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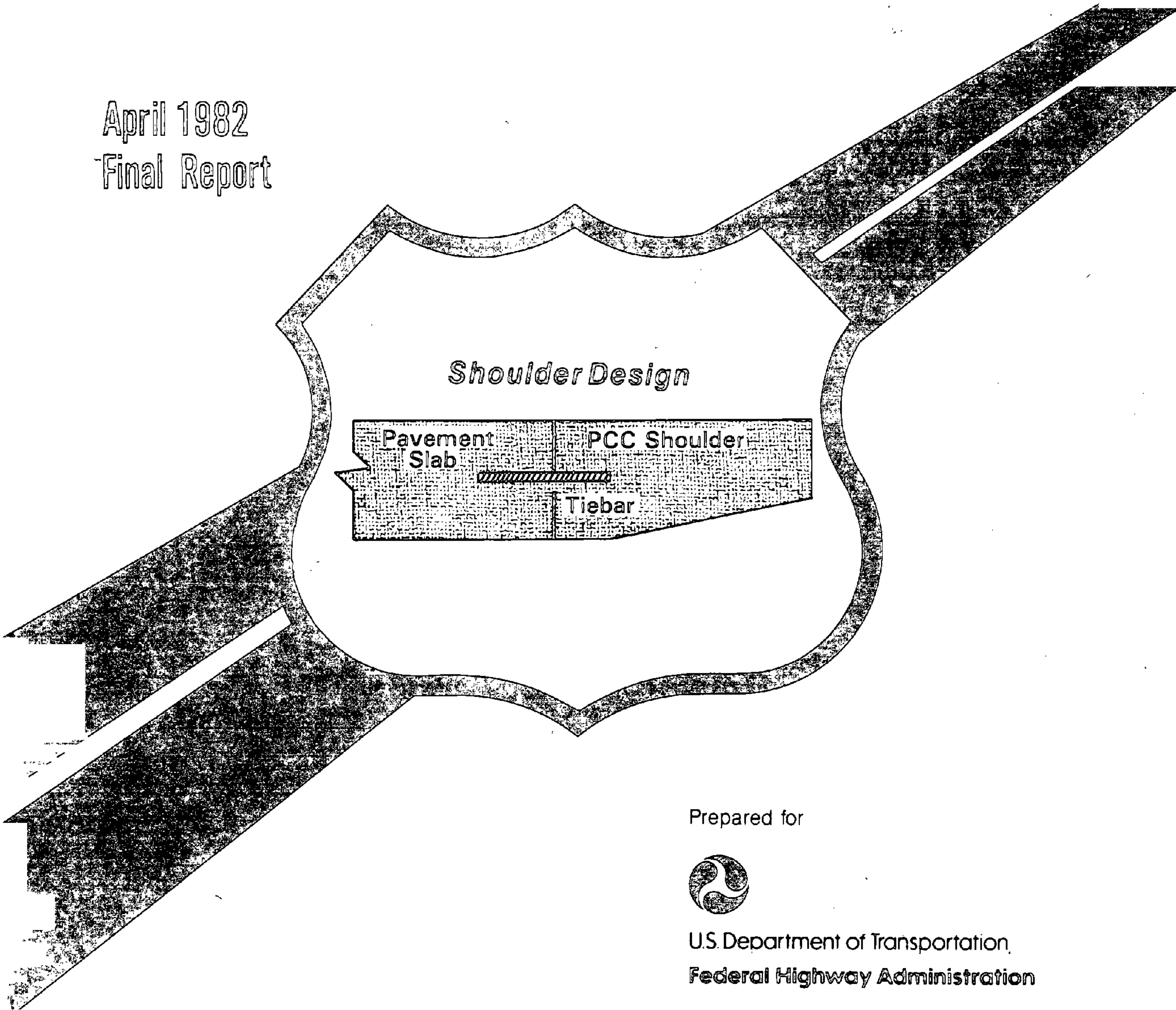
STRUCTURAL ANALYSIS AND DESIGN OF PCC SHOULDERS

April 1982
Final Report



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Offices of Research & Development
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FOREWORD

This report presents part of the results of research conducted by the University of Illinois for the Federal Highway Administration (FHWA), Office of Research, under contract DOT-FH-11-9175. The research study was part of FCP Project 5D, "Structural Rehabilitation of Pavement Systems." An analysis and design procedure for plain jointed concrete shoulders was developed, based on joint spacing, traffic use, fatigue, load transfer, and other factors. A design example is included, as well as a computer program listing for fatigue analysis.

Other reports resulting from this same study are:

FHWA/RD-81/077, "Improving Subdrainage and Shoulders of Existing Pavements - State of the Art"

FHWA/RD-81/078, "Final Report - Improving Subdrainage and Shoulders of Existing Pavements"

FHWA/RD-81/079, "A Pavement Moisture Accelerated Distress (MAD) Identification System - Volume I"

FHWA/RD-81/080, "A Pavement Moisture Accelerated Distress (MAD) Identification System - Volume II (User Manual)"

Sufficient copies of the report are being distributed to provide a minimum of two copies to each FHWA regional office, two copies to each FHWA division office, and three copies to each State highway agency. Direct distribution is being made to the division offices.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

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16. Abstract A structural evaluation of PCC highway shoulders has been conducted and a comprehensive design procedure for plain jointed concrete shoulders developed. The procedure can be used to provide PCC shoulders either for rehabilitation of existing pavement, or for new pavement construction. All major factors that are known to affect the behavior of PCC shoulders are considered in the mechanistic design approach including: encroaching moving trucks, parked trucks, foundation support, longitudinal joint load transfer, shoulder slab thickness and tapering, width of shoulder, and traffic lane slab. The finite element structural analysis technique was used along with a concrete fatigue damage model to sum damage for both moving encroaching trucks and for parked trucks. A relationship was established between the accumulated fatigue damage and slab cracking. Thus, the shoulder can be designed for an allowable amount of cracking which can vary depending on the performance level desired. Procedures for tieing the PCC shoulder to the mainline PCC slab are recommended to provide adequate load transfer and to avoid joint spalling. Long-term low maintenance performance of the PCC shoulder, along with significant improvement in performance of the traffic lane, can be obtained both for new construction and rehabilitation purposes if the shoulder is designed properly.

This report provides documentation of structural design of PCC shoulders as related to subdrainage, shoulder structures, and maintenance of existing pavement systems. Much of the material is applicable to new pavement construction. This report is one of several resulting from this research project.

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Approximate Conversions to Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply by	To Find	Symbol
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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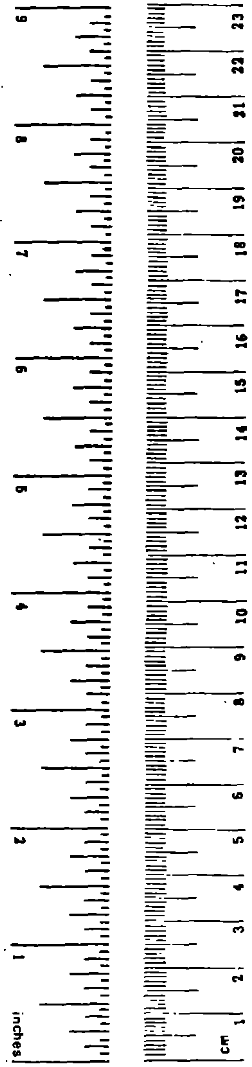
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	

MASS (weight)

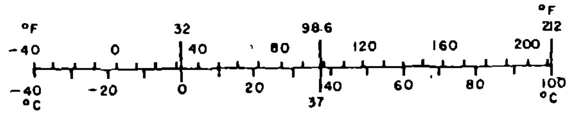
Symbol	When You Know	Multiply by	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CHAPTER 1

INTRODUCTION

A "well-designed and properly maintained" shoulder is considered by Taragin (1) to be a necessity with any "appreciable volume of traffic." He adds that the shoulder function is "multifold and all segments of traffic receive benefits from the additional cost over that of an improperly designed shoulder." Barksdale and Hicks (2) suggest that design approaches that can be taken to minimize the paved shoulder distress should include, among others, the selection of an adequate structural section for the shoulder as well as the provision of a positive means of removal of water from the vicinity of the longitudinal joint.

1.1 Purpose

The purpose of this research effort was to develop a rational structural analysis and design procedure for plain jointed portland cement concrete (PCC) highway shoulders. The design procedure may be used for the design of PCC shoulders for rehabilitation of existing pavements, and also for new pavement construction. A PCC shoulder must meet certain design requirements:

1. The shoulder must remain structurally sound in all kinds of weather to withstand:

a) the standing loads of disabled or otherwise stopped vehicles, and of maintenance equipment;

b) occasional traffic when the shoulder is used as a detour during maintenance operations;

c) regular traffic if the shoulder is used as an extra lane for peak periods, and

d) encroaching moving loads from the adjacent traffic lanes.

2. The longitudinal traffic lane/shoulder joint must provide high load transfer to reduce deflections and stresses in the traffic lane from edge loads. This will improve the performance of the traffic lane.

3. The traffic lane/shoulder joint must remain tight over the design life. This will improve the drainage of the pavement by directing runoff beyond the outer shoulder edge. The reduction in water entry at the traffic lane edge would eliminate or greatly reduce pumping potential under the joint which would also add to the service life of both the traffic lane and the shoulder.

4. If possible, the shoulder should be wide enough to accomodate parked vehicles. Objects on the shoulder that leave a clearance of 3 ft (0.9 m) or less from the pavement edge have been established to constitute a hazard (3).

5. The surface must be in such a condition that a motorist can safely leave the travel lane at high speed when necessary to avoid or lessen the severity of an accident. This condition further requires the PCC shoulder to be:

a) continuous (intermittent turnouts on some facilities do not provide the distance needed for decelerating or re-entering the traffic stream quickly and safely).

b) flush with the pavement edge: Brittenham, Glancy, and Karrer (4) found shoulder heights uneven with the edge of the pavements because of settlement or heave of the shoulder structure at nearly three-fourths of all the accident locations they studied.

c) sloped sufficiently to drain surface water across, but not sloped too steeply to constitute a hazard or create driver fear of rolling off.

d) reasonable skid resistance.

