Tests of Reinforced Concrete Beams Under Thermal Gradient and Mechanical Loading

J. Jokela, S. Huovinen

Technical Research Centre of Finland, Betonimiehenkuja 1, SF-02150 Espoo, Finland

Abstract

To check the theoretical parts of the investigation bending tests were made with altogether nine reinforced concrete beams. The load was linearly distributed thermal gradient between the upper and lower surface of the beam and/or external mechanical load. The beams had been reinforced and dimensioned in different ways. The order of loadings was also changed. The cracking and deflection and the indirect load caused by temperature difference were measured in service state. The rotation capacities and ultimate loads were measured in ultimate state.

1. Introduction

The structures in nuclear power plants are often very massive, cast in-situ and thus also very stiff. If such a structure is exposed to large temperature differences the stresses caused can be considerable. As the difference between the temperatures on the different surfaces can in the structures of the cooling system in emergency cases be almost 80 ^{o}C and even in working state even about 40 ^{o}C, it is obvious that the thermal stresses cause cracking in the most stressed parts of such structures. Ordinary cracking caused by thermal loads that do not change the strength properties of concrete is mostly at its initial stage, whereat the crack spacing is still indefinite, and the normal crack theory presupposing stabilized cracking pattern is thus not valid when the crack widths are evaluated. From certain assumptions corresponding to the cracking and real bonding properties of the reinforcement and concrete the Concrete and Silicate Laboratory has plotted a set of curved with which it is possible to determine the amount of steel and size of bar corresponding to a certain accertable crack width. To check the set of dimensioning curves an experiment was made where nine reinforced steel beams were loaded.

Because the thermal stresses depend decisively on stiffness of the structure also the changing of the stiffnessdistribution of the beams caused by thermal stress and external load was studied.

It is generally believed that the thermal stresses are released in ultimate state due to plastic deformations and cracking. In massive, strongly reinforced and possibly also pre-compressed structures the deformation capacity may not be sufficient enough to release the indirect loads completely, whereat their influence has to be considered also in checking the safety of the ultimate state. In connection with the experiment also the release of thermal forces was studied as well as the re-distribution of forces of the external load and the influence of thermal forces on the ultimate capacity and rotation capacity of the beams.

2. Specimens and tests

Reinforced concrete beams shown in figure 1 were used as specimens in the tests. The dimensions of the specimens have been shown in figure 1 and data of manufacture in table I.

In beams 1 - 8 the reinforcement was hot-rolled deformed bar and in beam 9 cold worked deformed bar.

In the tests the temperature difference between the beam upper and lower surface was increased to about 80 $^{\circ}C$. The beams were also subjected to mechanical load P as shown in figure 1.

Table II shows in which order the stresses of the different beams were applied. The loading of beams 2, 3, 4, 6, 7, 8 and 9 was started with thermal gradient and of beams 1 and 5 with mechanical load. The same beams were correspondingly loaded to failure with and without thermal gradient.

The crack widths, deflections and curvatures as well as the support reaction in the free supported end of the beam were measured in the tests.

3. Results

3.1 Materials

The stated strengths of the materials used in the specimens have been shown in table III.

3.2 Service state

Results of measurements and calculated values describing the behaviour of the beams in service state are shown in table IV.

The effect of thermal load and combined thermal and external load on the beam's stiffness distribution has been presented in figure 2. The corresponding stiffness distribution at ultimate state has been presented in figure 3.

3.3 Ultimate state

Table V shows the yield and ultimate loads measured in the tests compared with the theoretical results. The theoretical results has been calculated both with the elastic theory and plastic theory. The first mentioned values has been calculated both with and without thermal load.

In table VI are the rotation capacities on fixed support measured in the tests, and the rotation capacity of the support calculated with some methods.

4. Conclusions

From the results and comparision of results to calculational values following conclusions can be made.

1. The temperature-difference corresponding the opening of the first cracks varies considerably because the variation of the tensile strength of concrete and the stiffness

of the supporting.

