Load Transfer Characteristics of a Dowelled Joint Subjected to Aircraft Wheel Loads

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Interim results of a study being conducted on the load transfer characteristics of dowels used in airfield pavement expansion joints are presented. The slab consists of two 10-in. thick, 15-ft wide, and 25-ft long sections joined by a ¾-in. expansion joint across which 1⅛-in. diameter dowels are placed on 12-in. centers. Each dowel is instrumented with strain gages to measure bending moment along the dowel and shear transmitted across the joint. Moment, shear, and pressure curves are presented for all dowels in the joint for a wheel load of 50,000 lb applied at the center of the slab tangent to one face of the joint. Slab deflections are measured with mechanical dial indicators and complete transverse and longitudinal contours are presented. Results of the application of test results to current design equations are presented.

● SEVERAL DEVICES have been proposed for use in transferring wheel loads across expansion joints in concrete pavement during the past few years. Although some of these may be acceptable, there has been no completely satisfactory method of judging their efficiency or relative merits. Although the round solid steel dowel has for years been the standard load transfer device in Navy pavement construction, there is no presumption against devices of other design provided it can be shown that their use will not impair the integrity of the pavement over its expected life. Tests have been devised in which load transfer devices have been evaluated but they are not considered satisfactory because no provisions have been included for consideration of various slab thicknesses, device spacings, or moduli of subgrade reaction. Work was initiated on the development of a realistic evaluation procedure to provide a measure of the degree to which a proposed device satisfies the Navy's requirements. To insure, however, that the performance of a device in a test simulates its performance under actual loading in a pavement, it was necessary first to determine precisely the mechanics of load transfer. A review of the literature indicated that the interrelationships among deflection, moment, and shear during load transfer were not clearly established. In other words, it was not possible to state conclusively that load was transferred by moment, by shear, or by a combination of both. To obtain this basic information, it was decided to construct a full-size concrete slab with instrumented dowels across an expansion joint and impose upon the slab loads of the magnitude of those resulting from the use of modern aircraft. From the resulting data, it was thought possible to determine the load transfer characteristics of a dowelled joint which would form the basis for examination of load transfer devices in a realistic laboratory procedure.

The physical properties of the concrete slab, the instrumentation used, and the nature of the load application device were described at the 35th Annual Meeting of the Highway Research Board and will not be repeated here. This paper is an interim report describing the results of load tests on the slab and applying

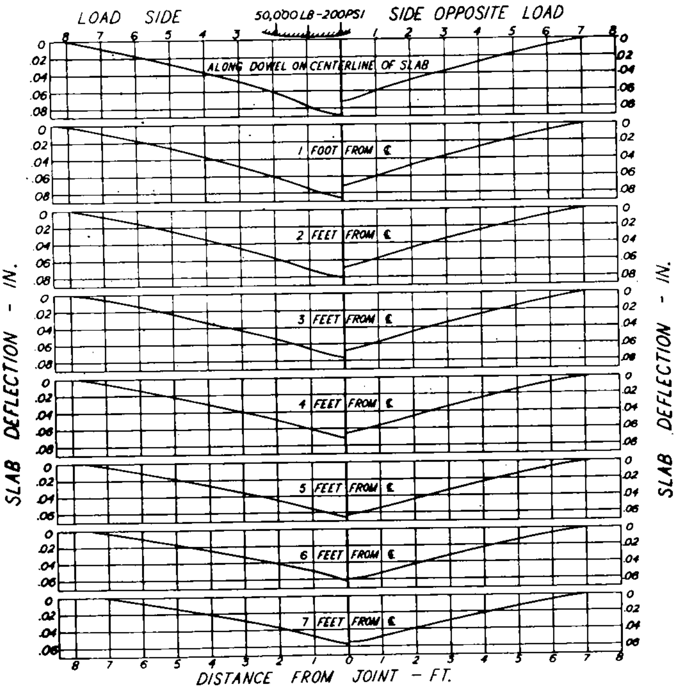

Figure 1. Slab deflection along centerline of dowels; 50,000-lb load applied tangent to joint at center of slab.

TABLE 1
SLAB DEFLECTIONS

Distance from Centerline, ft	Load Side Maximum Deflection, in.	Side Opposite Load Maximum Deflection, in.	Diff. Defl. Across Joint, in.
0	0.089	0.073	0.016
1	0.087	0.072	0.015
2	0.082	0.070	0.012
3	0.077	0.068	0.009
4	0.072	0.066	0.006
5	0.067	0.064	0.003
6	0.062	0.061	0.001
7	0.058	0.057	0.001

these results to some of the design equations currently in use.

Unless otherwise stated, results presented in this paper were obtained from tests conducted with a 50,000-lb, 200-psi single-wheel load applied on the centerline of the slab over the capped end of the center dowel with the tireprint tangent to one face of the expansion joint. Slab deflections along the centerlines of dowels on one side of the slab are shown in Figure 1. A summary of maxima of these results is given in Table 1. The maximum slab deflection is 0.089 in., and the maximum differential deflection across the joint is 0.016 in. Figures 2 and 3 show slab deflections on the load side and side opposite the load, respectively, transverse to the centerline of the slab. Slab deflection contours are shown in Figure 4. Tests have indicated the presence of an air void at the center of the slab at the joint amounting to about 0.04 in. Since the actual extent of slab-subgrade separation has not been determined, it is impossible to calculate subgrade pressures at this time.

Although one end of each dowel is greased, a certain amount of bond to the concrete could possibly exist. If the magnitude of the bond on these capped ends is great enough, the longitudinal (axial) strain in a loaded dowel would influence the strain readings on the moment gages

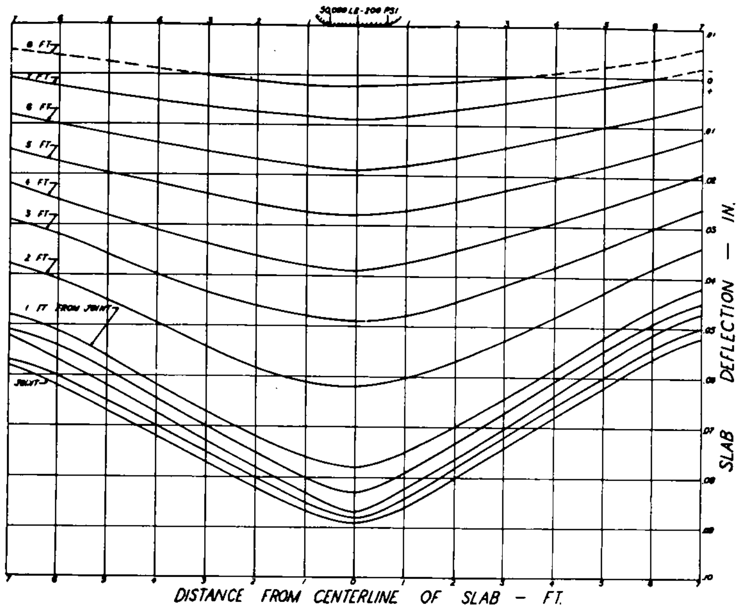

Figure 2. Transverse slab deflection, load side; 50,000-lb load applied tangent to joint at center of slab.

