using a microcomputer.

A displacement of about 20 mm, which was kept constant, was instantaneously forced onto the free support of beams 1b (upwards) and 2a (downwards). The temperature of these beams was kept at about 20 °C during the entire test.

Displacement of the support corresponding in size to that of beam 1b and 2a was gradually forced onto the simple support of beam 2b over a period of about 2weeks. Displacement was increased daily in approximately equal amounts; subsequently it was kept contant (Table II). The temperature of the beam was kept at about 20 °C throughout the test. The final displacement of supports produced a calculational steel stress of about 200 N/mm^2 at the fixed support, when the stiffness of the beams was chosen as the average value of the uncracked and cracked stiffness.

During the tests, measurements were made relating to crack widths and spacings, deflections and rotations, deformations at the upper and lower edges of a beam, support reactions and temperature of a beam at different depths.

Results

The main results of the relaxation tests are presented in the following figures:

- the temperature gradient of the beam 1a measured at different times during the test in Fig. 2

- the deflection in the mid-span of the beam 1a in Fig. 3
- the decrease in restraint effect during the test in Table III.

EXAMINATION OF RESULTS

In the heated beam, 1a, a linear thermal gradient of about 100 °C/m was produced about 8 hours from the onset of heating; subsequently it remained nearly constant during the entire test.

The effect of temperature on the creep of concrete and its relaxing influence on the restraint effects is surprisingly powerful. Short-term tests carried out earlier, lasting about 12 h (Jokela, 1984), yielded similar results.

In the tests reported here, as well as in earlier ones, the temperature of the heated, creeping part of concrete was about 80 °C. The maximum value of the restraint moment in beam 1a, due to thermal gradient, was 27.5 kNm and it was reached about in 5 h from the onset of heating. Due to the accelerated rate of creep, over 10 % of the restraint moment had relaxed as soon as 7 h from the onset of heating and about one third (1/3) during the first 24 hours. The relaxation of the restraint moment continued so that after about one month one third of the maximum original value was left and after 6 months the entire restraint moment due to heating had relaxed. The final measured support reaction of the free end of the beam is greater than the original because the fixed end of the beam had cracked and the weight of the loading equipment had been ignored.

In the beams, the ends of which were subjected to a restrained displacement corresponding to a steel stress of 200 N/mm^2, the relaxation of the support reaction took place quite rapidly even at normal temperature. A decrease in the support reaction with different beams is set out in Table III assuming that in all cases the proportion of the beams' own weight is 5 kN of the support reaction.

The proportion of the shrinkage during the tests was not measured. Its influence is estimated approximately from 5 - 10 %, because the tests beams were at the beginning of long-term tests 1.5 years old and stored in test hall conditions.

Relative relaxation of the support reaction due to the creep and shrinkage of more heavily reinforced beams 2 (ρ = 1.29 %) was distinctly slower than in the case of more lightly reinforced beams (ρ = 0.43 %).

The relative relaxation of the restraint moment in beam 2b, the restrained displacement of which took place in 2 weeks, was faster than in beam 2a, the restrained displacement of which took place momentarily. Also the degree of relaxation was considerable already at the beginning of the test.

The deflection downwards of the mid-span of the heated beam increased nearly linearly in relation to the thermal gradient; subsequently its value remained constant at 2.45 mm for about 12 hours. As the heated and compressed lower surface of the beam started to creep, the deflection decreased rapidly i.e. about 25 % in a few days. As it has been stated, the restraint effect also relaxed down to half of its maximum value in the equivalent course of time. Subsequently, the value of the deflection remained nearly unchanged for about 2 months, after which the deflection started to grow again. This is due to the fact that after 2 months 20 % of the maximum value of the restraint effect remained and owing to the moment caused by its own weight, the upper surface of the beam gradually became compressed and thus creep could begin. Since also the temperature of the upper surface was above the normal (about 35 °C) the rate of creep, even in this phase, was greater than normally. The increase in the deflection was slowed down about 6 months after the start of the test when the value of the deflection was approximately the same (about 2.5 mm) as the maximum deflection due to a short-term thermal load (about 100 °C/m).