6. The paved shoulder should have low maintenance. Shoulder maintenance requires workers and equipment to be working closely to traffic, and in spite of all precautions taken, this is a constant source of danger to the workers as well as the traveling public.

1.2 Background

Many concrete pavements in urban as well as rural areas are being subjected to heavy traffic volumes and severe environments which may cause deterioration and premature failure. Pumping of fine materials due to the high deflections at the outer edge of the slab caused by heavy traffic loadings and free water results in the most serious types of pavement distress such as severe cracking in jointed concrete pavement and edge punchouts in continuously reinforced concrete pavement. An important question is "how to rehabilitate a distressed pavement effectively and economically to serve the highway user for a substantial period of time with relatively low cost?" One alternative is the construction of a tied portland cement concrete shoulder. There is no drop-off at the shoulder inner edge when properly tied concrete shoulders are used with concrete traffic lanes. This eliminates a safety hazard which exists all too frequently with other types of shoulders. Properly tied concrete shoulders prevent the development of an open longitudinal joint between mainline and shoulder pavement. This open joint, which is quite common where other types of shoulders are used, permits much of the surface water to drain down at the slab edge and thus saturate the subbase and subgrade directly under the mainline slab outer edge of the truck lane. Free water in this joint frequently causes erosion along the slab edge, upward heave or drop-off at the joint, severe shoulder base erosion, and pumping and faulting at transverse joints or cracks in the mainline pavement. In 1967, Illinois constructed an experimental shoulder project on I-80 "to develop definitive information that would permit the selection from among alternative shoulder pavement designs and materials, those that will afford the best service and overall economy of construction and maintenance."(6) After five years in service, the following was concluded:

> "The performance of the PCC shoulders is significantly better than that of any other type (Bituminous Aggregate Mixture, Cement Aggregate Mixture, and Pozzolanic Aggregate Mixture) that were included. Tiebars appear to be a desirable feature that can be used to keep the shoulder-pavement joint closed only in connection with PCC shoulders . . . It would seem that of the various types of paved shoulders included in the experiment, the PCC shoulders may have the best chance of serving the longest time without need for special maintenance and can be considered as a satisfactory alternative paved shoulder type."(6)

The other shoulders had deteriorated so extensively that they were replaced in 1977. Very little maintenance has been required on the PCC shoulders as of 1980.

Design of PCC shoulders has been based upon trial and error, engineering judgment and past performance of a few experimental sections, since no structural design procedure is available. A most recent study by Hicks, Barksdale, and Emery (11) clearly demonstrates the lack of PCC shoulder design procedures. A rational method of structural analysis, as well as design procedure for highway shoulder system is, therefore, greatly needed. This procedure should provide, for both rehabilitation and new construction, a PCC shoulder that is structurally adequate to support traffic loads within a very aggressive environment and effective in improving the performance of the adjacent traffic lane throughout the design life.

1.3 Research Approach

The research approach used to develop the design procedure is illustrated in Figure 1.1. Literature review and field studies were conducted and several experimental plain jointed concrete shoulders were examined and some relevant data were collected. The major design variables that affect the performance of PCC were identified based upon the experience of the project staff, previous research studies, and analytical studies conducted as part of this research. Current PCC shoulder design practice was critically evaluated as to its ability to provide a structurally adequate shoulder that can withstand traffic loadings and be effective in improving the performance of the adjacent traffic lane. Limiting criteria were determined for structural design including the allowable concrete fatigue consumption. Design guidelines for factors such as traffic lane/shoulder joint, shoulder traffic, tapering of shoulder, and joint spacing are developed. All available data of PCC shoulders were compiled which included several sections that have been under regular traffic since 1965 on Route 116, I-74, and I-80 in Illinois. Analytical models and procedures for slab stress/strain computation and fatigue damage were developed. A comprehensive fatigue analysis procedure was developed and verified that gives accumulated fatigue damage at both edges of the PCC shoulder so as the fatigue damage of the encroached traffic from the mainline at the inner edge of the shoulder could be compared with the fatigue damage of the parked traffic at the outer edge of the shoulder in all circumstances.

1.4 General Design Approach

The general design approach consists of determination of material properties and structural thicknesses of the PCC shoulder slab and the subbase and on the degree of load transfer across the mainline/shoulder joint to ensure the compatibility between the shoulder and the traffic lane as a system. A flow diagram showing the major design steps is shown in Figure 1.1.

The structural design procedure is basically a shoulder slab fatigue analysis. A computer program is included that provides fatigue damage data used for selection of the structural design. The program is named JCS-1 and is written in FORTRAN.

The procedure shown in Figure 1.1 is iterative, indicating that there are, of course, more than one structural design alternative that could meet the limiting criteria. The design that gives the minimum construction costs is generally selected as the optimum design as long as it meets all of the limiting design criteria.

The justification for construction of a well-designed PCC shoulder over that of another method of rehabilitation for the mainline pavement as well as the shoulder itself must be compared with the costs resulting from maintenance, rehabilitation, and user delay if another method of rehabilitation or different type of shoulder is used. These costs must be computed over a given analysis period.

The results of this research are presented in the following sequence:

Chapter 2: Literature review and field studies of PCC shoulders and their current design practice.

Chapter 3: Structural analysis of portland cement concrete shoulders.

Chapter 4: Development of a structural design procedure for portland cement concrete shoulders based on the fatigue of concrete.

Chapter 5: Demonstration of the use of the design method by solving a detailed example problem.

Chapter 6: Conclusions and recommendations for implementation of the design procedure.

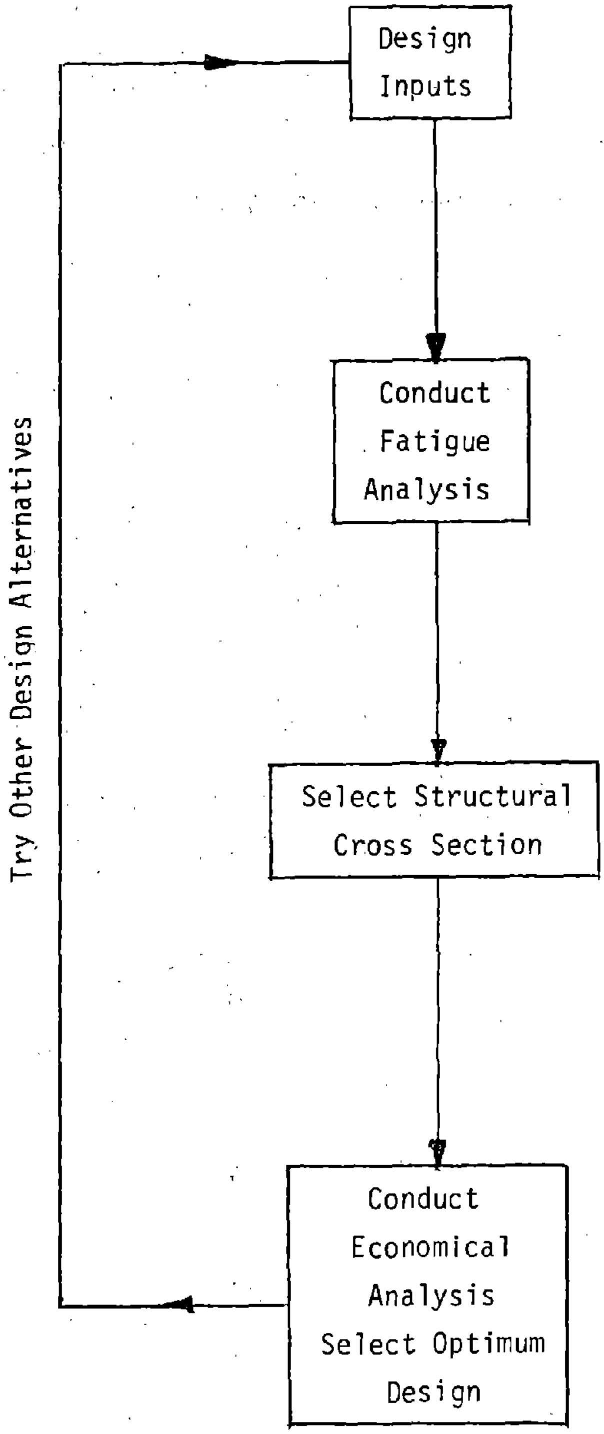


Figure 1.1. Structural Design Procedure for Plain Jointed Concrete Shoulders.

CHAPTER 2

PCC SHOULDER STATE-OF-THE-ART

2.1 General

PCC shoulders have been constructed for many years on some urban expressways, but only during the past 15 years on rural highways. The first experimental concrete shoulders were built in Illinois in 1965 as a part of a modernization project on Route 116. The good performance of these and other experimental shoulders built in Illinois on I-74 and I-80 resulted in favorable report by Illinois and NEEP project on PCC shoulders by FHWA in 1970. Since that time the use of concrete shoulders has spread to many other states for both new construction and as a part of several pavement rehabilitation projects. In 1974, FHWA published a notice removing concrete shoulders from the experimental status and from the NEEP program, and in 1976 new standards were issued for PCC shoulders. At the end of 1976, there were over 11 million square yards of PCC shoulders in service (8). An extensive literature review led Taragin to conclude that the use of portland cement concrete shoulders is increasing partly because "recent studies have shown them to perform better and may be more economical in the long run than other types of shoulders" (1).

The types of PCC shoulders that have been built so far consist of a concrete slab placed on a prepared material:

a) integrally with the mainline pavement,

b) after the new mainline pavement has been placed or,

c) adjacent to existing mainline pavement for rehabilitation purposes.

2.2 PCC Shoulder Distress

The development of design procedures to provide a structurally-adequate PCC shoulder requires the consideration and prevention of all the distress that cause premature failure and a substantial amount of maintenance. Results from a field study and other information were analyzed to determine the distresses occurring in existing PCC shoulders (14, 15, 16, 17).