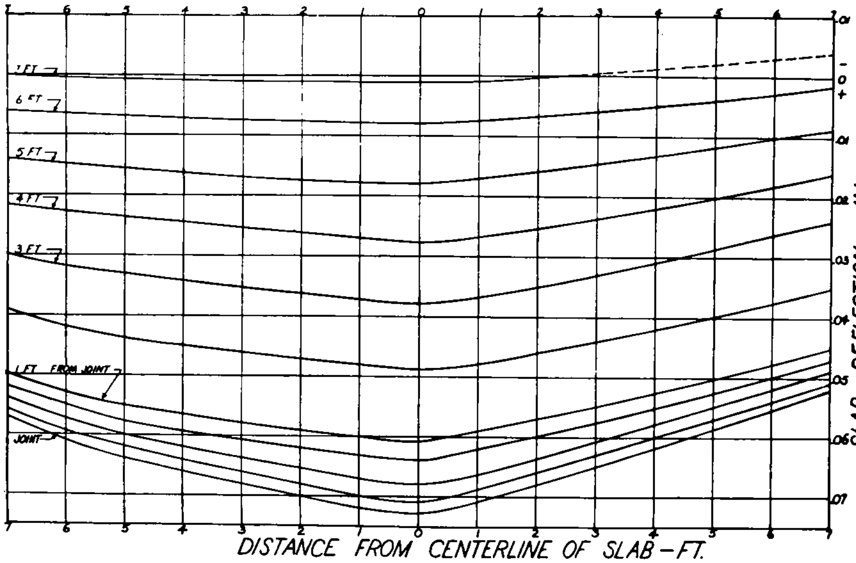

Figure 3. Transverse slab deflection, side opposite load; 50,000-lb load applied tangent to joint at center of slab.

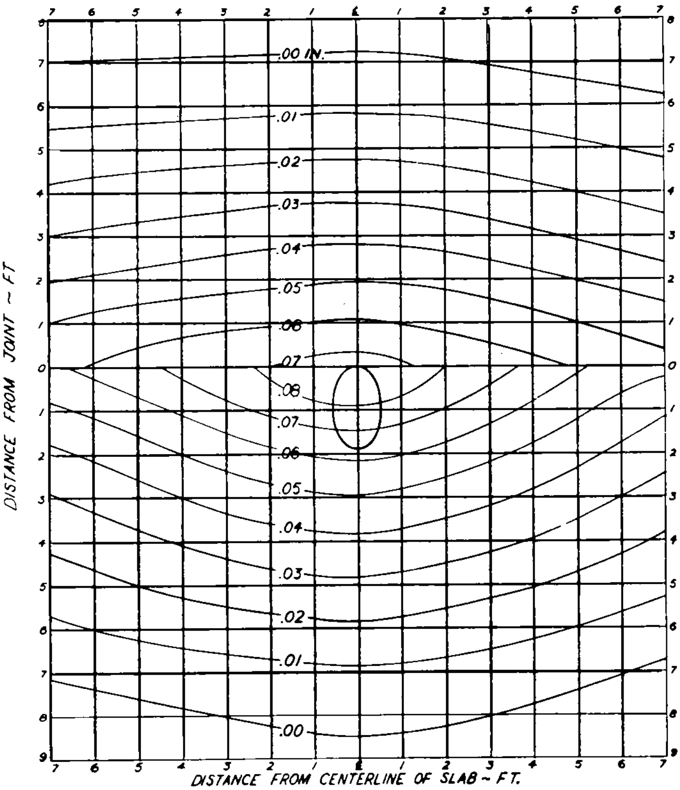

Figure 4. Slab deflection contours; 50,000-lb load applied tangent to joint at centerline of slab.

and would be considered bending strains. Tests have been made to determine the bonding condition on the capped ends of the dowels. Loads up to 4000 lb were applied directly to a dowel in the center of the joint. Separate strain measurements were made on two gages spaced symmetrically with respect to the center of the joint. With increasing loads, the strain on the gage on the bonded (uncapped) end of the dowel reversed direction, but the strain on the gage on the capped end continued in the same direction but in decreasing amounts. The strain reversal on the bonded end suggests that the support condition on the capped end has changed with increasing load. As the load is first applied, the dowel acts as a cantilever beam supported at the end, because the tight-fitting metal cap is firmly bonded to the concrete. As the applied load increases, the deflection of the dowel increases and more support is gained on the capped end. The changing support condition on the capped end eventually causes the strain reversal on the bonded end of the dowel. Similar results were obtained on two different dowels. The results indicate that the capped ends of the dowels are not bonded to the concrete along the length of effective embedment; hence no measurable axial strain is present.

Moment, shear, and pressure curves for four of the dowels are shown in Figures 5 through 8. Some of the essential values are summarized in Tables 2 and 3. Moment curves drawn through the test data were not consistent with the generally accepted assumption of contraflexure at the center of the joint. To establish the position of the point of contraflexure, two strain gages were placed on the upper surface of the dowels in the

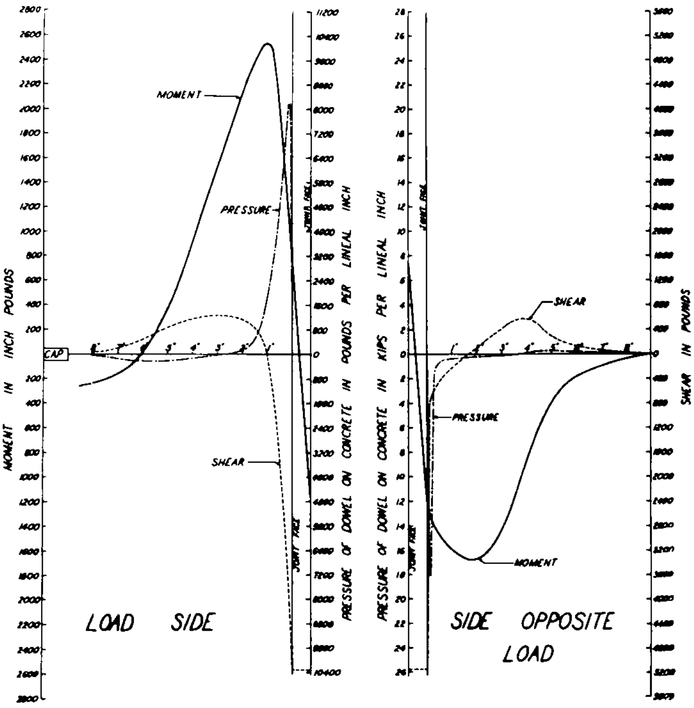

Figure 5. Moment, shear, and pressure curves for dowel on slab centerline.

