Dynamic behaviour of partially prestressed concrete structures

Dynamic Behaviour of Partially Prestressed Concrete Structures

Caractéristiques dynamiques des structures en béton partiellement précontraint

Dynamisches Verhalten von teilweise vorgespannten Betonbauwerken

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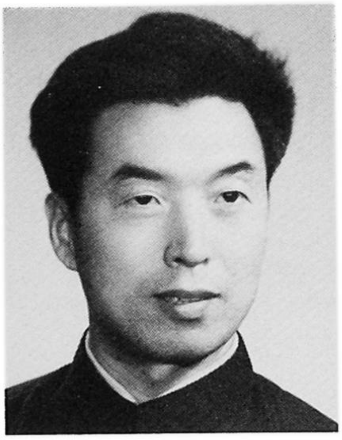

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SUMMARY
In order to study the dynamic behaviour of the tension zone in partially prestressed concrete structures a series of dynamic tests on axially tensioned specimens were conducted simulating the tension zone of beams. The tests demonstrated the dynamic effects on the stiffness of specimens, the relationship between the crack width and number of dynamic loading cycles, and the fatigue behaviour of both prestressing and nonprestressing reinforcements.

RESUME
Une série d'essais dynamiques de traction a été entreprise sur des éprouvettes afin d'étudier le comportement, dans les zones de traction, de structures en béton partiellement précontraint. Les essais ont montré les effets dynamiques sur la rigidité des éprouvettes, la relation entre la largeur des fissures et le nombre de cycles de charges et le comportement à la fatigue des armatures précontraintes et normales.

ZUSAMMENFASSUNG
Zur Erforschung des dynamischen Verhaltens der Zugzone von teilweise vorgespannten Bauteilen wurde eine Reihe von Versuchen an axial auf Zug belasteten Prüfkörpern durchgeführt. Die Belastung entsprach der Beanspruchung der Zugzone eines Biegeträgers. Die Versuche zeigten den Einfluss der dynamischen Belastung auf die Steifigkeit, das Verhalten der Risse in Funktion der Lastwechselzahl sowie das Ermüdungsverhalten des Vorspannstahls und des schlaffen Stahls.

1. INTRODUCTION

In PPC (partially prestressed concrete) structures under service loading, cracks are sometimes permissible in the concrete tension zone. Since cracks under dynamic loading show repeated progressing it is necessary, in order to achieve an appropriate evaluation of the service reliability of a structure, to carry out studies not only on its static behaviour, but also on the stiffness diminuation in its tension zone under dynamic loading, the dynamic effect upon crack development, and the fatigue behaviour of reinforcement as well. Hence a series of dynamic tests on axial-tension specimens were conducted simulating the reinforcement percentage in the effective area of tension zone of a beam subject to bending and reinforced with both prestressed and non-prestressed steels. The tests results rendered it possible: to establish the relationship between the tension zone stiffness of PPC structures and the dynamic effects; to investigate the relationship of the crack width versus the number of dynamic loading cycles and the reinforcement stress increase; to evaluate the fatigue life of both the prestressing and the non-prestressing reinforcements in the tension zone of structures provided with mixed reinforcement.

The tests showed that it is feasible to investigate dynamic effects on the tension zone in bending members through dynamic tests on axially loaded specimens.

2.TEST

2.1. Specimen and gauge points

Fig. 1 shows the configuration and dimensions of the specimen. 40 Si2MnV spiral bars were used for prestressing steel, with a diameter of 25 mm and an ultimate strength of 882.6 MPa. 20MnSi spiral bars 12 mm in diameter with an ultimate strength of 588.4 MPa were used for non-prestressing steel. The layout of the gauge points is also shown in Fig. 1. 10-inch (base) hand strain gauges were used to measure the following parameters: elastic compression of the specimen at the moment of tension-releasing; creep-shrinkage of the test specimen; strains in the specimen caused by static/dynamic loads. For the measurement of cracking load and decompressing load electric-resistance gauges were used.