1. Lane/Shoulder Drop-Off or Heave and Joint Separation: Lane/shoulder drop-off or heave occurs wherever there is a difference in elevation at the joint between the traffic lane and PCC shoulder. Joint separation is the widening of the joint between traffic lane and the PCC shoulder, generally due to drop-off or heave in the shoulder. Typically the outside shoulder settles due to consolidation, settlement or pumping of the underlying granular or subgrade material. Heave of the shoulder may occur due to frost action or swelling soils.

2. Transverse, Longitudinal and Diagonal Cracking: Cracking is caused by a combination of heavy load repetition, thermal and moisture gradient stresses and drying shrinkage stress.

3. Joint Spalling: Spalling is characterized by cracking and breaking or chipping of the pavement at the joint edge by some stress-producing action. Spalling is caused by infiltration of highly resistant particles to compressibility, often called incompressibles, into the joints. These particles resist joint closure during warm weather and produce horizontal shear stresses that can exceed the concrete shear strength. Spalls in pavements with short slabs usually are relatively small; however, in those with long slabs, larger spalls have occurred due to large movements and infiltration of incompressibles.

4. Pumping: Pumping is the ejection of water under pressure through cracks or joints under moving loads. As the water is ejected it carries fine material resulting in progressive material deterioration and loss of support. Surface staining or accumulation of material on the surface close to the crack or joint is evidence of pumping. Pumping becomes serious when the volume of displaced material is such that a large area of the slab is left unsupported. This results in increased surface deflections and permanent deformations under loads and ultimate failure.

5. Blow-ups: Blow-ups sometimes occur extensively in long jointed concrete pavements (> 30 ft [9.15 m] joint spacing). They occur in hot weather at a transverse joint that is not wide enough to permit expansion of the concrete slabs. The insufficient width is usually caused by infiltration of incompressible materials into the joint space during cool weather when the joint is open.

2.3 Current Shoulder Design Practice

During the 1972 Annual Meeting of the Transportation Research Board (TRB), a conference session was held on "Current Practices in Shoulder Design, Construction, Maintenance, and Operations" (18). This session showed a need for:

1. Construction of full-depth monolithic pavements throughout the entire width of the shoulder area;

2. Eliminating the "drop-off" or "raised shoulder" at the right-hand pavement edge; and

3. Eliminating shoulder structural distress due to traffic loadings.

Since that session was held, a considerable amount of research about the problems encountered in shoulder serviceability and maintenance and the basic needs for good PCC shoulders has been conducted. One of the most important conclusions that the overwhelming majority of researchers agree upon is that the PCC shoulder design in current use has developed primarily by trial and error (2) and past experience. Two recent surveys were conducted by Portigo (3) and Hicks, Barksdale, and Emery (11), illustrating the current status of shoulder design. Portigo (3) determined the following:

a. Only fifteen states have documented policies regarding shoulder design.

b. Twenty-eight states have no documented policies, but have shoulder paving standards. Six of these states evaluate individual projects before making decisions on paving.

c. Five states pave the shoulder integrally with the mainline pavement.

California and Iowa are the only states with a design procedure for their shoulders (3). The shoulders are designed for one percent of the mainline traffic with a minimum traffic index of 5 in California. Iowa designs its shoulders for the maximum wheel load, using the same design procedure as used for the mainline pavement (19).

Thus, most states do not have a set policy for design of PCC shoulders and the process of trial and error and engineering experience determined the shoulder construction practices that have developed. Hicks, Barksdale, and Emery (11) conducted a survey of portland cement concrete shoulder designs which is reproduced in Table 2.1.

During February, 1977, Taragin (1), as a part of NCHRP Project 20-5, "Synthesis of Existing Information Related to Highway Problems," (Topic

8-03 entitled "Design and Use of Highway Shoulders")(1), sent a questionnaire that consisted of a series of items divided into three main areas of concern related to highway shoulders: a) policy and procedures, b) design (geometric and structural), and c) operations (traffic and maintenance). Highlights of the replies from 43 out of all the 50 states that received the questionnaire are summarized in the following paragraphs:

In response to a question about the criteria used by the states to select the shoulder type, only one state (1 of 43) considers the percentage of trucks in the traffic stream as their criteria and uses it in design.

With respect to the criteria used to determine shoulder thickness, interestingly enough, no state reported using the truck traffic as their criteria. Eight states use past experience and trial and error, and another 8 states have no established policy for shoulder thickness.

Nearly two-fifths of the states (17 of 43) do not construct the shoulder originally for use as a travel lane, but they reconstruct the shoulder when and if needed for traffic use, and as mentioned earlier, none of these 17 states reported using truck traffic as a criterion for reconstruction. A like number of states (17 of 43) have no provision or policy to upgrade the shoulder, even when needed as a travel lane.

The predominant right shoulder width used by the states is 10 feet. The left shoulder width varies considerably more than the right shoulder width. Although 16 states of the 39 reporting this information specify a 4 feet (1.22 m) median shoulder, the remaining 23 states vary the median shoulder width from 3 to 10 feet (.91 to 3.0 m) depending on the traffic volume and on the number of traffic lanes.

On the question whether the states have special shoulder design, 36 states provided negative answers. Of the 7 remaining states that do have special designs for their shoulders, only 3 states are experimenting with shoulder material and full-depth paved shoulders. Of the 4 other states, only Pennsylvania requires that paved shoulders be provided for reconstruction, rehabilitation, or resurfacing projects on Interstates and other major arterials and/or collector roads.

One of the biggest problems of shoulder maintenance is the joint between the shoulder and the travel lane. Twenty-four of the 43 states reporting replied that they have no effective method to properly maintain the joint. Of the remaining 19 states a variety of methods have been tried, mostly experimental, with "more or less satisfactory results."

Are shoulders presently designed and constructed suitable for traffic operations? Although 25 states are satisfied with the suitability of their shoulders for the present time, and 7 states indicated that their shoulders are suitable only for certain condition, 10 of the 43 states indicated that the shoulders are not suitable for traffic operations.

Temporary use of shoulders during maintenance, construction or emergencies is allowed in 36 states at all times, in 4 states sometimes, and not allowed at all in only 3 states. The use of shoulders as a temporary lane during peak traffic is allowed only in 3 states. One state permits such use only as a turning lane. The reason for this restricted use of shoulders in most of the states is believed to be due to the structural and geometrical inadequacy of these shoulders in carrying the loads. On the other hand, nearly all of the states permit the shoulder to be used for disabled vehicles.

From the previous review of the state-of-the-art for PCC shoulder design and use, it is concluded that the lack of adequate PCC shoulder design is one of the major research areas that is of concern to researchers as well as to the states. The use of the AASHO Interim Guide procedure (21) to design PCC shoulders is highly questionable and should not be adopted without extensive study. The critical loading condition at the edge of the shoulder produces a stress and deformation state that is different from that caused by the largely interior loading condition in the mainline slab that occurred at the AASHO Road Test (trucks were intentionally kept away from the slab edge). Excessive moisture concentrations due to surface drainage at the edge of the shoulder and the resultant pumping of the fine material from under the shoulder can accentuate the difference and make the behavior of PCC shoulder under critical loading conditions even more complicated. The lack of consideration of tieing the PCC shoulder to the concrete travel lanes and its effect on stresses and deformations in the shoulder makes the AASHO procedure even less applicable.

Table 2.1. Summary of Portland Cement Concrete Shoulder Design (11).

	SLAB		BASE		TIE BARS	
STATE	TYPE	THICKNESS (inches)	TYPE	THICKNESS (inches)	SIZE NO.	SPACING (inch)
Alabama	CRC	8	Aggregate	6		
Arizona		Design Details Not Available				
Georgia	Plain	11 taper to 6	Subgrade		4	30
Idaho		Design Details Not Available				
Illinois	Plain	6 min.	Subgrade		4	30
Iowa	Plain	6				
Kentucky	Plain, rein.	5 to 7				
Maryland	Reinforced	7			4	30
Michigan	Plain	9 taper to 6-1/4	Aggregate	4	hook bolt	40
Minnesota		Design Details Not Available				
Nebraska	Plain	5-1/2	Subgrade			
New Mexico	Plain	8	Cement Stab. Base			
New York	Plain	6 min.	Aggregate	8" min.		
N. Carolina	Plain	7				
N. Dakota	CRC	8	Aggregate	2	5	48
Pennsylvania	Plain	6	Aggregate	12	hook bolt	
Ohio						
Texas	CRC	8	C. Stab. Base	6	4	36
Utah	Plain	9	C. Stab. Aggre.	5	5	36
W. Virginia	Plain	8	C. Stab. Aggre.	6		

(1 in = 2.54 cm)

CHAPTER 3

STRUCTURAL ANALYSIS OF PCC SHOULDERS

3.1 General

The structural analysis of concrete shoulders and adjoining traffic lanes requires a structural model with wide ranging capabilities. None of the classical methods have the required capabilities (22-27). The development of the finite element method of structural analysis has provided the technology for accurately characterizing concrete shoulders and traffic lanes.

3.2 Finite Element Model

The finite element model presented here was originally developed by Huang and Wang (28) for determining the stresses and deflections in concrete slabs with load transfer at the transverse joints. This method has been modified at the University of Illinois to handle problems such as PCC shoulder design. The method is based on the theory of minimum potential energy by dividing the slab into small elements interconnected only at a finite number of nodal points. The major advantages of the finite element method are that elements of varying sizes can be easily incorporated in the analysis and that no special treatment is needed at a free edge. As a result, the finite element method generally yields a stiffness matrix that is symmetric, positive, and definite, and the large number of simultaneous equations can be solved by an effective scheme, although this symmetric characteristic was not fully utilized in this model because of the assumption of load transfer at the joint.

3.2.1 Description of Model

The finite element model employed in this research is based on the classical theory of thin plates by assuming that:

a. The plane before bending remains a plane after bending;

b. The slabs are homogeneous, isotropic, and elastic;

c. The subgrade acts as a Winkler foundation, i.e., the reactive pressure between subgrade and slab at any given point is proportional to the deflection at that point (dense liquid approximation of the subgrade).