joint (as close as possible to the joint faces), and the load was applied as before. Test results from these gages indicate that with the wheel load applied, the position of the point of contraflexure on a given dowel depends upon the location of the dowel with respect to the centerline of the slab. It appears that contraflexure occurs in the joint only on dowels that are less than 3 ft from the centerline. The contraflexure on the capped ends of the dowels (Figures 5 through 8) is believed to be caused by the support condition at the caps. Because these ends are unbonded along the length of effective embedment, there is a concentration of moment at the cap; and, because the tight-fitting cap is bonded, the dowel resists downward bending at the cap. All shear measurements on the dowels at the joint face are reported in Table 4. Shear values corresponding to the stated test results are presented under the heading "Load Over Capped End." To determine the effect of the position of the capped ends of the dowels in relation to the load, the load was applied over the same dowel (center dowel) but on the opposite side of the joint, thus placing the load over the bonded end of the center dowel. The joint-face shears resulting from these tests are also presented in Table 4. The total percent of load applied is almost the same for the two loading conditions, but the individual dowel shears are very different. When the load is placed over the capped end of the dowel, the maximum shear is in the center dowel; whereas, when the load is placed over the bonded end, the maximum shear is 1 ft from the center dowel. The maximum shear in the latter case occurs in a dowel with a capped end on the load side. This seems to indicate that the maximum shear will occur in a dowel with a capped end on the load side regardless of the transverse position of the load. The uncertain support condition on the capped end of the dowel causes a shear concentration at the face of the joint. Under both loading conditions, the five dowels in the center of the slab

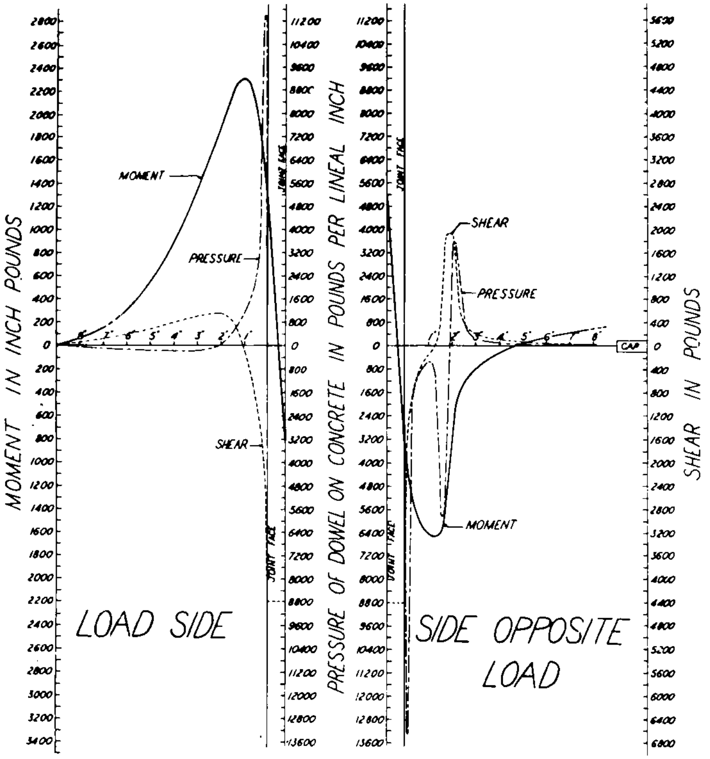

Figure 6. Moment, shear, and pressure curves for dowel 1 ft from slab centerline.

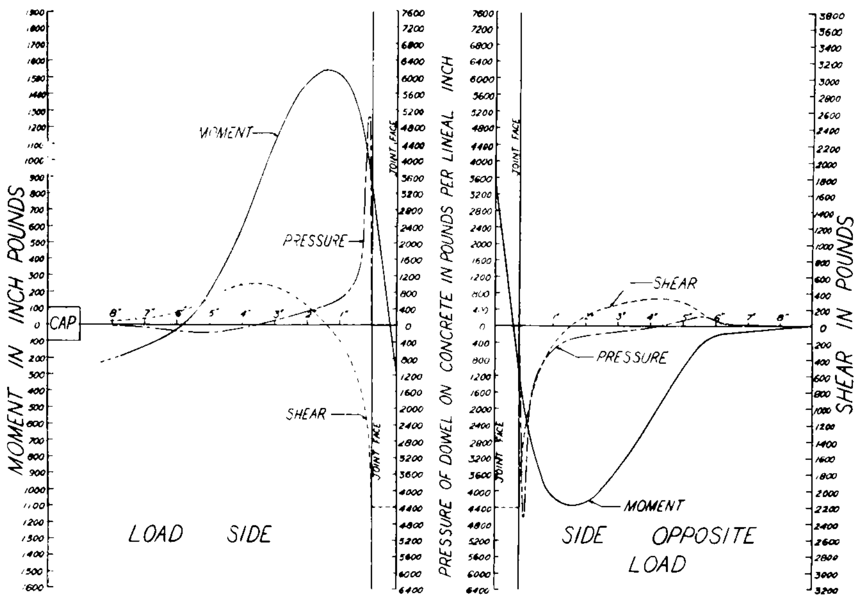

Figure 7. Moment, shear, and pressure curves for dowel 2 ft from slab centerline.

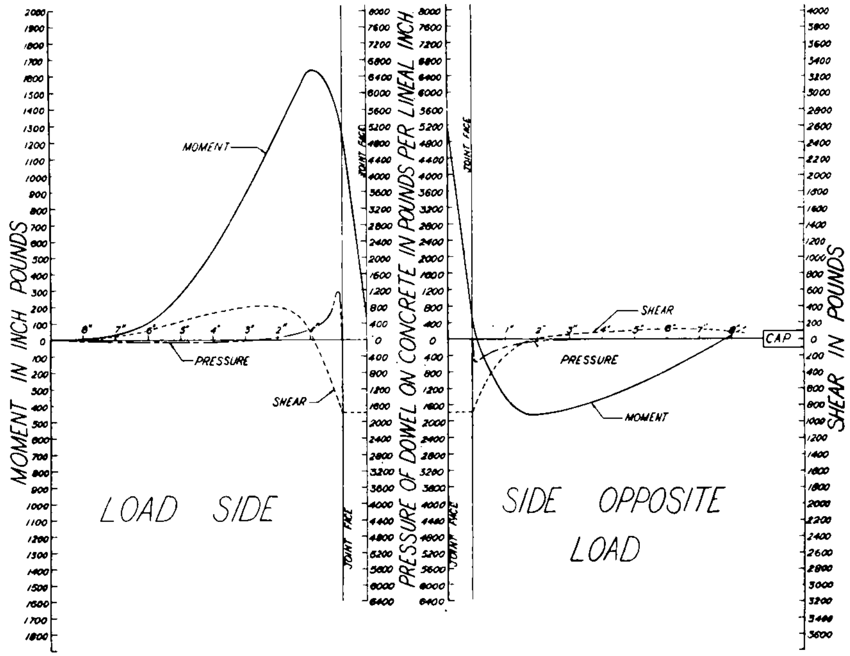

Figure 8. Moment, shear, and pressure curves for dowel 3 ft from slab centerline.

