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Behaviour of Four Prestressed Concrete Platform Roofs Between 1955 and 1963

Comportement de quatre marquises en béton précontraint entre 1955 et 1963

Verhalten von vier Spannbetonbahnsteigdächern zwischen 1955 und 1963

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Two pairs of two platform roofs were built at Potters Bar near London in 1954/55. As seen in Fig. 1, each of the four roofs is 130 ft. long and approximately 36 ft. wide supported by four columns. Each roof consists of a cantilever slab of a thickness of 3—4 in., supported by two main beams, the slab being prestressed by means of post-tensioned four-wire cables placed in grooves 12 in. apart. Each of the two main beams of 130 ft. length, cast and prestressed in situ, is supported by two columns 65 ft. apart. Thus in both cases for the slab as well as for the beams there are only negative bending moments with tension at the upper sides under uniformly distributed load which allowed the provision of straight posttensioned tendons.

The weather conditions were most unfavourable during the entire building operations, particularly in the second part of 1954, with almost constant rain. This delayed the work and also made it very difficult for the contractor to obtain uniform concrete strength. The concrete in the slabs was well compacted by means of internal vibrators placed horizontally within the concrete, whereas that of the main beams was less well compacted by means of so-called Kango

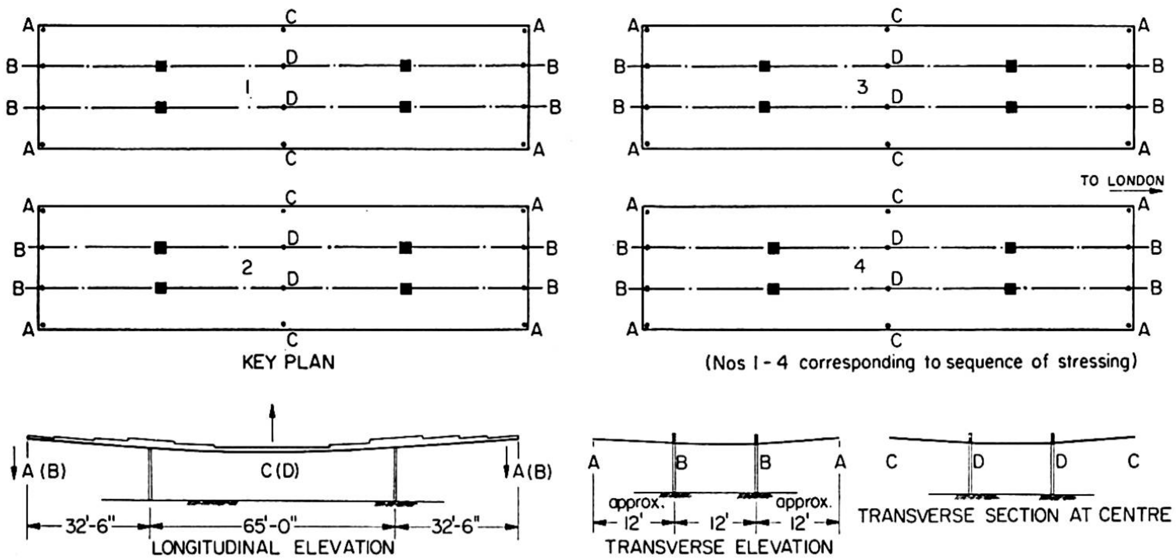

Fig. 1.

hammers. The provision of a rather light shuttering prevented the use of more efficient, heavier external vibrators. The concrete was further affected by the vibrations of passing traffic. Although there were speed restrictions for the trains on the main line London-Edinburgh, they might not have always been fully observed during the night and in the early morning, which was concluded from the fact that occasionally haircracks had developed overnight.

Prestressing was applied when the concrete test specimens showed sufficient strength. However, the strength in the roof beams must have been much less than that of the well compacted test specimens made on the ground in which the water content was not increased by rain. In consequence of the reduced strength, difficulties occurred during prestressing, particulars of which are described by the author elsewhere[1]), which required some repair work at the anchorages. When the prestress was applied, excessive deformations took place.