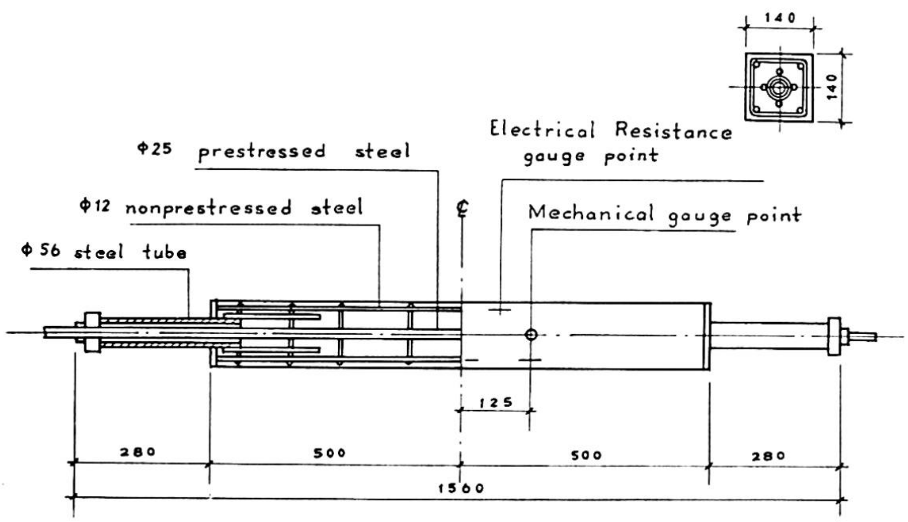

Fig. 1 Tensile specimens

2.2. Test procedures

Static test: aimed to determine the specimen stiffness in the elastic range and to measure its cracking and re-cracking loads. In each phase of dynamic load application (usually 5 x 10^5 cycles), static measurements were made to find out the dynamic effects on the stiffness and crack width of the members.

Dynamic test: Two different sets of tests were carried out. The first set was the dynamic crack-inducing test (A2-3(15)(17)), intended to help determine the dynamic load effect upon the cracking behaviour of the members subject to dynamic loading, the maximum value of which was kept under the cracking static load. It was also intended to enable observation of the entire process of variation of stiffness and crack width of the speciment with increasing dynamic loading cycles. The second set was the post-crack fatigue tests for determining the dynamic effects upon crack width and for measuring the ultimate fatigue strength of prestressing bars.

2.3 Load application

The load was applied to the specimen placed a fatigue testing machine through a special loading device which transformed the jacking pressure into a tensioning force applied to the specimen (Fig. 2). The magnitudes of the load were specified as follows:

(a) max. load $P_{max} < 156.9$ kN for the static elastic loading phase;

(b) $P_{min} < P_d < P_{max}$;

(c) $\sigma_{p,max} / \sigma_{pu} = 0.5 - 0.6$ for the upper limit of the dynamic load;

(d) the minimum load to be so chosen in correspondence with the prescribed maximum load as to keep the ratio $\sigma_{p,min}/\sigma_{p,max}$ in the prestressing bars at around 0.7.

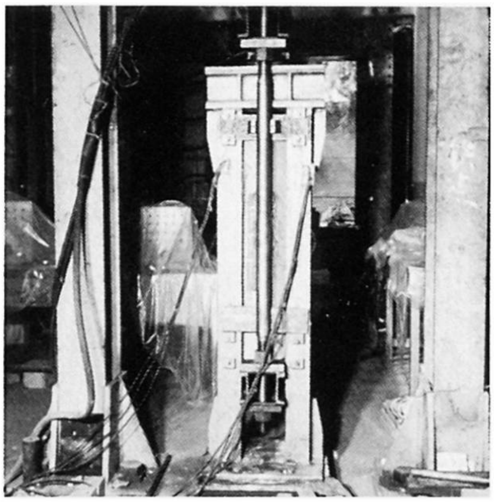

Fig. 2 Test equipment

where P_{min} is the minimum load, P_d is the decompressing load of the members, P_{max} is the maximum load, $\sigma_{p,min}$ is the minimum stress of prestressing bars, $\sigma_{p,max}$ is the maximum stress of prestressing bars, σ_{pu} is the ultimate strength of prestressing bars.

3. DYNAMIC EFFECTS ON STIFFNESS OF SPECIMENS

Through dynamic tests made on specimens A2-3(15) and A2-3(17) using hand strain gauges for step-by-step measurement in accordance with the loading sequence, the variation of the specimen stiffness with the increase of the load was well as the number of load applications was found out. In Table 1 are given the loading procedure and the corresponding stress values in the prestressing bars.

The range of the hand strain gauge was 10 inches, covering three cracks.

The measurements gave the average strain in this section, showing the bond deteriorating between concrete and steel and the influence of concrete stiffness dwindling as a consequence of the increase in the number of dynamic load applications. In Fig. 3 are shown the variation curves of the measured average strain values.