TABLE 2
MOMENTS, SHEARS, AND PRESSURES FOR LOAD SIDE

Dowel Position from Centerline, ft	Moment at Joint Faces, in. lb	Highest Moment		Shear at Joint Face, lb	Highest Pressure, kip/in.	Distance from Joint Face to Zero Pressure, in.
		Amount, in. lb	Distance From Joint Face, in.			
0	750	2550	1.00	5150	8.20	2.85
1	1320	2300	1.05	4390	11.40	2.10
2	860	1540	1.35	2200	5.04	3.55
3	1280	1640	0.87	890	1.16	2.35
4	750	1135	1.25	600	0.72	2.65

carried about 77 percent of the transferred load.

Inasmuch as the maximum slab deflection must occur under the dowel over which the load is placed, the higher shears in the other dowels can be rationalized only by uncertain support conditions on the capped ends of the dowels and by the non-uniformity of the subgrade, although the slab deflection measurement did not reflect any major nonuniformities.

After the loading, the slab was subjected to loads of 10,000 to 100,000 lb with the tire pressure maintained at 200 psi. In each case the load was applied over the capped end of the center dowel with the tireprint tangent to one face of the joint. The joint-face shears and slab deflections are presented in Table 5. Be-

TABLE 3
MOMENTS, SHEARS, AND PRESSURES FOR SIDE OPPOSITE LOAD

Dowel Position from Centerline, ft	Moment at Joint Face, in. lb	Highest Moment		Shear at Joint Face, lb	Highest Pressure, kip/in.	Distance from Joint Face to Zero Pressure, in.
		Amount, in. lb	Distance From Joint Face, in.			
0	-1190	-1680	1.70	5150	18.10	3.85
1	- 810	-1630	1.30	4390	13.32	1.90
2	- 280	-1085	1.55	2200	4.64	4.25
3	130	- 460	1.85	890	5.40	6.35
4	320	- 530	3.35	600	0.30	4.95

TABLE 4
RESULTS OF JOINT-FACE SHEAR MEASUREMENTS

Dowel Position from Centerline, ft	Load over Capped End of Center Dowel			Load over Bonded End of Center Dowel		
	Shear, lb	% of Applied Load	% of Transferred Load	Shear, lb	% of Applied Load	% of Transferred Load
0	5150	10.3	22.0	2360	4.7	9.3
1	4390	8.8	18.8	4120	8.2	16.2
1	2660	5.3	11.4	10700	21.4	42.0
2	2800	5.6	12.0	2400	4.8	9.4
2	2100	4.2	9.0	1300	2.6	5.1
3	890	1.8	3.8	1540	3.1	6.1
3	1120	2.2	4.8	770	1.5	3.0
4	460	0.9	2.0	610	1.2	2.4
4	750	1.5	3.2	220	0.4	0.9
5	1050	2.1	4.5	70	0.1	0.3
5	900	1.8	3.8	60	0.1	0.2
6	100	0.2	0.4	350	0.7	1.4
6	420	0.8	1.8	600	1.2	2.4
7	390	0.8	1.7	110	0.2	0.4
7	180	0.4	0.8	240	0.5	0.9
Totals	23,360	46.7	100.0	25,450	50.7	100.0

cause the five center dowels are most effective in transferring load, only data on these dowels are reported. Only the deflections at the load side joint face over the center dowel are shown in Table 5.

The percentage of the load transferred through the center dowel is substantially constant, varying from 7.1 to 11.0 percent. Similarly the total percentage of load transferred through the five center dowels is seen to vary from 32.5 to 38.0 percent of the applied load.

No failures were apparent in either concrete or dowels as a result of these loadings. To insure that this was the case, repetitive loadings of 50,000 lb were applied to the slab. Approximately 200 load repetitions indicated that the shears in the joint on the center dowel were essentially the same as those measured at the same load prior to application of the 100,000-lb load. No conclusions are inferred concerning the performance of this slab under repetitive loads, because the only purpose of these tests was to determine whether or not a load twice the design load had caused structural failure.

Because this is a study of the load transfer characteristics of a dowelled joint consisting of 15 dowels, and not a study of the individual performance of any one of them, it is not surprising to find that the experimental data obtained in this investigation do not give reasonable results when used in theoretical de-

TABLE 5

JOINT-FACE SHEARS AND SLAB DEFLECTIONS FOR VARIOUS LOADS

Applied Wheel Load,* lb	Shear Under Load, lb	% of Applied Load	1 ft from centerline Shear, lb		% of Applied Load		2 ft from centerline Shear, lb		% of Applied Load		Load-Side Slab Deflection at Joint on centerline, in.	Total % of Applied Load for 5 center Dowels
			A**	B	A	B	C	D	C	D		
10,000	710	7.1	850	630	8.5	6.3	710	480	7.1	4.8	—	33.8
20,000	1760	8.8	1560	1100	7.8	5.5	1270	820	6.4	4.1	—	32.6
30,000	3120	10.4	2600	1440	8.7	4.8	1880	1170	6.3	3.9	—	34.1
40,000	4150	10.1	3230	2100	8.1	5.2	2200	1400	5.6	3.5	—	32.5
50,000	5150	10.3	4390	2660	8.8	5.3	2800	2100	5.6	4.2	0.089	34.2
55,000	5660	10.3	5280	3820	9.6	6.9	1920	1810	3.5	3.3	0.095	33.6
60,000	6340	10.6	6060	4260	10.1	7.1	2520	2360	4.2	3.9	0.099	35.9
65,000	6850	10.6	6190	4640	9.5	7.1	2610	2590	4.0	4.0	0.105	35.2
70,000	7230	10.4	6700	4750	9.6	6.8	2940	2610	4.2	3.7	0.111	34.7
75,000	8290	11.0	7600	5590	10.2	7.4	3620	3470	4.8	4.6	0.116	38.0
80,000	8510	10.6	7670	5680	9.6	7.1	3450	3200	4.3	4.0	0.125	35.6
85,000	8950	10.6	7910	5990	9.3	7.0	3510	3270	4.1	3.8	0.130	34.8
90,000	9750	10.8	8770	6520	9.8	7.2	3870	3560	4.3	4.0	0.137	36.1
100,000	9940	9.9	8970	6740	9.0	6.7	3910	3780	3.9	3.8	0.140	33.3