CONCLUSIONS

1. The effect of temperature (+80 ^{o}C in the test) on the rate of the creep in concrete and thus on relaxation is considerable. With the thermal gradient used in the test, the restraint effect was reduced to 30 % of its original value during one month when the corresponding reduction without heating was only to 65 % of the original value. After six months the restraint effect was totally vanished in the heated beam.
2. The relaxation of the restraint effect in a stiff, heavily reinforced beam is relatively slower than in a lightly reinforced beam, and the degree of relaxation is not as great.
3. The slower development of the restraint effect causes a faster relaxation and a greater degree of relaxation.
4. If a structure is subjected to a thermal gradient and some other mechanical load (e.g. own weight) the structural system and the relaxation of the restraint effects must be taken into account when estimating structural long-term deformations in order to find out the direction of curvature that is caused by creep. The change of the deflections direction may vary according to which side of a structure is compressed or heated and according to the degree of relaxation of the restraint effects and the redistribution of the external load effects due to cracking.
5. The average width of cracks is not essentially changed at the relaxation of the restraint effects, but instead cracks keep approximately the same width they had at formation.

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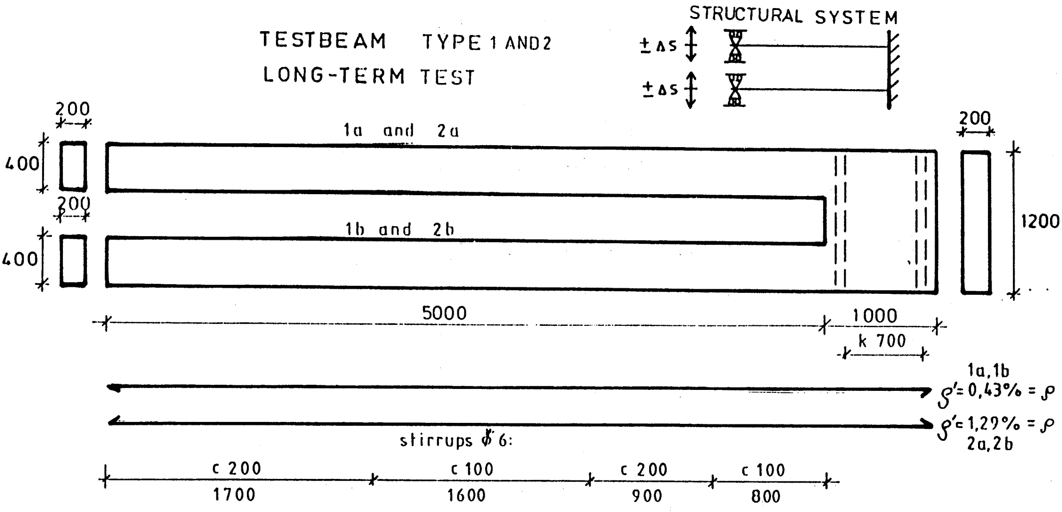

Fig. 1. Dimensions and structure of the test beams.

Table I. Material properties of the test beams based on samples.

Beam	Concrete	Reinforcement (A400H)						
	Compressive strength MN/m^2	Yield stress MN/m^2	Ultimate strength MN/m^2	Diameter mm	Rib angles α	β	Rib spacing mm	Relative rib area α_{sb}
1a, 1b	52	458	690	10	48	61	6.5	6.7 %
2a, 2b	52	434	630	20	53	69	13.6	8.0 %

Table II. Displacements at the simply supported ends and at the centre of beams in long-term tests.