2. The width of the first cracks in test beams varied between 0,01...0,04 mm when the corresponding calculational values were 0,01...0,09 mm.
3. The crack widths corresponding about the temperature-difference of 70...80 ^{o}C were in tests 0,02...0,12 mm and the calculational values according CEB model code were 0,03... 0,12 mm. At this state the crack pattern is not yet stabilized according calculations, through the spacing of the cracks at the area of highest moment in test beams clearly was stabilized.
4. The effect of cracks on stiffness is considerable. When the temperature-difference was 80 ^{o}C, were the stiffnesses of the beams no. 1...3 and no. 9 23...33 % from the calculational stiffness value of corresponding non-cracked beams. Corresponding stiffness value of beam no. 4 was 49 %, beams no. 5...7 33...75 % and beam no. 8 42 %. The support moment was decreased with some amount.
5. The rotation capacity in all beams was sufficient to release the support moment caused by thermal gradient.

NOTATIONS

P external load
P_k service load (external, $_s$ = 200 N/mm^2)
P_y yield load (external)
P_n ultimate load (external)
ΔT thermal gradient
f_c concrete compressive strength
f_y steel yield strength
f_u steel rupture strength
w width of crack
ρ relative steel area (lower side)
ρ' relative steel area (upper side)

REFERENCES

/ 1 / JOKELA, J., HUOVINEN, S., "Behaviour and design of concrete structures under thermal gradients", Technical Research Centre of Finland, Research Reports, (in print), (Finnish text).

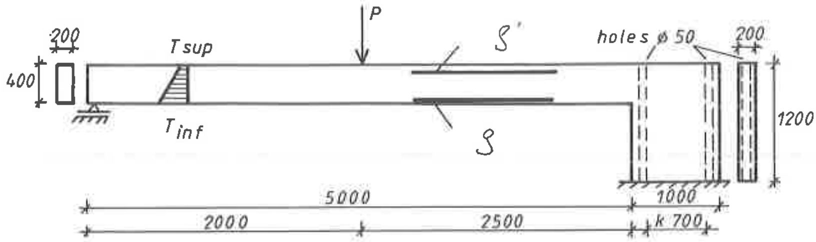

Fig. 1. Specimens and loads.

Table I. Planned manufacturing data of the specimens

Specimen n:o	Reinforcement ρ (%)	ρ' (%)	design strength N/mm^2	Concrete design strength N/mm^2
1...3	0,43	0,43	400	50
4	0,43	1,72	400	50
5...7	1,29	1,29	400	50
8	1,29	2,69	400	50
9	0,43	0,43	500	50

Table II. Order of beam stresses

Beam n:o	Load	Order and magnitude of stress types. 1	2	3	4	5	6	7
1 and	P	→ P_k	→ 0	0	→ P_k	→ 0	0	→ P_n
5	ΔT	0	0	→ 80^{o}C	80^{o}C	80^{o}C	→ 0	0
2,3,4	P	0	0	→ P_k	→ 0	0	→ P_n	-
6,7,8,9	ΔT	→ 80^{o}C	→ 0	0	0	→ 80^{o}C	80^{o}C	-

Table III. The stated average strengths of the materials (N/mm^2)

Beam n:o	Results: Reinforcement field f_y	field f_u	support f_y	support f_u	Concrete
1...3	458	690	458	690	52
4	458	690	434	630	53
5...7	434	630	434	630	51
8	434	630	505	735	50
9	660	725	660	725	54

Table IV. Calculated and measured values in service state.