The procedure follows essentially that of Zienkiewicz and Cheung (29) and its general approach is as follows:

The rectangular plate element used in this model, originally developed by Melosh (30), is shown in Figure 3.1. At each node of this element there are three forces and three corresponding displacements. The three forces are a vertical force, F_w, a couple about the x-axis, $F_{\theta x}$; and a couple about the y-axis, $F_{\theta y}$. The three displacements are the deflection in the z-direction, w, a rotation about the x-axis, θ_x; and a rotation about the y-axis, θ_y. These forces and displacements are related by:

$$\begin{bmatrix} F_i \\ F_j \\ F_k \\ F_l \end{bmatrix} = [K] \begin{bmatrix} \delta_i \\ \delta_j \\ \delta_k \\ \delta_l \end{bmatrix} + kab \begin{bmatrix} \delta'_i \\ \delta'_j \\ \delta'_k \\ \delta'_l \end{bmatrix} \tag{3.1}$$

in which [K] = stiffness matrix, the coefficient of which depends on the dimensions, a and b, of the element, and the Young's modulus and Poisson's ratio of the slab; k = modulus of subgrade reaction; and at any given node i:

$$F_i = \begin{bmatrix} F_{wi} \\ F_{\theta xi} \\ F_{\theta yi} \end{bmatrix}, \quad \delta_i = \begin{bmatrix} w_i \\ \theta_{xi} \\ \theta_{yi} \end{bmatrix}, \quad \delta'_i = \begin{bmatrix} w_i \\ 0 \\ 0 \end{bmatrix} \tag{3.2}$$

The stiffness matrix for a rectangular element was tabulated by Zienkiewicz (29) and is used in this model. By superimposing the stiffness matrices over all elements and replacing the nodal forces with the equivalent of the externally applied loads, a set of simultaneous equations was obtained for solving the unknown nodal displacements and a force-displacement relationship for all nodes of the pavement model in the global system is developed as

$$\{F\}_g = [K]_g \ \{\delta\}_g \tag{3.3}$$

where $\{F\}_g$ is a vector containing all the global forces, $\{\delta\}_g$ contains all global displacements, and $[K]_g$ is the global stiffness matrix. The nodal moments and stresses were then computed from the nodal displacements, using the stress matrix tabulated by Zienkiewicz (29). Because the stresses at a given node are computed by means of one element, they might be different from than by the neighboring elements. Thus the stresses in all adjoining elements were computed and their average values obtained.

3.2.2 Transverse and Longitudinal Joints

The finite element model provides an effective method for analyzing concrete slabs with doweled or rebar tied joints. The efficiency of load transfer at the joint can be defined in terms of either deflection or stress:

$$\text{Eff}_{def} = \frac{d_u}{d_L} \times 100 \tag{3.4a}$$

$$\text{Eff}_{\text{stress}} = \frac{s_u}{s_L} \times 100 \qquad (3.4b)$$

where: EFF = efficiency of deflection or stress in percent

d_u = deflection at unloaded side of joint

d_L = deflection at loaded side of joint

s_u = stress at unloaded side of joint

s_L = stress at loaded side of joint

When no load is transferred across the joint the $d_u = 0$, $s_u = 0$, and the efficiency is zero. When $d_u = d_L$ and $s_u = s_L$ both sides of the joint have the same deflection and stress, and the efficiency is 100 percent.

By assuming the discontinuity of the two adjacent slabs at the joint, equilibrium equations for the whole system of nodal points in terms of unknown displacements are developed. In this step it is assumed there is neither moment nor shear transfer across the joint. Since dowel bars transmit only a small moment from one slab to the other, addition of the dowel bars can be assumed to effect only those equations that give vertical forces at each node. Finally, by equating the sum of two equations corresponding to vertical forces at every two adjacent nodes at the joint, to the external force applied at that node, the number of equations is reduced. However, at every two adjacent nodes at the joint the efficiency equation (Eq. 3.4) is added to the set of the equilibrium equations and the total number of equations remains unchanged.

The finite element model used in this analysis of concrete shoulders (called MODKEN) provides for an equality between load transfer between deflection and stress. For example, if the deflection load transfer EFF is 50 percent, then the stress load transfer EFF is also 50 percent. Thus all graphs and equations contained herein follow this definition. In reality, there is a difference between deflection and stress load transfer. A more comprehensive FE model called "ILLI-SLAB" (59) was used to account for the difference between the two efficiencies. Figure 3.2 was prepared using the "ILLI-SLAB" program. This plot shows that, for example, if deflection load transfer is 80 percent, the stress load transfer is only 42 percent. This difference will be considered in the design of concrete shoulders in Chapters 4 and 5.

3.2.3 Computer Program

The finite element model computer program can determine the slab stresses and deflections due to applied traffic loadings. The program can handle one slab, two or three slabs connected by transverse joints, or four or six slabs connected by longitudinal and transverse joints. The efficiency of load transfer at each joint can be specified as defined in Equation 3.4.

The tire imprints of the wheel load are specified as rectangular areas, and the coordinates of their sides must be input so that the program can distribute the wheel loads among the adjacent nodal points by statics. The program can handle any number of wheel loads at the same time. The additional computer time due to these additional loads is very small because Guass elimination of the coefficient matrix is carried out only once regardless of the number of loads involved.

The program can be used to investigate the effect of partial subgrade contact on stress distribution. The nodal number, at which subgrade reaction resulting from loss of subgrade contact does not exist, can be assigned, and the second term on the right side of Equation 3.1 will be automatically eliminated at these nodal points when forming the simultaneous equations. The modified version of the program (called MODKEN) was written in FORTRAN IV for the IBM 360 computer and is available at the University of Illinois computer center.

3.2.4 Comparison of Measured and Computed Load Stress and Deflection

A comparison is made between the finite element solutions and experimental measurements so that the validity of the method as applied to actual pavements can be tested. The results of the strain and deflection measurements from the AASHO Road Test (13) provide excellent data for making such comparisons. Tests were conducted on the main traffic loops where the strain and deflection due to moving traffic were measured at the slab edge far from a transverse joint. The length of slabs consisted of 15 ft (4.6 m) non-reinforced sections and slab thickness ranged from 5 to 12.5 in. (12.5 - 31.25 cm).

The finite element program requires the modulus of elasticity and the Poisson's ratio of concrete, the modulus of subgrade reaction, k, and the axle load. The measured dynamic modulus of concrete was 6.25 x 10^6 psi (4.31 x 10^7 kPa) and the Poisson's ratio was 0.28. The determination of the subgrade k-values is much more difficult because it changes appreciably with the time of the year. The elastic k-values on the subbase obtained by the plate bearing test at the AASHO Road Test varied from approximately 85 to 200 lb/in.^{3} (231 to 543 kPa/cm) over all the loops throughout the two years. Two k-values of 108 and 150 pci (293 and 407 kPa/cm) were used in the FE analysis conducted to verify the closeness of the program to the measured values at the AASHO Road Test. The first value, 108 pci (293 kPa/cm), is the mean k-value that was measured during the spring trenching program between April 23 and May 25, 1960. The second value, 150 pci (407 kPa/cm) is somewhat of an overall average from the loops as indicated from Figure 3-8, Reference 13.

The single and tandem axle loading configurations are shown in Figures 3.3 and 3.4, respectively.

The stress comparison for single axles is shown in Figure 3.5 and for tandem axles is shown in Figure 3.6. The deflection comparison for single axles is shown in Figure 3.7 and for tandem axles is shown in Figure 3.8. The distance from the edge of the slab to the center of the wheel load was 20 in. (50 cm) in the FE analysis, which is similar to the 17-22 in. (43-56 cm) measured for the actual loadings. Compressive strain at the top of the slab was measured in the longitudinal direction, 1 in. (2.5 cm) from the edge of the slab. The strain and edge deflection measurements were correlated with axle load, PCC slab thickness, and temperature difference (standard differential) and regression equations were developed (13). The theory of elasticity was used to convert the strain equations into stress equations (31). The axle loads used for these plots were 18 kip (80 kN) single and 36 kip (160 kN) tandem. The results show good correlation between the stresses and deflections computed with the finite element program and those computed with the AASHO equations for both single and tandem axles. Thus, the finite element program can be used with confidence to computer stresses and deflections cuased by axle loads.

3.3 Major Design Factors and Guidelines

The two major engineering design objectives for this research are: (1) provide a shoulder that will have structural adequacy to support encroaching and parking traffic loads for long-term low maintenance performance, and (2) provide a shoulder that will reduce the rate of deterioration of the adjacent pavement traffic lane (which is usually the heaviest traveled truck lane). If both objectives can be accomplished economically, then there is considerable benefit in placing PCC shoulders during new construction, or in replacing deteriorated shoulders on existing highways with PCC shoulders.

As a result of the field surveys and the literature review conducted in this research, the major design variables that affect the structural behavior of PCC shoulders are: (1) slab thickness and tapering of thickness, (2) joint spacing, (3) foundation support and loss of support, (4) tie between shoulder and traffic lane (including load transfer across the longitudinal joint), (5) width of shoulder slab, and (6) design and condition of the adjacent traffic lane. The PCC shoulder must withstand both repeated moving loads and static loads from parked vehicles. Each of these conditions involve an edge loading condition from heavy trucks. The critical stress for this load position is at the bottom of the slab edge, parallel to the edge beneath the wheel load, at midpoint between transverse joints as shown in Figures 3.3 and 3.4. The edge loading condition has been proven to be the most critical for fatigue damage (32) and the stresses and deflections resulting for that condition are, therefore, referred to in this study as critical stresses and deflections. The actual amount of loading has to be estimated, and it varies widely along a given project and from one project to another. The effects of moisture and loss of support from pumping and settlement should also be considered because of the edge loading conditions.

The critical effect of edge loadings on the performance of all types of PCC pavements has been studied several times through the years. Recent field and analytical studies have concluded that the edge loading condition results in transverse cracking of jointed concrete slabs, and edge punchouts of continuously reinforced concrete pavements (32, 33, 34, 35). Traffic encroachment studies have shown that there exists much more edge loading of the traffic lane slabs and shoulder encroachment than previously believed (11, 36).