Loading sequence	1		2		3		4		5		6	
Load (kN)	max	min	max	min	max	min	max	min	max	min	max	min
	176.5	70.6	196.1	78.5	215.7	86.3	235.4	94.1	255.0	102.0	274.6	109.8
σ_p.max(MPa)	472	367	495	368	519	370	543	374	574	392	589	393
$\Delta\sigma_p$ (MPa)	105		127		149		169		182		196	
N ($\times 10^4$)	4 x 50 = 200		66		50		50		50		50	

Table 1 Load, stress and cycles for specimen A2-3(15)

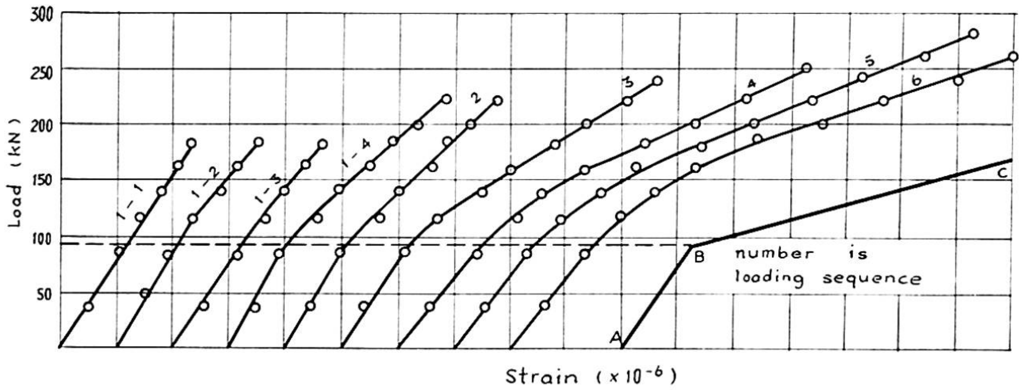

Fig. 3 Loading cycles vs strain for specimen A2-3(15)

The first sloping line at the left hand of the figure represents the load/strain curve for the first load application. It can be seen without difficulty that the specimen in this case is in the range of linear elasticity before the appearance of cracks. All the other curves are load/strain ones obtained from measurements made according to the loading sequence. The curves deflect downward in their upper portions as the number of loading cycles and the load magnitude increase until the loading cycle reaches around 4×10^6 when the up-per portion becomes nearly parallel to the curve section BC (drawn in bold line) at the right hand of the figure. This BC line is the load/strain curve for the measured section when the external load is considered to be taken up by the prestressing and non-prestressing steels only. Apparently, the effect of concrete stiffness in this instance is completely null. The broken line ABC is an idealized load/strain curve for 4×10^6 cycles of repeated load application.

Some preliminary conclusions can be drawn from the above test results:

(1) For the first 5×10^5 loading cycles, the upper limit of the dynamic

load equals the maximum static load on first application (without appearance of any cracks), P_{max} = 176.5 kN. However the load/strain curve exhibits marked deflection for P >88.3 kN. This implies that the specimen has been dynamically loaded to crack. With continued application of load up to 2 x 10^6 cycles, the upper limit remaining unchanged, the slope of the deflected section of the load/strain curve does not show any noticeable change but the point of deflection moves downward slightly. This demonstrates that the number of cycles bears no significant influence on the specimen stiffness for lower levels of dynamic loading, even though cracking has heretofore occurred.

(2) As obtained from measurement, the average value of the re-cracking load (decompressing load) of the specimen is P_d = 91.7 kN. It is observed from Fig. 3 that, with the accumulation of loading cycles, the upper portion of the load/strain curve slopes further downward, yet the lower portion of the curve maintains basically the same inclination as that of the original linear elastic curve (the first curve at the left hand of the figure). This indicates that the cracked specimen will close up and resume its elastic behaviour under the action of prestressing force on the removal of the dynamic load which is not very large. Beyond the point where the upper limit of the dynamic load exceeds 235.4 kN, the upper portion of the curve is practically parallel to line BC with the concrete entirely out of function. In this case, the curve cannot regain its original slope on unloading to 88.3 kN and under, when the stress in the prestressing bar would have increased by 166.7MPa, which is highly improbable to occur under normal service loading conditions.

4. DYNAMIC EFFECT ON CRACK WIDTH

As has been described in the foregoing paragraphs, the bond between the tension reinforcement and the concrete in PPC structures deteriorates gradually under the action of dynamic loads, and the concrete gradually recedes from its function. At the same time, the crack width in the concrete tension zone also displays some changes.