This was almost twice the amount of the values expected, based on an assumed instantaneous E-value of 5.25×10^6 psi corresponding to the specified cube strength of 6500 psi. Thus, the actual strength at transfer in the beams must have been appreciably less. The instantaneous deformation at transfer increased further due to creep, but this was again much more than originally expected for the specified strength. The photo Fig. 2 shows the deformations of the roofs in Summer 1955.

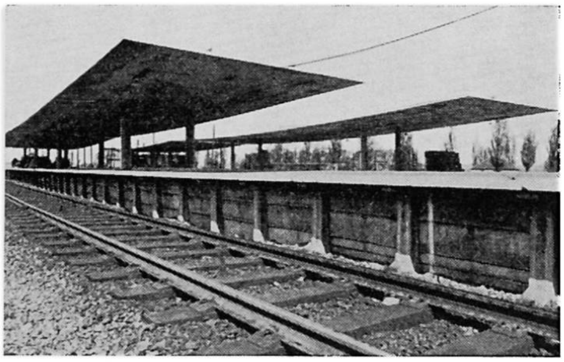

Fig. 2.

The four platform roofs had been built in the sequence 1 to 4, as indicated in Fig. 1, and the temperature conditions varied to a very great extent during this time, with the consequence that quite different deformations of the roofs occurred owing to different shrinkage and creep. This was particularly conspicuous along the two pairs of edges of adjacent roofs where different deformations occurred and the two adjacent levels did not meet. This difference in age and shrinkage and creep history between the individual roofs has remained quite apparent all the time, although the degree of discrepancy was slightly reduced by the end of 1955.

The conditions were further aggravated by the fact that owing to the

[1]) See Chapters 23 and 25 of the author's book "An Introduction to Prestressed Concrete", to be published by *Concrete Publications Ltd.*, London, 1964.

excessive deformation and by the infiltration of water into a lightweight concrete topping (which was afterwards provided at the centre portion to improve the drainage), the deadload was appreciably increased and exceeded there the working load with the consequence that cracks developed at the underside i. e. where compressive stresses were expected, as described in more detail elsewhere[1]). Consequently, modifications were made by removal of the "lightweight" concrete topping and roofing cover over the centre portion of the roof and ensuring satisfactory drainage, thereby keeping the dead load within the design value, when all cracks at the underside closed. Figs. 3 and 4 show the

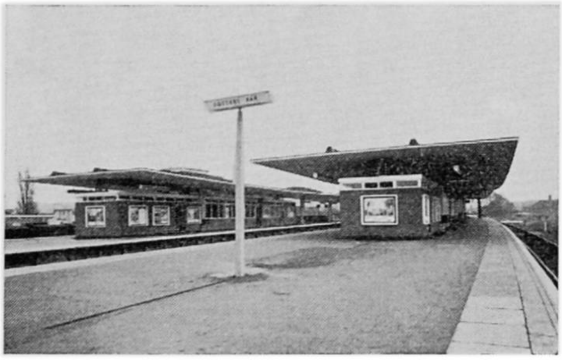

Fig. 3.

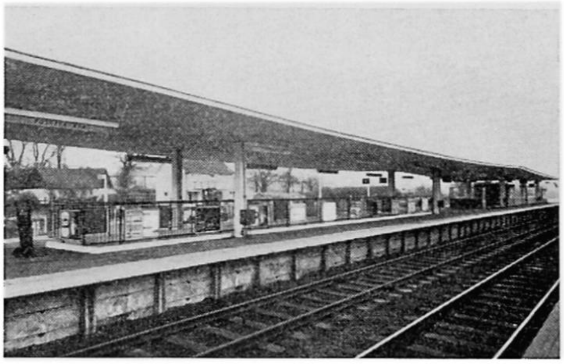

Fig. 4.

roof after this modification, when the deformations were greatly reduced and the recoveries were in good agreement with the anticipation based on the calculation with an E-value more appropriate to the actual strength.