The influence of the major design factors on the structural performance of PCC shoulders is determined using both the finite element (FE) model previously discussed and results from field studies.

3.3.1 Major Design Factors

Shoulder Thickness

The effect of thickness of the PCC shoulder on the critical tensile stress caused by an encroaching wheel load (18-kip single axle load (80 kN)) is shown in Figure 3.9. The design configuration is typical and consists of a traffic lane thickness of 8 in. (20.3 cm), width of 12 ft (3.6 m), and length of 15 ft (4.6 m). The PCC shoulder is 10 ft (3.0 m) wide and ranges in uniform thickness from 4 to 12 in. (10 - 31 cm). Three different lane/shoulder longitudinal joint stress load transfer efficiencies are shown.

As the thickness (h_s) increases from 4 to 12 in. (10 - 31 cm), tensile stress decreases. The rate of decrease is much more rapid for slabs less than 8 in. (20 cm) when stress load transfer efficiency is low (i.e., 0 to 50 percent). When the shoulder is not tied to the lane (i.e., EFF = 0 percent) the stresses approach or exceed the range of flexural strength of PCC, for slabs less than 8 in. (20 cm). Stresses greater than about 500 psi (3450 kPa) will result in cracking of the shoulder with only a few heavy load applications. The effect of joint load transfer is large as subsequently discussed. If there is reasonable load transfer (i.e., 50 percent) and slab thickness ($\geq$ 8 inches) the effect of increased thickness on stress is reduced at the lane/shoulder joint. For parking trucks, a wheel load will occur at the outside edge of the shoulder where the load transfer is, of course, 0 percent. Thus, the thickness design of PCC shoulders should consider both loading positions and the number of applications at each position.

Width of PCC Shoulders (B)

The width of shoulder affects both critical stress and deflections in the shoulder slab. Figures 3.10 and 3.11 show these effects over a range of design conditions. The load transfer efficiency is 0 percent, h_s, varies from 6-12 in. (15-30 cm), and foundation support varies from "poor" (k = 50 pci or 136 kPa/cm) such as saturated clay, to "stiff" (k = 500 cpi or 1360 kPa/cm) such as a thick stabilized subbase. The deflection increases very rapidly for a width of less than about 5 ft (1.5 m). For "poor" foundations narrow PCC shoulders experience high deflections with thickness (h_s) having minimal effect. Wider shoulders (B > 5 ft) show thickness having a more significant effect on deflections.

The effect of width on critical stress is shown in Figure 3.11. Widening the shoulder from 3 ft to 5 ft (0.9 - 1.5 m) reduces stress 20 percent for an 8 in. (20 cm) thick slab for example, and widening the shoulder from 5 to 10 ft (1.5 - 3.0 m) causes a decrease of only 5 percent. The effect of shoulder width on tensile stress is about the same regardless of slab thickness. Thus, for structural purposes, a shoulder wider than 5 ft (1.5 m) has a reduced effect on the critical stresses from encroaching truck traffic near the longitudinal joint. If a narrow shoulder is required, the critical stress can be reduced to allowable levels by increasing the shoulder slab thickness and/or joint efficiency. For example, a 10 ft (3.0 m) wide shoulder of 8 in. (20 cm) thickness has a tensile stress of 370 psi (2551 kPa) under an encroaching truck wheel load shown in Figure 3.11. If the shoulder were to be constructed only 3 ft (0.9 m) wide, the thickness required for the same stress is 10.1 in. (25.6 cm).

Tapering of PCC Shoulder

Tapering of the PCC shoulder has been used on some existing CRCP projects. The effect of tapering on deflections and stresses in the shoulder and the CRCP traffic lane is shown in Figures 3.12 through 3.17. Uniformly tapered, stepwise tapered, and uniform-equivalent thickness of concrete shoulders (Figure 3.12) were analyzed and compared for three different loading conditions. Traffic lane loading (Figure 3.13), encroached loading (Figure 3.14), and parked traffic loading (Figure 3.15 and Figure 3.16) conditions were used for comparison. The thickness of the uniform-equivalent shoulder was chosen such as it will result in the same cross-sectional area as the other two shoulder types (equal quantities of concrete are used in the three shoulder sections).

The effect of shoulder tapering on stresses and deflections in the traffic lane due to traffic lane loading is shown in Figure 3.13. There is only a minimal effect on stresses and almost no effect on deflections. The load transfer systems used in this example kept the stresses within an acceptable range (about 250 psi)(1723 kPa) for the different shoulder designs.

The effect of shoulder tapering on stresses and deflections in the concrete shoulder due to encroached traffic is shown in Figure 3.14. The effect is minimal to none also in this case, and the load transfer system used kept the stresses within an acceptable range (about 300 psi) (2070 kPa) for the different shoulder designs. The effect of shoulder tapering on stresses and deflections in the shoulder due to parked traffic is shown in Figure 3.15 and Figure 3.16. In this case the effect on stresses near the outer edge of the shoulder is relatively higher than the previous two cases. Using a shoulder with uniform thickness of 7 in. (17.8 cm) will reduce the stresses to 400 psi (2758 kPa) from the 500 psi (3447 kPa) when 6 to 8 in. (15-20 cm) tapering is used (Figure 3.15). Using a shoulder with a uniform thickness of 8 in. (20 cm) will reduce the stresses even more to 320 psi (2206 kPa) from the 450 psi (3102 kPa) when 6 to 8 in. (15-20 cm) tapering is used (Figure 3.16). The effect on deflections, however, is minimal to almost nil.

The previous figures show that shoulder tapering does not have any effect on the critical stress in the traffic lane or in the shoulder near the longitudinal joint. However, critical stresses, in the shoulder near the outside edge, occuring from parked trucks on the shoulder with the wheels at the outer edge, make the use of uniform-equivalent thickness more favorable. Figure 3.17 shows that, with the levels of stress shown in Figure 3.16 and Figure 3.17, from the concrete fatigue side point the ratio of allowable load applications at the inner edge of the shoulder to those at the outer edge, is very high. This indicates that the outside shoulder edge will probably need far fewer load applications until cracking than the inside edge near the traffic lane. On the other hand, the ratio of the allowable load applications until failure of both edges of the PCC shoulder when tapered shoulder is used is higher than the ratio when uniform-equivalent shoulder thickness is used. Then the uniform-equivalent thickness of PCC shoulder will provide a cross section that experiences fatigue consumptions at both edges closer to each other than is the case with the tapered shoulder. This is an important step for optimization of PCC shoulder structural design since the fatigue lives of both edges of the shoulder are closer to each other.

Foundation Support and Loss of Support

The impact of varying subgrade support is illustrated in Figure 3.18. The influence of the subgrade is much greater for thin shoulder sections (e.g., bins).

The effect of loss of support beneath the shoulder edge near the lane/ shoulder joint is shown in Figure 3.19. A loss of support of 12 in. (30 cm) is considered, which could be caused by, for example, the settlement of a subsurface drain trench beneath the shoulder. The increase in critical stress, when this 12 in. (30 cm) loss of support occurs, is about 25 percent. This increase in stress can be adjusted by increasing shoulder slab thickness by approximately 1.4 in. (3.5 cm) for an original 6 in. (15 cm) shoulder, for example.

Lane/Shoulder Tie (Load Transfer (EFF))

The extent of "tie" between the concrete traffic lane and PCC shoulder affects load transfer, separation of shoulder from lane, and settlement or heave of the PCC shoulder. The effect of the lane/shoulder tie as indicated by joint stress load transfer efficiency on critical stress in the shoulder is shown in Figure 3.9. At the 4-8 in. (10-20 cm) range of thickness, the extent of stress joint efficiency has a very large effect on stress. Changing from 0 to 50 percent efficiency reduces stress by a factor of 2.1, and to 100 percent a factor of 3.3 for a 6 in. (15 cm) shoulder slab. The reduction in critical stress for a joint efficiency from 0 to 50 percent is most significant.

Shoulder Joint Spacing

The effect of joint spacing on the performance of PCC shoulders is shown in Figures 3.20 and 3.21. These are based on data obtained from the field survey of the three sections of 10 year old plain PCC shoulders located in Illinois. Most of the sections were tied with rebars to the mainline pavement. Figure 3.20 shows the effect of joint spacing on percent joints spalled. As the shoulder joint spacing exceeds 20 ft (6.1 m), the proportion of spalled shoulder joints increased rapidly to the point where, with a spacing of 100 ft (30 m), all joints are spalled.

The relationship between shoulder joint spacing and percent shoulder slabs cracked is shown in Figure 3.21. Again, as the joint spacing exceeds 20 ft (6.1 m) a very rapid increase in slab cracking occurs. A number of the transverse cracks had spalled. Also, numerous blowups were found in sections having joint spacings of about 40-100 ft (12-30 m), and only one blowup for joint spacing of 20 ft (6.1 m).

Other field surveys on mainline pavements and experimental field tests have shown the benefits of using short joint spacings (32, 35).

PCC Shoulder Effect on Traffic Lane

The PCC shoulder also has an influence on the performance of the adjacent traffic lane. Figures 3.22 and 3.23 show the influence of tied PCC shoulder to continuously reinforced concrete pavements (CRCP) on stresses at the top of the slabs and deflections along section x-x (see figures). Using a load transfer system that consists of #3 tiebars at 24 in. (61 cm) center to center, for example, reduced the maximum stresses by about 50 percent. Also Figure 3.23 (where a 2 ft (60 cm) loss of support under the traffic lane exists) shows that it reduced the stresses from a very high level (more than 500 psi (3447 kPa)) that will result in the start of an edge punchout after only a few load applications, to an acceptable stress value (about 250 psi (1723 kPa) in either of the two slabs. The deflections, especially in Figure 3.23, are reduced drastically; consequently, the possibility of pumping of fine materials is also reduced. Figures 3.24 and 3.25 show the influence of PCC shoulder thickness and the load transfer efficiency across the lane/shoulder, respectively. An increase from 4 to 8 in. (10-20 cm) in shoulder thickness in Figure 3.24

will decrease the tensile stress at point B (see figures) by only about 15 percent and will decrease the deflections at point A by only about 10 percent. However, Figure 3.25 shows that by improving the load transfer system from no tie (0 percent) to a perfect load transfer (100 percent), the tensile stress at point B will be reduced by almost 70 percent and the deflections at point A by almost 50 percent. The importance of points A and B is in the fact that point A is the critical point in the CRCP traffic lane for deflections that cause pumping of the fine materials from underneath the slab. Point B is the critical point for the initiation of punchouts in CRCP pavement due to high stresses.