In this test 13 specimens were put under dynamic loading and were observed for the development of crack widths. For this purpose systematic observations and measurements were made on specimens A2-3(2)(11)(16)(20)(21). The measured static cracking loads and decompressing loads for the 5 specimens before they were put under dynamic test are given in Table 2. The corresponding crack widths measured under different loadings are summed up in Fig. 4. Regression analysis of the measured data gave the following relationship: w = -0.0534 + 0.00693 P. From this can be obtaned the calculated decompressing load P_d = 75.5 kN at w = 0. This calculated value is slightly smaller than the average value given in Table 2.

Transforming the above regression equation into the correlation equation of crack width against stress increase in prestressing steel, we have:

$$w = 0.57\,\Delta\sigma \times 10^{-3} \text{ (mm)}$$

where $\Delta\sigma$ is the stress increase in the prestressing steel in MPa.

Load (kN) \ Specimens	A2-3(2)	A2-3(11)	A2-3(16)	A2-3(20)	A2-3(21)	Average
Crack Load P_{cr}	124.5	160.8	192.2	165.2	140.7	156.8
Decompresing Load P_d	73.5	81.4	96.1	70.1	74.5	79.1

Table 2 Cracking and decompressing loads

5. FATIGUE BEHAVIOUR OF SPECIMEN

Studies of the fatigue behaviour of PC structures are generally carried out on real members or model beams. Sometimes such a study is done with prestressing steel and concrete separately. The first method involves expensive costs, and the test is limited in scale, while with the second method the applicability of the test results to fatigue design of actual structures is yet to be examined. In this paper, another mothod of fatigue test is described. This method reveals the fatigue behaviour of the tension zone of a bending members with united action of concrete, prestressing steel and non-prestressing steel in carrying the dynamic load. And it is simple, explicit and inexpensive.

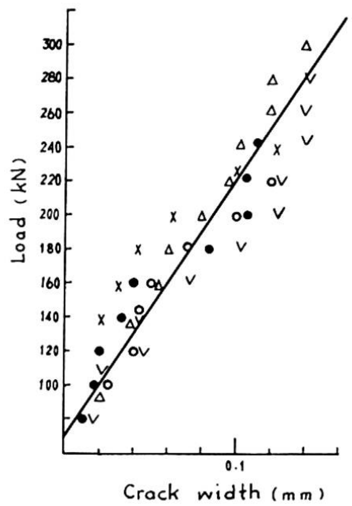

Fig. 4 Crack width vs load

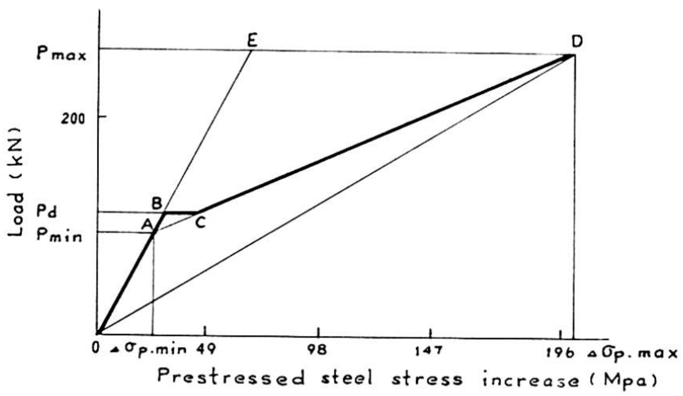

Fig. 5 Prestressed steel stress increase vs Load

The loading procedure for the fatigue test was the same as described in paragraph 2. The fact that the range of fatigue test load defined by its upper and lower limits contained the decompressing load for the specimen reflects the most unfavourable condition for fatigue resistance of the tensionzone of PPC structures. Fig. 5 shows the theoretical correlation curve of the load versus the stress increase of the prestressing steel for specimen A2-3(12). The sloping line OE in the figure is equivalent to the correlation curve for full prestressing. Since generally $P_{min} < P_d < P_{max}$ (in the case of bending member $M_{min} < M_d < M_{max}$) for PPC structures, the stress increase in prestressing steel will vary along the curve definid by 0, B, C and D. This curve, being a theoretical one with its BC section a smooth line, has been verified by test results. It can be seen from Fig. 5 that, in the case of PPC structures subject to dynamic loading, there is an abrupt change of stress increase in the steel at the crack. Thus for the same load amplitude the stress increase becomes larger than that in the case of fully prestressed concrete structures.

In Fig. 6 are summed up the results obtained form the fatigue rupture tests of 11 specimens. In all cases, the break point was located in the effective middle portion of the specimen. Regression analysis gave the equation of correlation between the cycle number N and the stress behaviour of the prestressing steel S_{max}.

$$S_{max} = 1.265 - 0.1105 \text{ Log } N$$

where $S_{max} = \sigma_{p,max} / \sigma_{pu}$, where $\sigma_{p,max}$ being the maximum prestressing steel stress value at the point of fatigue rupture, σ_{pu} the ultimate strength of the prestressing steel with an assumed value of 944 MPa.