* Tire Pressure = 200 psi.
** (A), (B), (C), and (D) refer to dowels spaced symmetrically on opposite sides of slab centerline.

sign equations for dowelled joints. The presence of the air gap between slab and subgrade in the vicinity of the joint obviously contributes to the non-uniformity of the subgrade support. Theoretical design equations, for mathematical expediency, are based on assumptions such as uniform subgrade support, elasticity in all parts of the structure, proportionality between pressure of concrete on dowel and dowel deflection, and unbonded dowels. Inasmuch as these conditions apparently do not prevail in an actual field installation, experimental data can hardly be expected to satisfy the theoretical equations. If the same relationships among shear, load transfer, influence of the dowel cap, slab deflection, and non-uniformity of subgrade support can be shown to exist in other full-size joint installations, some modification or further study of the design criteria for joints may be indicated.

ACKNOWLEDGMENT

The authors gratefully acknowledge the painstaking and skillful work of the technicians of the Soils and Pavement Division, without whose efforts no undertaking of this magnitude could be accomplished. Special thanks is given to J. R. Mooney, Jr., whose mechanical ingenuity enabled the successful completion of the test program.

DISCUSSION

BENGT F. FRIBERG, *Consulting Engineer, St. Louis, Missouri.* — This paper deserves close study as the first published observations of dowel load transfer across a full-scale concrete pavement slab joint, with the dowels instrumented to observe their behavior. The researchers deserve credit for their painstaking experimental work. Many items of the test, in addition to those included in the paper, and covered by this discussion, would deserve study.

Generally accepted principles and formula (*1*) for analysis of doweled joints are as follows:

1. Individual dowels are assumed to act in accordance with principles of continuous elastic support, governed by a modulus of support G, in the surrounding concrete, assuming dowels of unlimited embedment.
2. A point of contraflexure is assumed to exist in the dowel at the center of the joint opening.
3. For dowels away from the wheel load center line the effective load transfer is assumed to decrease linearly to zero at a distance of $1.8l$, where l is the radius of relative stiffness of the pavement.

The purpose of dowel analysis is threefold:

(a) To determine the differential deflections between the two joint edges incident to dowel load transfer across the joint, and the total amount of load transferred by any dowel system from a slab across the joint, to the adjacent slab, with a wheel load at the joint corner or joint edge on different subgrades;

(b) To determine the maximum bending stress in the dowel, so as to avoid dowel yielding, for the most stressed dowel; and

(c) To determine the maximum bearing stress between the dowel and the concrete, at the face of the joint, so as to avoid crushing (funneling) of the concrete around the dowel, for the most heavily loaded dowel.

As long as differential deflection, total load transfer across the joint, and the maximum stresses for the single dowel under the load are obtained with fair accuracy, computational variations such as the effect of caps, are unimportant. The test shows points of contraflexure near center of joint opening in the dowels with maximum load; it is immaterial where they occur in dowels further away.

The tests permit experimental evaluation of all the design assumptions, except unlimited embedment. However, comparative computations, even for embedments much shorter than the experimentally used 9 in., show insignificant differences from moments computed for unlimited embedment. The general formulas (*1*) are submitted to comprehensive comparison with these tests.

Experimental Variations

Independent analysis of the tests would have been facilitated if experimental values of shear strains and moments had been given, because some experimental variables are subject to multiple derivation.

Dowel shears were observed by means of 45-deg strain gages at center of joint opening; other gages were presumably placed on top surface of dowels in the ¾-in. joint opening as close as possible to the joint faces, but no quantitative data are given for them. Gages on the dowels inside the concrete were 0.75, 1.50, 2.25 in., and further from the face. The moment curves (Figures 5 to 8) apparently refer to strain gages on the dowels inside the concrete, but the shears (Figures 5 to 8) refer to the shear gage values. The change in moment across the joint opening should equal "shear times joint width"; however, these experimental values do not agree well. Table 6 shows shears, as derived from moment change across the joint, according to moment curves, and as given in Table 4 of joint shear measurements.

The differences between shear values

TABLE 6

Dowel Position from Centerline, ft	Moment Change,[1] in.-lb	Shear,[2] lb	Shear Values,[3] lb		Load on Other Side		Av. Meas. Shear, lb
			Right	Left	Right	Left	
0	1,940	2,600	5,150	—	2,360	—	3,760
1	2,130	2,800	4,390	2,660	4,120	10,700[4]	3,460
2	1,140	1,500	2,800	2,100	2,400	1,300	2,150
3	1,410	1,900	890	1,120	1,540	770	1,130
4	1,070	1,400	460	750	610	220	510

[1] Tables 2 and 3.
[2] From moment curve.
[3] Table 4.
[4] Lacking further experimental correlation this value is discarded and 2,660 lb substituted.

derived from moments and those measured are too great for reliable plotting of shears and pressures along the dowel embedment. It is possible that the shear measurements are subject to quantitative influences for which adjustment has not been made.

The subgrade data and slab deflections do not permit an estimate of load distribution on the two slabs. In Figure 9, de-

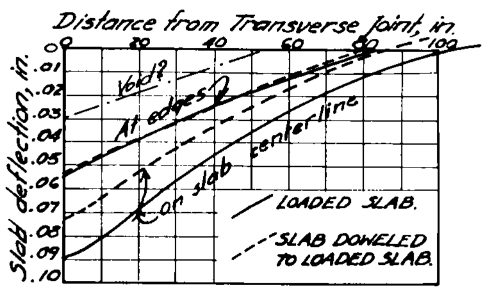

Figure 9. Observed deflection profiles on both sides of the joint for estimation of subgrade reaction volumes and their distribution under the two slabs for 50,000-lb wheel. Possible void under each slab is indicated.

flection profiles perpendicular to the joint for 50,000-lb load are shown for both slabs, with profiles taken on slab center line and at both edges. The total deflection volume approximates 950 cu in. for the 50,000-lb wheel load, rather than 250 cu in. which would correspond to a subgrade k-value of 200 psi per in. A clue to the experimental deviation is given by deflection values in Table 5, but these have not been shown for loads under 50,000 lb; extrapolation to 0 load indicates a possible void of 0.03 in. under the unloaded slab at the joint. The existence of voids of that magnitude could be possible for unwarped slab conditions, or considering the unusually high test wheel loads for a 10-in. slab; such voids might be roughly triangular with contact some 4 to 5 ft back from the joint for the 12.5-ft long slabs, except for maximum day warping.