PCC shoulders also influence stresses and deflections when built and tied to jointed concrete pavements (JCP) as shown in Figures 3.26 through 3.28. Figure 3.26 shows the influence of PCC shoulder on the critical traffic lane edge stress. As the stress load transfer efficiency increases from 0 percent (no effect) to 100 percent, the critical edge stress reduces about 50 percent. The decrease is more rapid for up to 50 percent efficiency. The influence of the PCC shoulder on traffic lane deflections is shown in Figure 3.27. If the joint has 100 percent efficiency, the deflection decreases about 50 percent for this example.

The influence of both shoulder width and load transfer efficiency on critical stress is shown in Figure 3.28. The width of the shoulder has a large influence in reducing stress in the traffic lane for a width up to 3 ft (0.9 m). Beyond that width there is almost no effect. The strong influence of joint load transfer is again indicated.

These analytical results show that PCC shoulders should have a beneficial influence on the performance of the adjacent traffic lane if the load transfer is reasonable. Field surveys were conducted along the entire length of two projects (I-74 and I-80) where PCC shoulders were located. All distress types were recorded in the traffic lane adjacent to the PCC shoulders. Both projects were constructed about 10 years previous and contained CRCP in the traffic lanes. In general, extensive structural distress was found in portions of both projects that did not contain PCC shoulders, and little distress was found in the portions containing the shoulders. Results are given in Table 3.1. On I-74 there was evidence of pumping in areas not including the PCC shoulders.

Joint separation and settlement of the shoulders were also determined on the two projects. On I-74, it was found that the sections with tie bars experienced virtually no joint separation while the sections without tie bars experienced joint separation that ranged between 1/2 - 1 in. (12.5 - 25 mm). On I-80, all sections with PCC shoulders that were surveyed are tied to the traffic lane with anchor bars. It was found that some joint separation up to 0.5 in. (12.5 mm) had occurred where the bars had pulled out (the anchors were only embedded 2 ins. (51 mm) into the traffic lane slab).

The survey on Illinois Route 116 showed that the sections that have tie bars had joint separation of less than 0.2 in. (5 mm) while the section that had a longitudinal keyway <u>only</u> had a joint separation of up to 0.5 in. (12.5 mm). The section that has neither tie bars nor keyway experienced a joint separation up to 1 in. (25 mm). Thus, tie bars embedded sufficiently into the traffic lane and shoulder slabs are absolutely required to maintain a tight joint so that high load transfer efficiency can be maintained over a long time period.

3.3.2 Design Guidelines

Slab Thickness and Tapering

The PCC shoulder thickness has a very significant influence on critical stress from encroaching traffic loads (Figure 3.9). Two load positions must be considered to determine required thickness: (1) the inside edge near the lane/shoulder longitudinal joint, and (2) the outside "free" edge. The inside longitudinal joint edge is subjected to many more load applications than the outside edge, but if the shoulder is tied to the lane with reasonable load transfer, the inside edge stress will be significantly reduced (i.e., from 580 - 290 psi (4000 to 2000 kPa) for a 6 in. (15 cm) shoulder with 50 percent joint efficiency) as shown in Figure 3.9. Because the stress reduction is so large, it is believed that the outer free edge may control design thickness when a reasonable lane/shoulder tie is provided (Figures 3.12 through 3.17). A minimum thickness of 6 in. (15 cm) is presently recommended since thinner slabs will have very high stresses when loaded with typical heavy trucks, that would tend to crack the slab with only a few applications. Thicker shoulders may be required depending on truck traffic, the amount of traffic lane edge structural support desired, foundation support, load transfer at joint, and shoulder width.

A summary of performance data from two Illinois projects is shown in Table 3.2. Both pavements carried heavy truck traffic (especially I-80). The 50 percent slabs cracked on I-74 are some cause for concern, but the long 25 ft (7.6 m) joint spacing had an effect on the cracking since similar adjacent 10 ft (3 m) long slabs did not show any cracking. The 8 - 6 in. (20 - 15 cm) tapered shoulders on I-80 under heavy traffic performed very well with only 5 percent cracked slabs.

Although tapering of the shoulder thickness between the two edges has been considered to save on concrete quantities, it may not be the best design for the following reasons:

a. The critical stress load position is the outside free edge when reasonable load transfer is used across the lane/shoulder joint, caused by either parked trucks or moving traffic using the shoulder as a detour around a closed lane.

b. Tapering tends to put the entire pavement section in a "bathtub" which entraps water in the structural section (i.e., water may seep back under the shoulder slab towards the traffic lane).

c. It is doubtful if there is any construction economic benefit due to the additional grading required for tapering.

Shoulder Width

Required shoulder width is generally dictated from geometric/safety considerations. However, the width influences stresses and deflections in the shoulder and in the adjacent traffic lane if they are tied together. Tied shoulder width should be at least 3-5 ft (91-152 cm) to provide maximum structural benefits (stress and deflection) to the traffic lane and shoulder. A narrower shoulder could be used (with load transfer) to help reduce edge stresses in the traffic lane, but a thicker PCC shoulder slab is required.

Lane/Shoulder Tie

The lane/shoulder tie is a very effective way of reducing the critical stress and deflection to prevent separation at the joint. The effect of joint efficiency (or extent of load transfer) on the critical shoulder stress is shown in Figure 3.29 for a typical design situation. The provision of a tie system that provides at least 50 percent load transfer would reduce critical stress to acceptable levels. The shape of the curves show that there is really only a small advantage in providing more than 50 percent load transfer.

There are essentially two methods of obtaining this level of load transfer and tieing the lane and shoulder together along the longitudinal joint:

a. Use of a keyed joint with tie bars that hold the joint very tight.

b. Use of a butt joint with tie bars that hold the joint very tight.

Tie bars or anchor bolts have been used on most PCC shoulders constructed to date. Field studies were conducted and the long term deflection load transfer of the experimental shoulders in Illinois was determined. Results are shown in Table 3.3 and Table 3.4. On I-74, after 10 years in service (2.7 million 18 kip (80 kN) ESAL), the deflection load transfer efficiency for rebar <u>tied shoulders with a keyway</u> ranged from 70 to 98 percent. Those without tiebars had very low deflection efficiency (i.e., 16 percent) due to lane/shoulder separation (See Table 3.2 for the design). On I-80 after 9 years in service (7 million 80 kN (18 kip) ESAL; the load transfer efficiency for anchor bar tied shoulders without a keyway (butt joint) ranged from 31-47 percent. The I-80 joint had opened an average of about 10 mm (3/8 in.) and some of the 2 in. (51 mm) embedded anchor bars had pulled out. Thus the joint design on I-80 was not adequate to provide long term deflection joint efficiency of 50 percent or greater. Some of the anchor bars had pulled out and spalled the surface of the traffic lane.

Laboratory tests by PCA (37) showed that steel tie bars are effective in extending the endurance of aggregate interlock and keyed joint under repeated loading. Load transfer efficiency after about 5 million load applications was greater than 70 percent for aggregate interlock, keyway, and smooth joints all having steel ties.

Thus, if a tied shoulder has at least 50 percent stress load transfer efficiency, stresses in both the traffic lane and shoulder are significantly reduced. A 50 percent stress transfer efficiency corresponds approximately to an 85 percent deflection transfer according to Figure 3.2. Figures 3.23 and 3.25 show a reduction of almost 50 percent in critical tensile stress in CRCP traffic lane (Point B). Figures 3.28 and 3.29 show 30 and 55 percent reduction for JCP traffic lane and PCC shoulders, respectively. One problem that has been noticed is when the PCC shoulders are on high fills there is a tendency for the outer edge to settle and some joints have separated either by pulling out the tie bars from the PCC or rupture of the steel. Consideration should be given, therefore, to increase the number of tie bars for greater load transfer reliability and to prevent separation.

Foundation Support

The PCC shoulder can be placed directly on the subgrade soil, a granular subbase, or a stabilized subbase. These foundation conditions can generally be considered as "poor", "moderate", and "stiff", respectively. Analysis shows that PCC shoulders having "poor" support (i.e., $k \simeq 50$ pci (136 kPa/cm)) have high deflections and stresses. The provision of a "moderate" support level (i.e., $k \simeq 200$ pci (544 kPa/cm)) appears justified. However, using a stiffer foundation support is not very effective in reducing deflections or stresses further. Field results (5, 6) in Illinois have shown little difference in performance to date for those sections having granular subbase or fine grained soil subbases. However, drainage continuity considerations and the effect of moisture on the types of materials used should be considered when selecting the subbases to avoid a "bathtub" cross section and to minimize the tendency of frost heave under the shoulder.

Slab Length

Based on results from the field survey, a maximum slab length of 15 ft (4.6 m) is recommended. The rationale behind this choice is shown in Figures 3.20 and 3.21. These two figures clearly show that using slabs longer than 15-20 ft (4.6 - 6.1 m) will result in shoulder distresses, namely joint spalling and increased transverse cracking.

Short slab lengths eliminate the need for steel reinforcement and reduce the joint movement to a small enough level that it does not force cracks to open up on the adjacent traffic lane for either CRC or JCP pavements. For plain jointed pavements, the shoulder joint pattern should match the traffic lane, although intermediate joints may be placed if the traffic lane joint spacing is greater than 20 ft (6.1 m). Intermediate joints should be placed where the traffic lanes are jointed reinforced concrete. None of the transverse joints require dowels, unless the shoulder is to be used as a regular traffic lane.