Given the correlation factor r = -0.8316 and remnant standard difference $S_x = 0.245$, the fatigue strength of prestressing steel corresponding to 2×10^6 cycles was calculated as follows: $S_{max} = \sigma_{p,max} / \sigma_{pu} = 0.5774$, $\sigma_{p,max} = 546$ MPa. Assuming 95% as the guaranctee rate, the average value of fatigue strength $\sigma_{p,max} = 513$ MPa, $\sigma_{p,min} = 341$ MPa, $\Delta\sigma = 172$ MPa.

As has been demonstrated by tests, the PPC structures with mixed reinforcement as described in this paper can satisfy service requirements under dynamic loading so far as fatigue life is taken into consideration.

It was found on cutting the specimens across through the fatigue break point that in all cases fatigue break occurred on prestressing steels, shown in Fig. 7, whereas all non-prestressing steels were still in good order. Computational analysis also indicated that it was only natural for the prestressing steel, the maximum stress amplitude of which under dynamic loading had reached 196 MPa, to fail by fatigue prior to non-prestressing steel, which had an initial compression due to its constraining effect against concrete shrinkage and creep, and thus had a stress amplitude as low as 78 MPa.

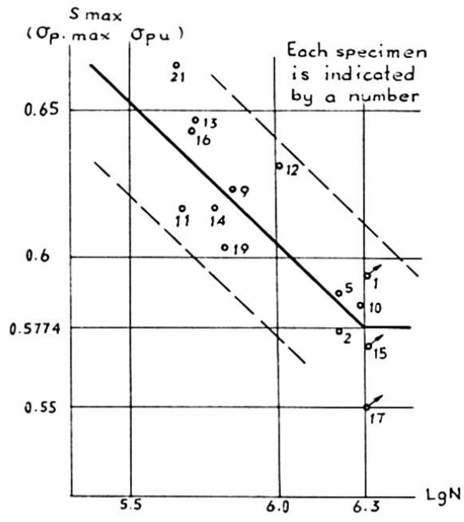

Fig. 6 S-N curve for prestressing steel

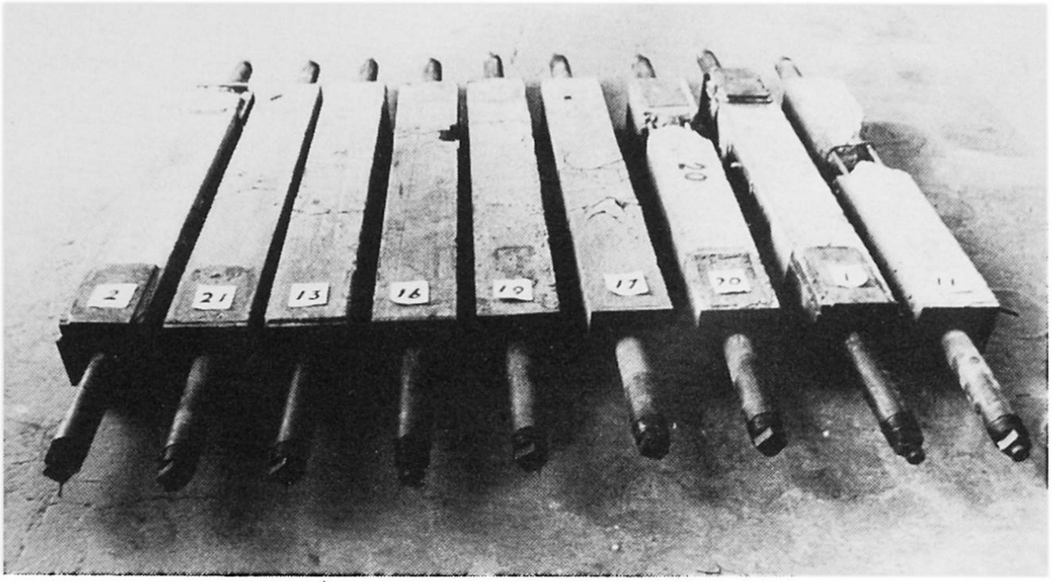

Fig. 7 Specimens after break

The hereby adopted method of experimental study may be applied to structures using forms of reinforcement other than mentioned in this paper. Its practical significance will be further manifested when the test results are compared with those to be obtained from bending beams using the same form of reinforcement.

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