Although the deformations of the roofs were greatly reduced, they were still much more than they should have been if the concrete had its specified strength. In order to investigate the further changes in deformation, measurements were made since November 1955 when the new platforms had been in use; special bench marks were made and all following measurements were related to the actual deformations in November 1955 which became the zero points.

Measurements of the levels of the four corners A, of the four cantilever ends B and of the two points C and D at the centre of the roofs have been made for all four roofs at certain intervals. In Fig. 5 the maximum and minimum levels of each roof have been plotted for the time between November 1955 and November 1960. The abscissa representing the time is divided into 10 divisions, each of which indicates half a year, and the date is given underneath. The maximum and minimum of deflections of all four roofs are shown by solid lines when at least two readings were available and by dotted lines where only a single reading applied. Fig. 5 relates to the measurements of 16 points each at the corners A and the cantilever ends B, and covers the points C and D at the centres where eight readings each were taken.

The temperatures are given for the individual dates in degrees of Fahren-

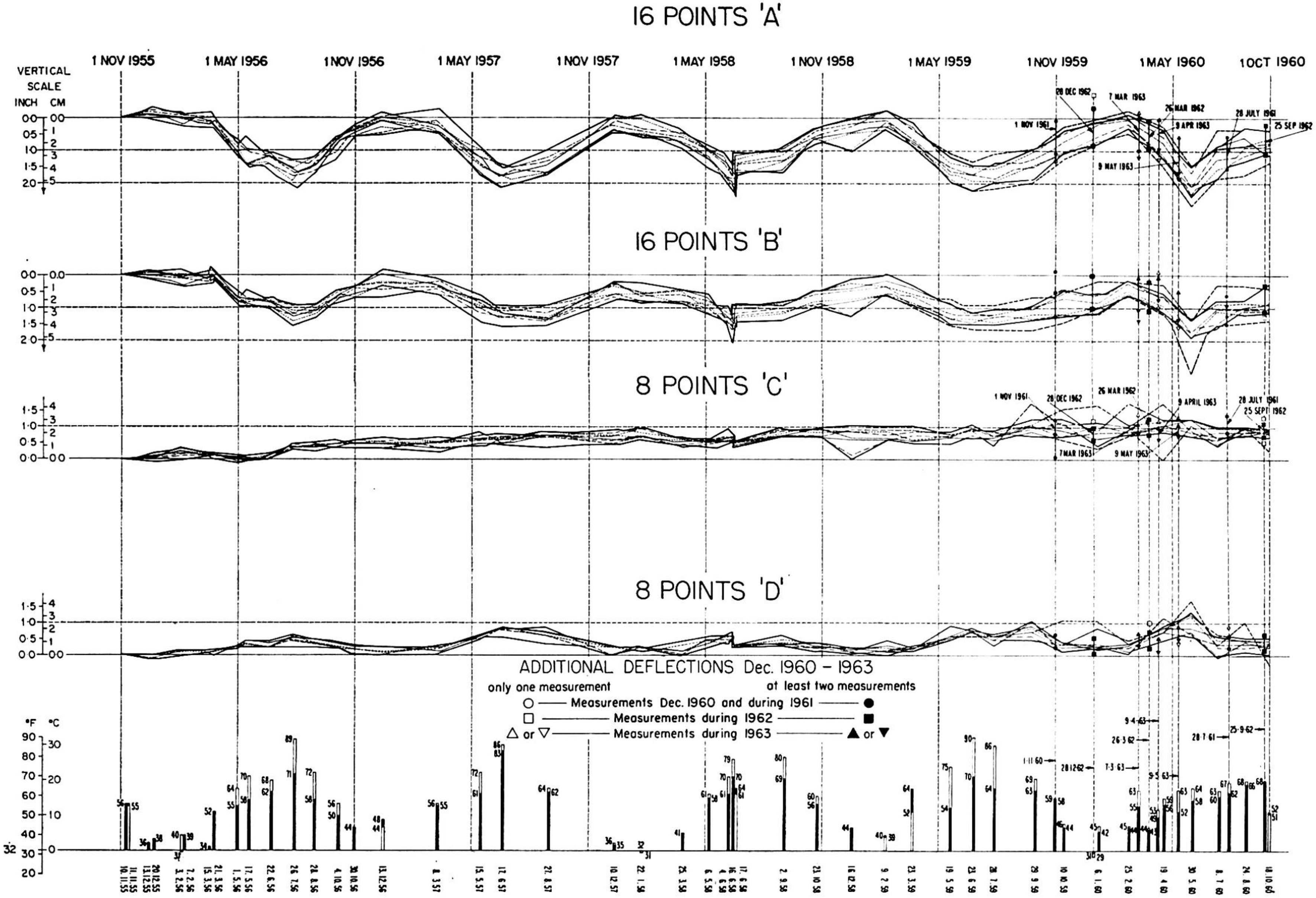
16 POINTS 'A'
1 NOV 1955
1 MAY 1956
1 NOV 1956
1 MAY 1957
1 NOV 1957
1 MAY 1958
1 NOV 1958
1 MAY 1959
1 NOV 1959
1 MAY 1960
1 OCT 1960
VERTICAL SCALE
INCH CM
16 POINTS 'B'
8 POINTS 'C'
8 POINTS 'D'
ADDITIONAL DEFLECTIONS Dec. 1960 - 1963
only one measurement
at least two measurements
Measurements Dec. 1960 and during 1961
Measurements during 1962
Measurements during 1963
°F °C