Effect of Shoulder on Traffic Lane

The effect that the shoulder has on stress and deflection of the traffic lane is through (1) the load transfer of the longitudinal joints, and (2) minimizing the edge pumping potential. As shown in Figures 3.22 through 3.28, the efficiency of load transfer between the traffic lane and shoulder is of significant importance to the traffic lane. Figures 3.23 and 3.25 show that CRCP traffic lane critical stress (Point B) could be reduced by more than 50 percent if a reasonable load transfer (e.g., #3 tie bars @ 24 in. (61 cm) corner to corner) is used. Deflections at Point A would be reduced by more than 40 percent from the same load transfer system. Figures 3.26 and 3.28 show that JCP traffic lane critical edge stresses could be reduced by more than 30 percent if joint stress transfer efficiency of 50 percent is used. Figure 3.27 shows that the traffic lane edge deflection could be reduced by about one-third with 50 percent efficiency. Reduction of stresses and deflections would, therefore, improve the performance of the traffic lane as indicated by the data in Table 3.1 for CRCP. From Figures 3.22 through 3.28 an optimum design of a shoulder with regard to improving the performance of the traffic lane is to provide maximum load transfer across the longitudinal joint with a thickness ($\geq$ 6 in. (15 cm)), width (> 3 ft (.9 cm)), and foundation support ($\approx$ 200 pci (54.2 MN/m^3)). Provision of a PCC shoulder either on new construction or for rehabilitation of an existing shoulder is expected to have a beneficial effect if these design requirements are provided.

The condition and design of the existing traffic lane should be determined. If distress associated with edge traffic loadings are occurring, then special consideration should be given to provide high load transfer and adequate shoulder thickness to reduce the critical stresses and deflections in the traffic lane.

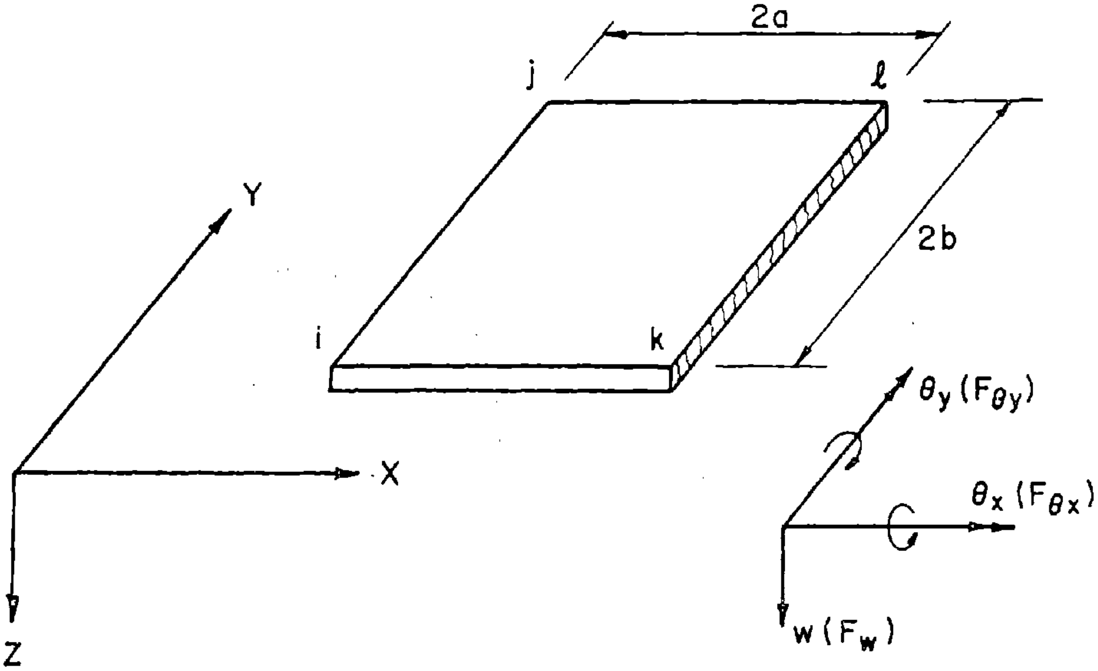


Fig. 3.1. Rectangular Plate Element

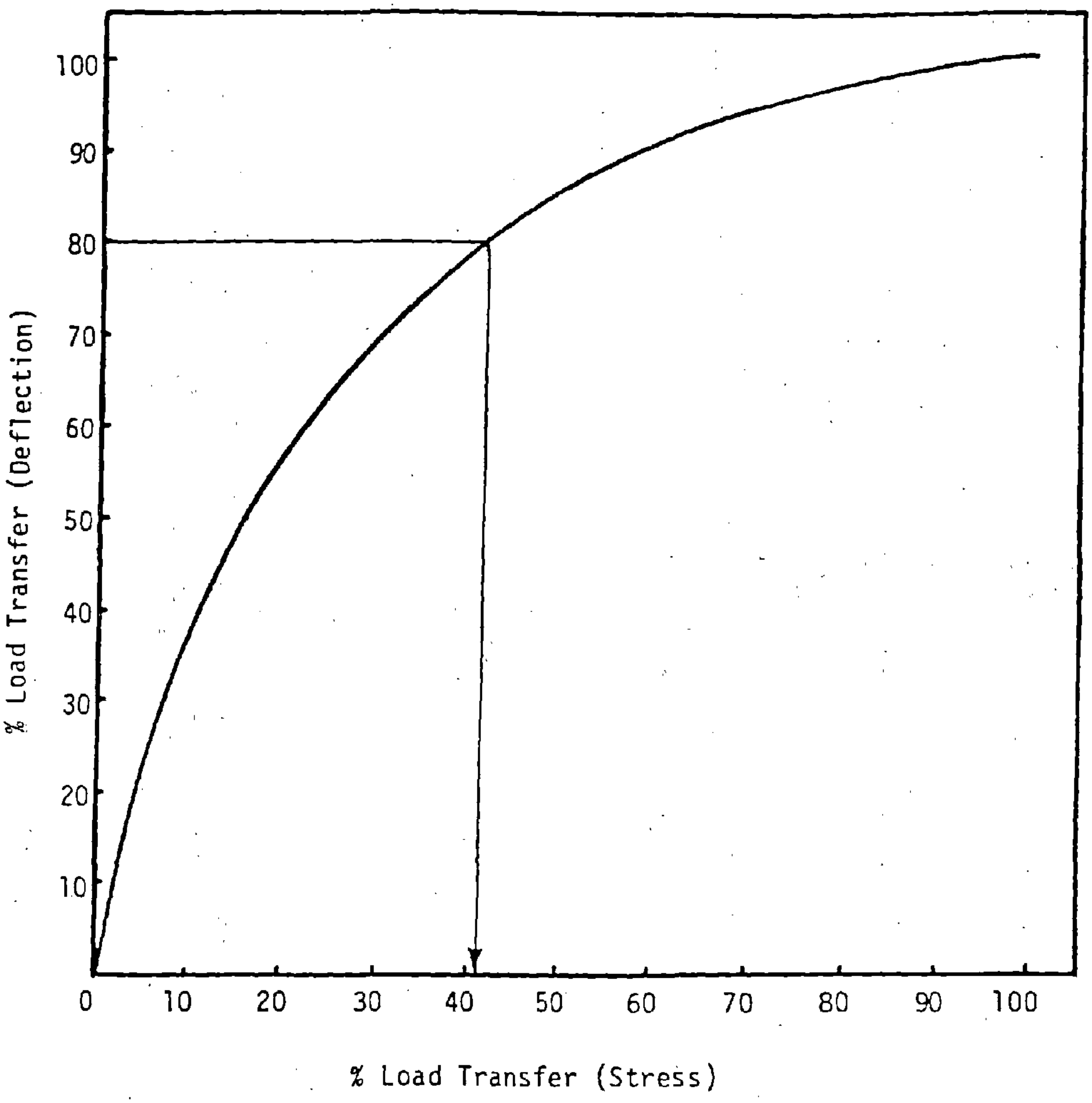


Fig. 3.2. Relationship Between Load Transfer Efficiency Based on Deflection and That Based on Stress to be Used for Adjustment.