Beam n:o	Bar size mm	Calculated values: ΔT corresponding 1st crack °C 1)	Calculated values: widht of the 1st crack w_m mm 1)	Calculated values: widht of cracks at ΔT = 80°C w_m mm 2)	Measured values: ΔT corresponding 1st crack °C	Measured values: widht of the 1st crack mm	Measured values: widht of cracks at ΔT = 80°C mm
1 3)	10	33,6	0,09	0,09	38	0,04	0,12
2	10	33,6	0,09	0,05	23	0,02	0,12
3 4)	10	33,6	0,09	0,12	39	0,01	0,09
4	20	30,0	0,02	0,03	19	0,02	0,04
5 3)	20	30,0	0,03	0,05	42	0,01	0,02
6	20	30,0	0,03	0,12	25	0,02	0,06
7 4)	20	30,0	0,03	0,06	41	0,01	0,07
8	25	29,7	0,01	0,03	22	0,02	0,06
9	10			0,10	18	0,02	0,08
variation		30...34	0,01... 0,09	0,03... 0,12	18...42	0,01... 0,04	0,02... 0,12

1) method is based on real bonding properties and initial cracking phase
2) calculation made according CEB, model code
3) external load has influenced before thermal load, effects on support in the same direction
4) effects on support in different directions

Table V. Yield and ultimate load (P_y and P_u) (kN) calculated with strength properties in table III and test results.

Beam n:o	Calculated results: Elastic theory, P and ΔT=80°C, P_y	P_u	Elastic theory, only P, P_y	P_u	Plastic theory, P, P_y	P_u	Test results P_y	P_u
1	-	-	54,8	81,4	61,8	91,9	60,0	81,0
2	33,7	60,4	54,8	81,4	61,8	91,9	59,0	82,0
3	53,4	85,5	54,8	81,4	61,8	91,9	60,0	81,0
4	104,3	136,4	66,1	98,2	113,2	160,2	73,0	145,6
5	-	-	147,7	206,1	166,7	232,6	138,0	193,1
6	94,2	152,6	147,7	206,1	166,7	232,6	150,0	188,2
7	145,9	216,3	147,7	206,1	166,7	232,2	150,0	201,0
8	223,4	303,7	178,1	248,6	229,5	309,0	-	160,0
9	57,0	64,4	78,0	85,4	88,0	96,4	87,0	94,5

Table VI. Calculated rotation capacities of the support and the values measured in the test.

Specimen n:o	Theoretical rotation capacity · 10^{-3} (rad)					Test result
	Baker	Corley	CEB	Plem	own method	θ_p
1	14,7	42,0	52,1	42,6	27,2	47,9
2	14,7	42,0	52,1	42,6	27,2	44,2
3	14,7	42,0	52,1	42,6	27,2	35,2
4	14,8	17,0	12,9	13,1	13,8	38,1
5	12,3	19,3	17,3	14,2	11,4	41,8
6	12,3	19,3	17,3	14,2	11,4	36,2
7	12,3	19,3	17,3	14,2	11,4	30,3
8	7,9	17,2	8,3	7,6	7,5	28,2
9	15,1	33,6	41,7	34,5	23,5	18,7

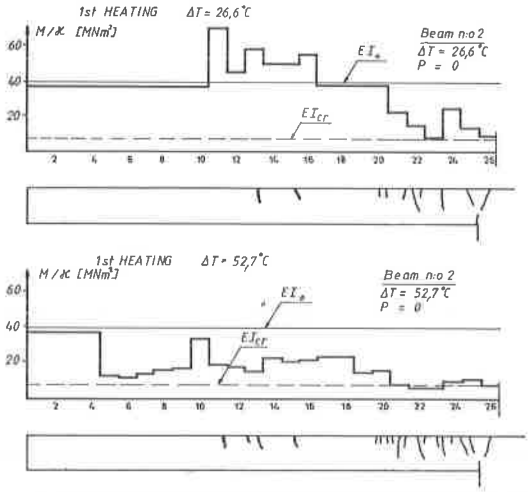

Fig. 2. Effect of thermal gradient on the stiffness of the beam.

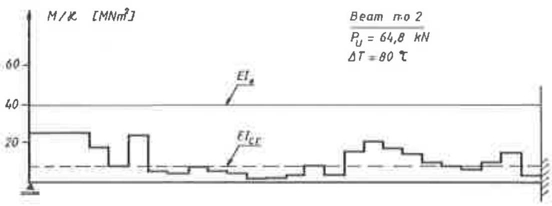

Fig. 3. Stiffness of the beam no. 2 at ultimate state.