Fig. 5.

heit, plotted from 32 deg. F. (zero C). Two different temperatures are given in each case, one measured below the roof and the other above. The temperature below the roof is indicated by blacking-in the rectangle drawn, whereas the upper level is shown without the blacking-in. Normally the temperature was higher above the roof and thus in the diagrams 5 the positions shown in black usually terminate below those given for the top. In a few instances these two temperatures were equal, in which case the entire rectangles are blackened. In a few other instances the temperature was higher below than above the roof, in which case the lower portions of the rectangles are left white, whereas the upper portions are shown black.

It is seen that the deflections varied to a great extent during each year and were mainly dependent on the temperature. Obviously, also, sunshine and relative humidity are of some influence. However, it was impossible, as originally intended, to make some distinction between the effect of temperature, sunshine and relative humidity. The latter was ascertained since Autumn 1959 and varied between 36 and 88 per cent relative humidity. The weather in England, as is well known, is very changeable and thus appreciable differences in temperature and humidity occurred often between the levelling of the first and last roof. This accounts for great variations between the minimum at individual measurements.

The exactness of the level readings may be taken as $^1/_{100}$ ft. corresponding to $^1/_8$ in. or about 3 mm. As the diagrams were not always plotted immediately after the levels had been taken (except for the first two years) a few discrepancies occurred. In one or two cases, when it was obvious that there must have been a mistake, the reading was excluded, but in all other instances even doubtful values as those in April 1960 (for *C*) and in May 1960 (for *A* and *B*) were included.

It must be realised that in November 1955 which is the basis of the comparison, the ages of the four roofs varied to a great extent. Roofs (1) and (2) were well over a year old, whereas roofs (3) and (4) were of ages slightly above or below $^3/_4$ year respectively. Obviously the difference in age and thus in creep history had a great influence upon the subsequent behaviour. Unfortunately, it was impossible to base the deformations on the original levels, which applied before transfer of the prestress, since the scaffolding which was required for concreting was in the way.

It was considered as possible that the excessive deformations (comprising upward deflections at the cantilevers and downward deflections at the centres of the roofs) might even increase in the course of time in consequence of further creep and shrinkage of the concrete and relaxation of the steel. However, the measurements, as shown in Fig. 5, indicate that there has, in principle, not been an excessive increase in the deformations. In general, it can be seen that with increasing temperature a relief in deformation takes place, the cantilever ends lowering and the centres of the beams rising, as indicated in Fig. 1.

Sudden changes in temperature caused immediate deviation in deflections as can be seen for the measurements on 4, 16 and 17 June 1958. The sudden increase in temperature on the 16th June and the subsequent reduction brought about immediate changes in the deflections.