The more probable net reactive deflection volumes would then be 350 cu in. under the loaded slab and 250 cu in. under the doweled slab, corresponding to an average subgrade k between 80 and 90, and about 40 percent of the wheel load transferred from the loaded slab by dowel load transfer, or about 20,000 lb for all dowels. This value compares with 20,600 lb average measured total dowel shear for the two positions of loading.

Shear Distribution on Dowels away from Wheel Track

In Figure 10, average observed dowel shear, from Table 4, and differential deflection across the joint, from Figures 2 and 3, are shown for all dowels from center line to 7 ft away. Dowel shears derived from the moment diagrams, Figure 12, have also been indicated. Lines have been drawn in the graph, corresponding to linear decrease in effective dowel shear to zero at $1.8l$ for $E = 4{,}000{,}000$ psi and k-values of 100, and 200 psi per in. Dowel deflections and effective shears derived from moments are in good agreement with the line for 100 k-value, measured dowel shears are in better agreement with the line for 200 k-value.

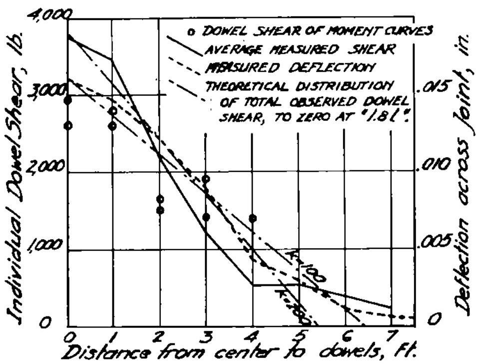

Figure 10. Distribution of dowel shears, both measured and as computed from moment curves, and differential deflections across the 3/4-in. joint, for dowels spaced 12 in. and up to 7 ft from the 50,000-lb wheel load. Assumed decrease in effective dowel shear is indicated for subgrade k of 100 and 200 psi per in.

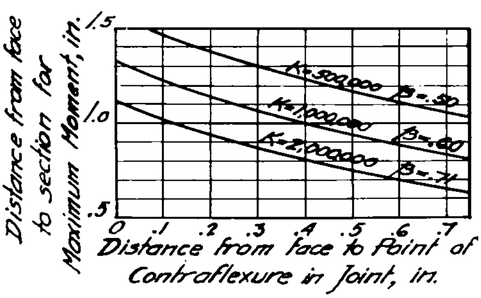

Figure 11. Theoretical relation between location of contraflexure in the 3/4-in. joint and distance to section of maximum moment in 1 1/8-in. dowels, for modulus of dowel support from 500,000 to 2,000,000 psi per in.

Dowel Design and Elastic Support Assumptions

If design procedures for elastic support conditions permit determination of location and magnitude of maximum moment in the dowel, and the deflection at the face of the joint, and across the joint, with fair accuracy, then these design procedures are usable tools for dowel design, provided the modulus of support can be estimated close enough. Theoretical and experimental coincidence in non-essential details is not necessary.

The modulus of support K does not enter directly into the dowel design formulas, but determines the relative stiffness, β (*1*), as follows:

for $K = 500{,}000$ psi/in., $\beta = 0.50$
$K = 700{,}000$ psi/in., $\beta = 0.545$
$K = 1{,}000{,}000$ psi/in., $\beta = 0.60$
$K = 2{,}000{,}000$ psi/in., $\beta = 0.71$

Test observations can be applied to formulas (*1*) for different β-values; using the consonant β-value so determined, other principal data can be computed and compared with test observations. Good agreement justifies the use of the theory. In this discussion terms and symbols of Ref. (*1*) are used.

The excellent strain gage instrumentation on the dowels inside the concrete permits determination of sections of maximum moments with some accuracy. The location of these sections gives a basic quantity of dowel design formulas (*1*) for determination of the modulus of dowel support. It is assumed that the moment curves (Figures 5 to 8) are exact. However, it would not be correct to apply the observed moment curves directly to the theoretical comparison.

The observed moments in the dowels with the pavement loaded are due to, the dowel shear and tilt of both slabs toward the joint with corresponding angle change at the joint and positive "tilt moment" (without shear at the joint) in the dowel on both sides of the joint. The shear causes dowel moments positive on the loaded side, with tilt moments additive, and negative on the unloaded side, with tilt moments counteracting. This is clearly evident in the observed maximum moments, those on the loaded side (Tables 2 and 3) being from 455 to 1080 in. lb greater numerically for the five dowels listed.

Tilt Moments. The slab tilts toward the joint are visible in Figure 1, and, except for about 0.0005 radians directly under the wheel, fall in a narrow range of 0.0008 to 0.0009 radians on each side of the joint at the five dowels investigated. The total angle change is, for the center dowel, 0.0014, for other dowels about 0.0017 radians.

The angular change t on each side at the joint face, $x = 0$ is obtained from Eq. 3 (*1*) for $P = 0$, Moment M_t:

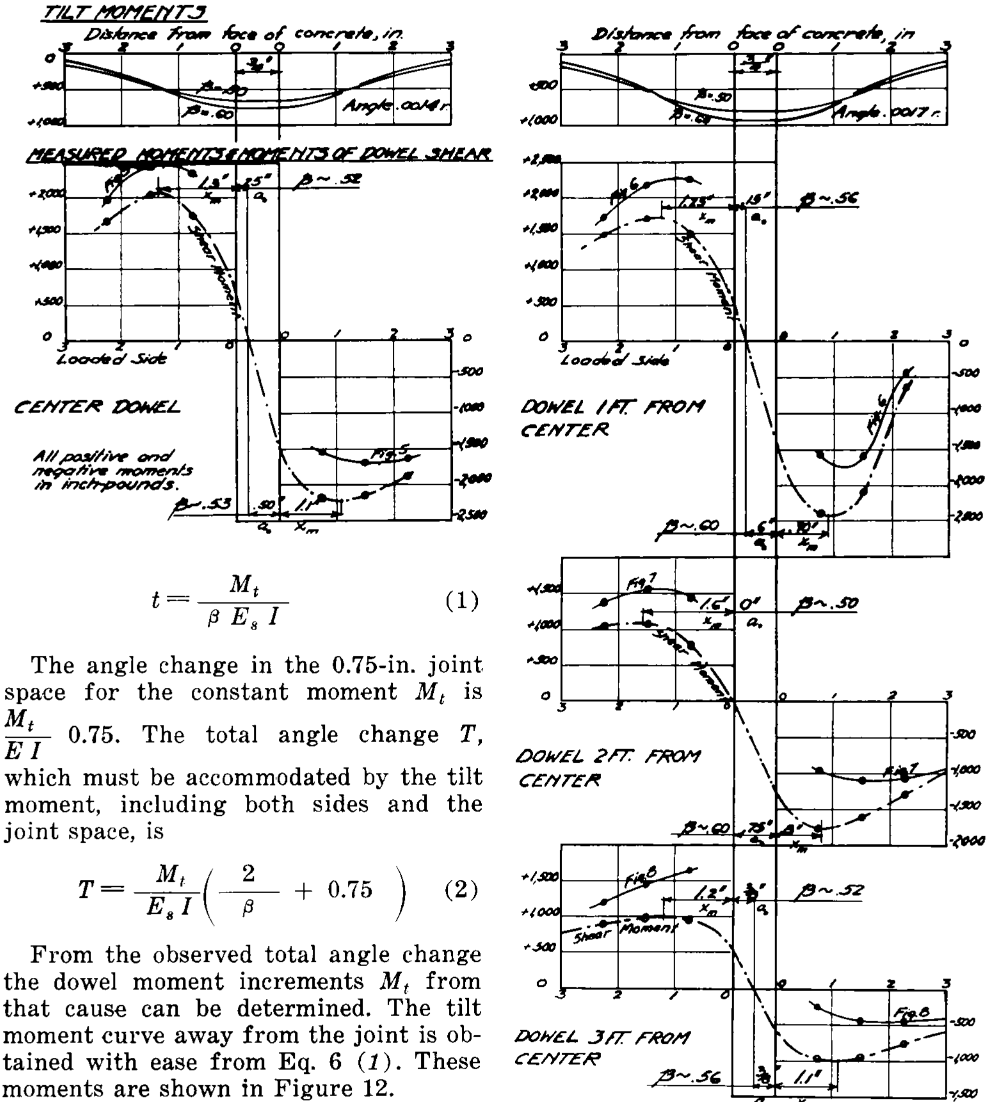

Figure 12. Analysis of moment observations in 1 1/8-in. dowels crossing the 3/4-in. joint between two 10-in. slabs for 50,000-lb aircraft wheel at the joint edge center, considering tilt moments and shear load moments in relation to dowel design theories, for derivation of design constant.

$$t = \frac{M_t}{\beta\, E_s\, I} \qquad (1)$$

The angle change in the 0.75-in. joint space for the constant moment M_t is $\frac{M_t}{E\,I}$ 0.75. The total angle change T, which must be accommodated by the tilt moment, including both sides and the joint space, is

$$T = \frac{M_t}{E_s\, I}\left(\frac{2}{\beta} + 0.75\right) \qquad (2)$$

From the observed total angle change the dowel moment increments M_t from that cause can be determined. The tilt moment curve away from the joint is obtained with ease from Eq. 6 (*1*). These moments are shown in Figure 12.

Moments due to Dowel Shear. To obtain moment curves for dowel shear from the observed moments, tilt moment curves can be applied to the observed moments as corrections, fitting the corrections for appropriate β-values, so that agreement is realized with the β-values deduced from the resulting dowel shear moment curves.

In analysis of the tests distances from the face of the concrete to section with maximum dowel moments, x_m in., are used for β-determination. The applicable formula is Eq. 12 (*1*); however, in the analysis contraflexure cannot be assumed at mid-joint, $a/2$. With observed distance a_0 from the face of concrete to point of contraflexure in the joint opening substituted, the location of maximum moment is determined by

$$\tan \beta\, x_m = \frac{1}{1 + 2\, \beta\, a_o} \qquad (3)$$

The distance x_m for a_o-values from 0 to 0.75 in. is shown in Figure 12, for applicable β-values.

In Figure 12, appropriate corrections for tilt moments, as shown, have been made in the observed moments for the dowels at center, and 1, 2, and 3 ft away, taken from Figures 5 to 8. Values for a_o and x_m are estimated as shown in the graphs, and corresponding β-values as shown are obtained from Figure 11.

With the test moment observations analyzed in this manner, it is seen that β-values obtained from the moment curves applicable to dowel shears are fairly uniform, with a range from 0.50 to 0.60, and individual estimates for:

Distance from Center Dowel ft.	Loaded Side	Doweled Side
0	Capped, 0.52	Bonded, 0.53
1	Bonded, 0.56	Capped, 0.60
2	Capped, 0.50	Bonded, 0.60
3	Bonded, 0.52	Capped, 0.56
Average	0.525	0.57

The average value for β is 0.55, corresponding to modulus of support over 700,000 psi per in. The lowest β-values are observed for the center dowel, and for the loaded side of the joint, which is most highly stressed by the positive combination of dowel shear and tilt moment.

The point of contraflexure moves across mid-joint, with and without tilt moment. Apparently no serious error results from assuming it at mid-joint.

Dowel Deflections

With reasonable β-values derived from one set of observed experimental data, the moments and dowel stresses, face deflections and concrete stresses, and differential deflections across the joint can be computed, and in turn compared with test observations, as further checks of the applicability of theories of elastic support for dowel design.

With reference to tilt moment, the maximum concrete stresses occur at the face of the joint, and, derived from Eq. 4 (*1*), are

Center dowel: $\beta = 0.525$, angle change 0.0014 radians, face deflection 0.00056, concrete stress 340 psi;

Other dowels: $\beta = 0.56$, angle change 0.0017 radians, face deflection 0.00063, concrete stress 480 psi.

These stresses, although small, are probably higher than expected for lower normal loads on 10-in. slabs, with correspondingly smaller slab tilts.

With reference to dowel shear, the stresses and deflections can all be computed from equations (*1*). In Figure 13, dowel moments, face deflection and concrete stresses for 1⅛-in. dowels are shown for β-values corresponding to modulus of support from 500,000, to 2,000,000 psi per in., and for contraflexure at the joint faces as well as at center of ¾-in. joints. Only the dowel moment is influenced drastically by variation in location of zero moment in the joint.

The deflection across the joint is also shown in Figure 13. It is insensitive to location of contraflexure, because the corresponding changes in deflections and dowel slopes for both joint faces are compensatory. Tilt moment causes no differential deflection or substantial change in dowel slope at mid-joint; the dowel shear, on the other hand, causes dowel slopes and face deflections several times greater than the slab tilt. Therefore, the differential deflection across the joint, according to theory, is relatively independent of slab tilt, as well as of location of zero moment in the joint. The deflection across the joint is then most suitable for experimental comparison, made in terms of shear, as follows:

The agreement is good between shears theoretically computed from observed cross joint deflections and shears deduced by other means for the two heavily loaded dowels which govern for the dowel design.