Beam	Restrained displacements (mm) 1)							
	1a		1b		2a		2b	
Date	end	centre	end	centre	end	centre	end	centre
28.8.-85	-1.55	-0.84	19.10	7.02	-18.60	-7.56	0.05	-0.23
2) 29.8.-85	-1.56	-0.75	19.10	6.99	-18.54	-7.51	3.97	1.07
30.8.-85	-1.86	-3.10	18.92	6.73	-18.54	-7.57	6.09	1.70
3) 10.9.-85	-1.79	-2.68	18.97	6.95	-18.52	-7.37	19.73	6.60
7.1.-86	-1.80	-3.04	18.99	6.69	-18.55	-7.39	19.82	6.50
5.5.-86	-1.78	-3.23	19.00	6.54	-18.59	-7.47	19.84	6.43

1) direction of displacements positive upwards
2) heating of beam 1a starts
3) increase in the settlement of beam 2b was discontinued

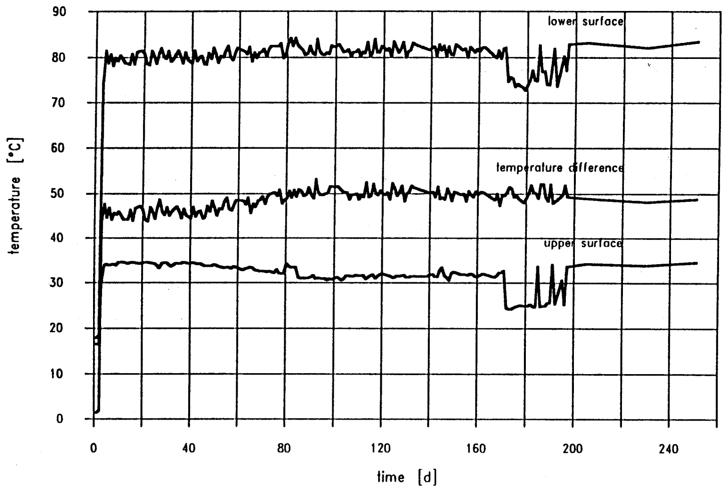

Fig. 2 . Temperature of upper and lower surface and temperature gradient of the heated beam during the test.

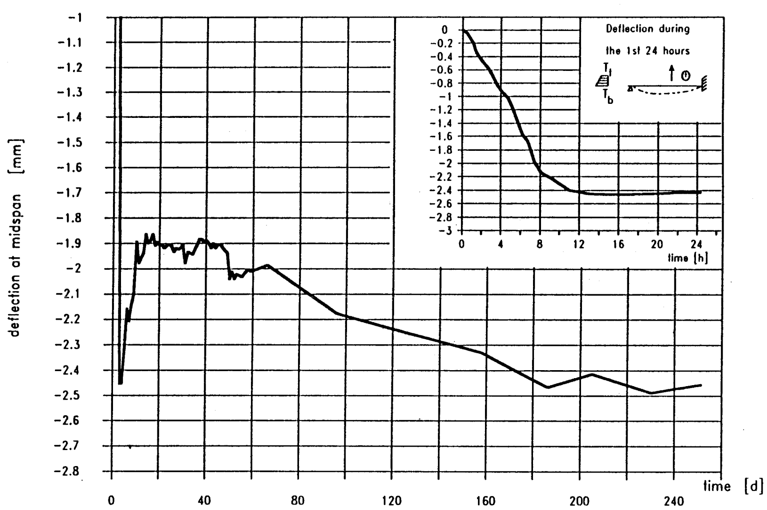

Fig. 3 . Measured mid-span deflection.

Table III. Decrease in restraint effect owing to creep.

Beam	Proportion of the relative value of the restraint effect to its greates value during different testing periods, %							
	14 days	1 month	2 months	3 months	4 months	6 months	8 months	
1a 1)	42	31	22	18	10	0	-3	3)
1b	71	67	61	58	55	53	52	
2a	97	94	88	85	84	84	82	
2b 2)	90	84	78	76	74	71	68	

1) heated
2) displacement of a support carried out step by step during the course of 2 weeks
3) due to cracking of the support and the measuring equipment's own weight