Greater variations between maximum and minimum deflections occurred in 1963 after a prolonged sustained loading due to snow in January and February 1963. Already at the loading on 28th December 1962 snow was on the roof, but the deformations differ relatively little from those obtained at investigations without live load. However, greater deviations occurred at the measurements in March 1963. For this reason further investigations were carried out in April and May 1963.

The results are summarised in the Table 1 for the points *A* and *B*, where the individual deflections in May 1956 were compared with those in 1963, and also a number of intermediate readings are shown for December 1962 with the snow load and those in March and April 1963, the latter made in the morning and afternoon at different temperatures. Similar results were obtained for the points *C* and *D*. However, they are not shown as in these cases only two levels instead of four were available, and consequently the results are not so conspicuous; but also in these cases a similar behaviour was noticed.

A comparison of the results in May 1956 with those in May 1960 at similar temperatures shows that the downward movement of the cantilevers increased during these seven years which corresponds to a reduction in the rather excessive original deformations of the roofs. For example, the greatest reduction (average of four roofs) in the levels of the corners *A* was 1.05 in. in 1956 and 1.50 in. in 1963. This is not very excessive when the entire variations are taken into account which amounted at the cantilever ends to approximately 2 in., whereas those at the centre are about 1 in. However, the corresponding differences between maximum and minimum levels in the four roofs changed to a much greater extent; they were, for example, on the average 0.34 in 1956 and 0.84 in 1963. This appreciable increase may have been caused by the snow loading in the Winter 1962/63, which was certainly not uniformly distributed over the roofs. At the beginning of the snow loading in December 1962 the average differences between maximum and minimum deflections of the four roofs were less pronounced and amounted for point *A* to 0.48 in., as can be seen from Table 1, while they became immediately larger in the subsequent investigations in March, April and May. Another point may be mentioned, i.e. a difference in the sequence of taking the levels for the individual roofs. In the first years the levels of each roof were taken separately and thus the difference in temperature during this operation was relatively small. Later the levels were taken by other assistants carrying along each platform covering two roofs before levelling the other side along the other platform, with the consequence that a longer time was required for taking the levels of each roof (although the overall time was reduced). Hence subsequently in many cases

Table 1. Maximum and Minimum Deflections of Points A and B in the 4 Roofs at Different Time (in inches)

points		*A*					*B*				
roof		1	2	3	4	all	1	2	3	4	all
1st May 1956	max.	1.02	0.78	1.14	1.08	1.14	0.84	0.78	1.02	0.90	1.02
	min.	0.66	0.78	0.60	0.60	0.60	0.48	0.48	0.48	0.66	0.48
	diff.	0.36	0	0.54	0.48	0.54	0.36	0.30	0.54	0.24	0.54
Dec. 1962	max.	0.54	0.42	0.54	0.78	0.78	0.84	0.42	0.72	0.66	0.84
	min.	0.18	0	0	0.18	0	0.12	-0.24*	0.48	0.36	-0.24*
	diff.	0.36	0.42	0.54	0.60	0.78	0.72	0.66	0.24	0.30	1.08
March 1963	max.	1.14	0.84	0.90	0.66	1.14	1.02	1.02	0.96	0.96	1.02
	min.	0	0.12	0.12	0.30	0	0.18	0.06	0.30	0.60	0.06
	diff.	1.14	0.72	0.78	0.36	1.14	0.84	0.96	0.66	0.36	0.96
April 1963 morning	max.	0.54	0.42	0.54	0.30	0.54	0.96	0.54	0.66	0.66	0.96
	min.	-0.12	-0.12*	0	0.06	-0.12	0.12	-0.06	0.12	0.36	-0.06
	diff.	0.66	0.54	0.54	0.24	0.66	0.84	0.60	0.54	0.30	1.02
April 1963 afternoon	max.	1.20	0.78	0.54	0.72	1.20	1.20	0.90	0.96	0.72	1.20
	min.	0.24	0.06	0.06	0.12	0.06	0.30	0.30	0.54	0.48	0.30
	diff.	0.96	0.72	0.48	0.60	1.14	0.90	0.60	0.42	0.24	0.90
9th May 1963	max.	1.80	1.50	1.50	1.20	1.80	1.56	1.26	1.20	1.20	1.56
	min.	0.84	0.60	0.54	0.66	0.54	0.84	0.72	0.78	0.60	0.60
	diff.	0.96	0.90	0.96	0.54	1.26	0.72	0.54	0.54	0.60	0.96

* The deflections are shown negative in Fig. 5 (downwards), but in this Table as positive, while the upward deflections, which are positive in Fig. 5 are in this Table indicated negative and, where the difference between maximum and minimum deflections are computed, added to the maximum.