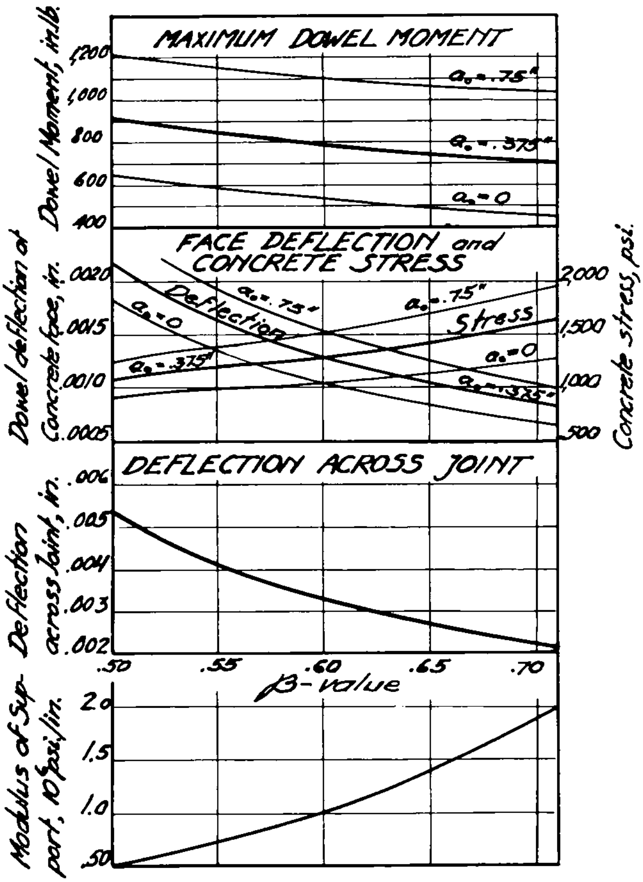

Figure 13. Computed values, per 1,000 lb of dowel shear, of maximum moment in 1 1/8-in. dowels, of face deflection and concrete bearing stress, and of deflection across 3/4-in. joint, for modulus of dowel support from 500,000 to 2,000,000 psi per in. Dowel moment, face deflection, and concrete stress are shown for point of contraflexure at mid-joint, and at the two joint faces.

TABLE 7

Dowel Distance from Center, ft	β	Shear from Deflections			Measured Shear Fig. 11 lb
		Observed Fig. 11 in.	Rate, Fig. 14 in./1000 lb	Computed Shear, Fig., 11 and 14 lb	
0	0.525	0.016	0.0047	3400	3800
1	0.58	0.0145	0.0036	4000	3500
2	0.55	0.012	0.0041	2900	2100
3	0.54	0.009	0.0043	2100	1200

Dowel and Concrete Stresses

The tests permit some deductions concerning stresses in and around the 1⅛-in. dowels under the 50,000-lb wheel load. The maximum stresses are on the loaded side of the joint as combination of stresses due to dowel shear and tilt. Table 8 shows computation for the highly stressed dowels. The measured maximum dowel moments are substantially lower than moments computed from joint deflections, especially for the dowel 1 ft from center, having strain gages on the bonded half; the computed moment for the capped end of the center dowel is within acceptable design variation. The computations show the degree to which tilt moments would influence the stresses in and around the dowels, which should be taken into account in design. Variations in location of the point of contraflexure for critical dowels is predominantly related to tilt moment magnitude.

REFERENCES

1. FRIBERG, BENGT F., "Design of Dowels in Transverse Joints of Concrete Pavements." *Trans. ASCE*, 105: 1076 (1940).
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J. R. KEETON and J. A. BISHOP, *Closure.* — As emphasized in the paper, the primary objective of the research is the development of a realistic evaluation procedure for load transfer devices. Because this investigation is a study of the structural action of an entire dowelled joint, no attempt was made to analyze the performance of any individual dowel. The data presented in the paper indicate the interrelationship of the dowels, which seems to emphasize that no joint should be designed solely on the basis of the theoretical performance of any one dowel in the joint. The action of each dowel is directly related to the performance of other dowels; therefore, it is not surprising that the moment change across the joint does not equal the product of shear and the joint width.

The substitution of 2,660-lb shear for the 10,700-lb shear in Table 6 makes possible the close correlation between theoretical load transfer and observed load transfer. The justification for substitution of one experimentally determined quantity for another to facilitate correlation of other empirical data with theoretical values seems questionable. The importance of the effects of expansion caps and of bonding on one end of the dowels depends on the application of the experimental data. It is believed that these and other hitherto unrevealed quantities must be considered in an analysis of joint load transfer device action. It is recognized that the introduction of these variables makes a mathematical analysis

TABLE 8

Item	Unit	Center Dowel	Dowel 1 ft away
Distance to face, a_0	in.	0.75	0.15
Dowel stiffness, β		0.52	0.58
Moment, Fig. 14, per 1000 lb shear	in.-lb	800	650
Shear computed from deflection	lb	3400	4000
Distance from face, x_m, Fig. 12	in.	1.3	1.25
Moment due to shear, at x_m, Fig. 13	in.-lb	2720	2600
Moment due to tilt, at x_m, Fig. 13	in.-lb	450	600
Computed total dowel moment	in.-lb	3170	3200
Computed dowel stress	psi	22,600	22,900
Measured dowel moment	in.-lb	2550	2300
Concrete stress, Fig. 14 per 1000 lb	psi	1100	1100
Concrete stress due to shear	psi	3750	4400
Concrete stress due to tilt	psi	340	480
Computed concrete stress	psi	4090	4880

extremely difficult, but slab and dowel design based on the assumptions necessary to facilitate a mathematical analysis may include a greater factor of safety than is actually necessary. If these peculiarities can be shown to be commonplace in connection with the performance of loaded concrete pavements, it may be necessary to base the design of joints on some considerations other than those presently used.

It is most probable that the void beneath the center of the slab at the joint is the result of slab warping during curing. The slab is inside a building and is therefore subject to minimum ambient temperature changes and is not exposed to the direct rays of the sun. The modulus of subgrade reaction was measured at the joint two days before the construction of the slab and was found to be about 200 psi per in. If the slab were in intimate contact with the subgrade, the measured slab deflections would indicate a maximum subgrade pressure of 17.8 psi based on $k = 200$. This pressure is not likely to cause subgrade failure to the extent of 0.03 in. The results of the loading tests represent averages of several series of tests made at different times of the year; a minimum of ten tests constituted a series. Over 400 load applications (50,000 lb) were made on the slab. From beginning to end, the test results did not reflect any drastic changes in the subgrade such as would be evident in event of a subgrade failure. The load application of 100,000 lb was made after the 50,000-lb load series were finished. It is probable that if subgrade failure occurred, it was during the application of the 100,000-lb load.

Moment in the dowels resulting from tilting of the loaded slab is an inherent part of the load-transferring action of a dowelled joint. Measured moment at a given point on a dowel represents the actual amount of moment existing at that point, and inasmuch as working stress is of prime importance, it does not seem necessary to try to separate the contributing factors and adjust measured values accordingly. As Mr. Friberg indicates, increased stresses caused by such factors as tilting of the slab at the joint should be considered in dowelled joint design.