In the columns, headed "all" the maximum and minimum deflections of all 4 roofs are given.

The temperatures at the individual investigations are seen in Fig. 5, except for April 1963, when different values for morning (47/50 deg. F.) and for afternoon (51/56 deg. F.) apply.

a greater change in temperature may have occurred for each roof than previously. Bearing all this in mind the behaviour of the roofs seem to be quite satisfactory, but unfortunately it is impossible because of the complexity of the conditions to draw definite conclusions regarding the effect of the stress history, delayed shrinkage and creep.

The author would like to thank the Chief Civil Engineer of British Railways, Eastern Region, for permission to publish this investigation and would like to acknowledge the work of the New Works Department in carrying out the measurements.

Summary

Due to unfavourable weather conditions, the concrete strength of 4 prestressed cantilever platform roofs (each 130 ft. by 36 ft., supported by 2×2 columns), built in 1954/55, was relatively low, with the consequence that relatively large deformations occurred at and after prestressing. At certain intervals between Nov. 1955 and Nov. 1960 the levels were measured at 4 points each at both ends and at the centre of each roof, and the variations were plotted in relation to the zero points of November 1955. These measurements were augmented by further levels, taken between December 1960 and May 1963. From the deflection diagrams and the Table, shown in the paper, it is seen that considerable variation in deformation occurred during each year, mainly dependent on the temperature, but that otherwise the behaviour of the roofs seems to be satisfactory in spite of the difficulties which occurred at construction.

Résumé

Par suite de conditions météorologiques défavorables, la résistance du béton précontraint dans 4 marquises construites en 1954/55 (mesurant chacune 40×11 m et supportée par 2×2 colonnes) était relativement faible. En conséquence, il se produisit des déformations relativement importantes pendant et après la précontrainte. A certains intervalles, entre novembre 1955 et novembre 1960, les niveaux de quatre points étaient mesurés aux deux extrémités et au centre de chaque marquise, et les variations étaient tracées par rapport aux points zéro de novembre 1955. On a fait des mesures complémentaires entre décembre 1960 et mai 1963. A partir des diagrammes de flèches et de la table, reproduits dans ce travail, on peut se rendre compte que des variations appréciables des déformations se produisirent chaque année, surtout à cause des variations de température. Toutefois, de tous les autres points de vue, le comportement des marquises semble être satisfaisant malgré les difficultés rencontrées pendant la construction.

Zusammenfassung

Infolge ungünstigen Wetters war die Betonfestigkeit von 4 in den Jahren 1954/55 erbauten vorgespannten Bahnsteigkragdächern (jedes 40×11 m mit 2×2 Stützen) ziemlich niedrig und daher ergaben sich sehr große Verformungen bei und nach der Vorspannung. Zwischen November 1955 und November 1960 wurden in gewissen Abständen Niveaumessungen an je 4 Punkten an beiden Enden und in der Mitte an jedem der 4 Dächer vorgenommen und von den Nullpunkten entsprechend der Verformung im November 1955 aufgetragen.

Weitere Messungen wurden vom Dezember 1960 bis Mai 1963 vorgenommen. Die Durchbiegungsdiagramme und die Tafel, die im Artikel enthalten sind, zeigen, daß beträchtliche Verformungen innerhalb jedes Jahres entstanden, die in erster Linie von der Temperatur abhängen; aber andrerseits scheint das Verhalten der Dächer trotz der Schwierigkeiten, die sich bei der Ausführung ergaben, zufriedenstellend zu sein.

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