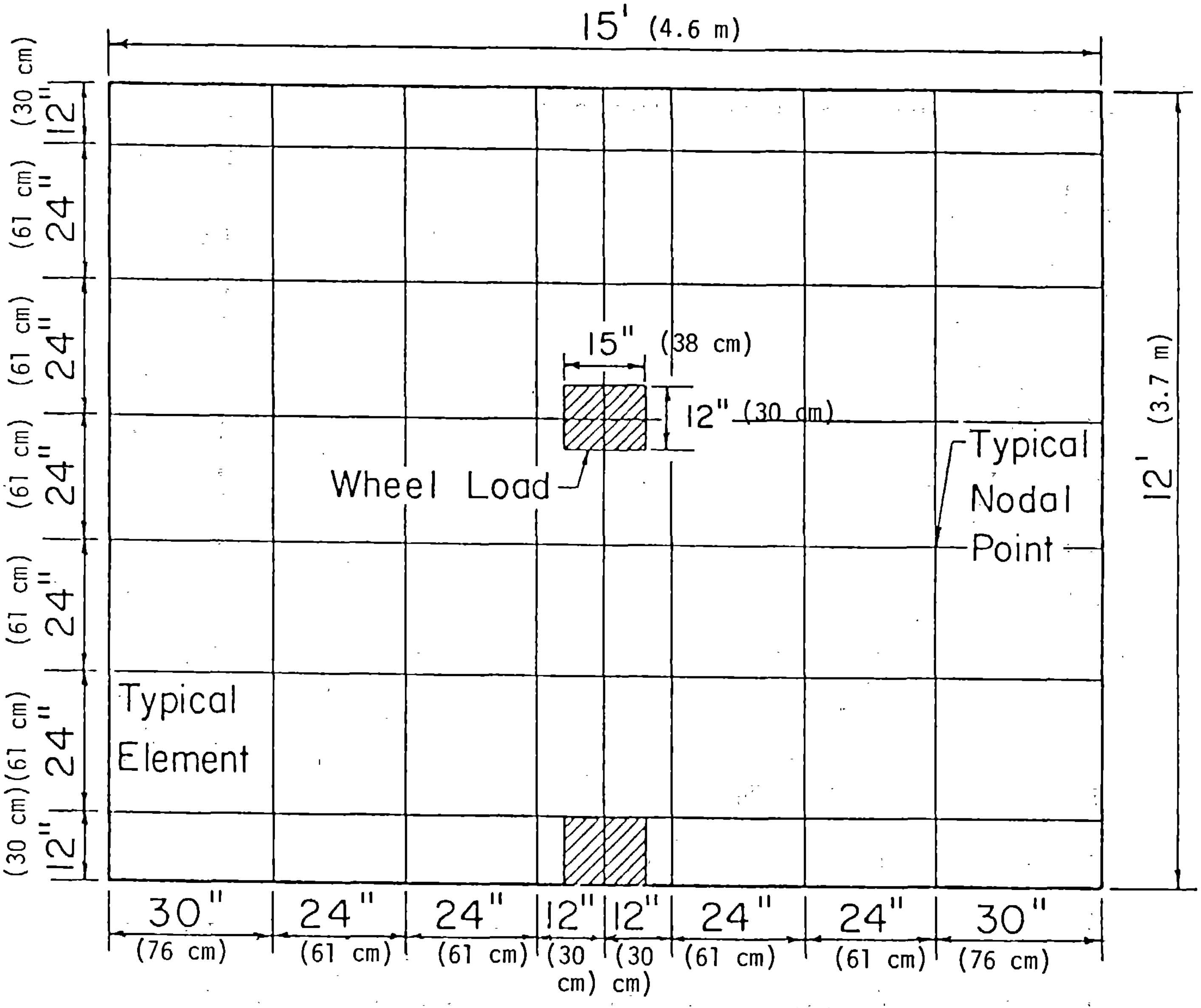


Figure 3.3. Finite Element Slab Layout for Single Axle Load.

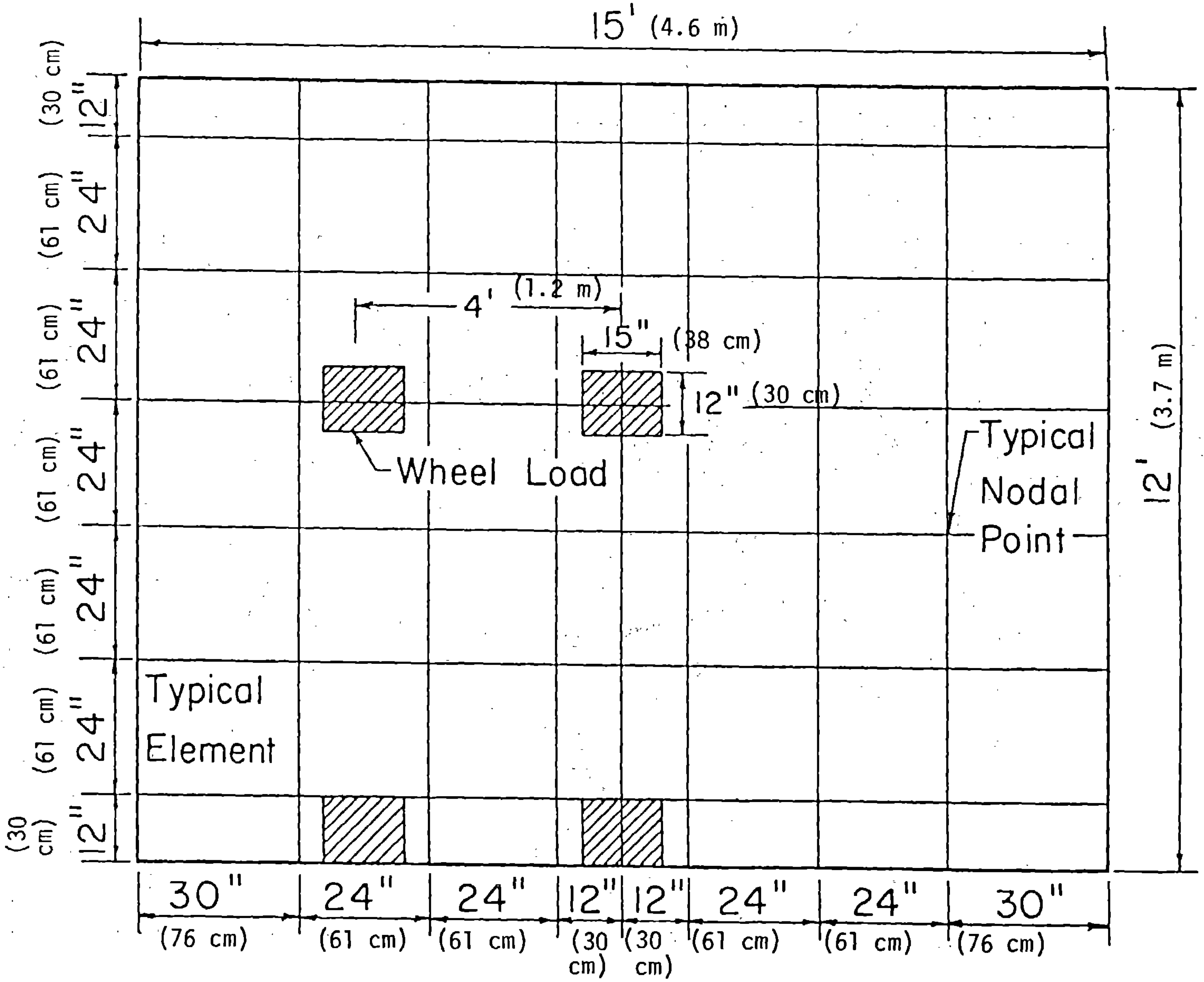


Figure 3.4. Finite Element Slab Layout for Tandem Axle Load.

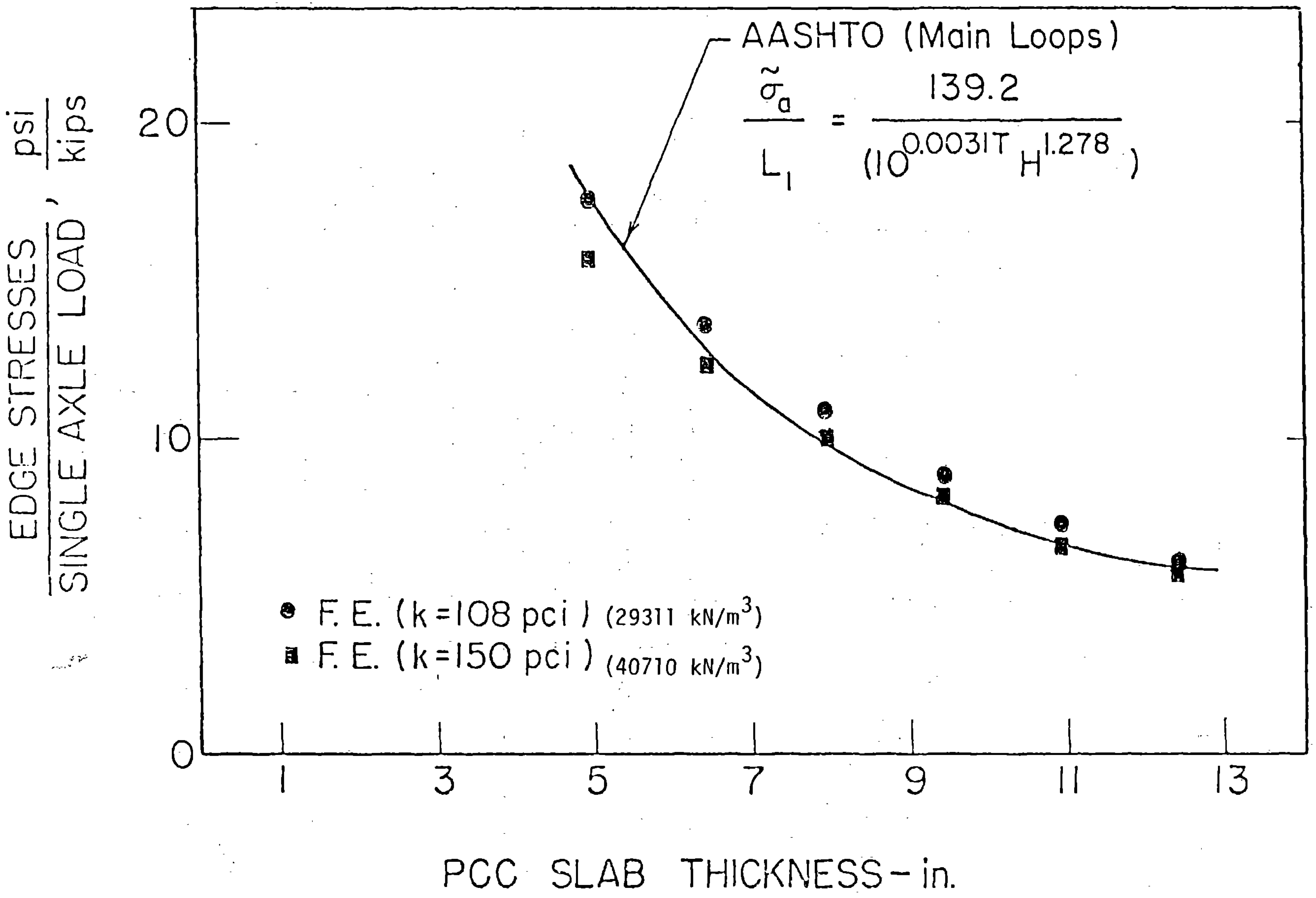


Figure 3.5. Comparison of Edge Stresses Computed with the Finite Element Program and those Measured at the AASHO Road Test for Single Axle Load (load placed 20 in. from edge of slab, but strain measured at edge).

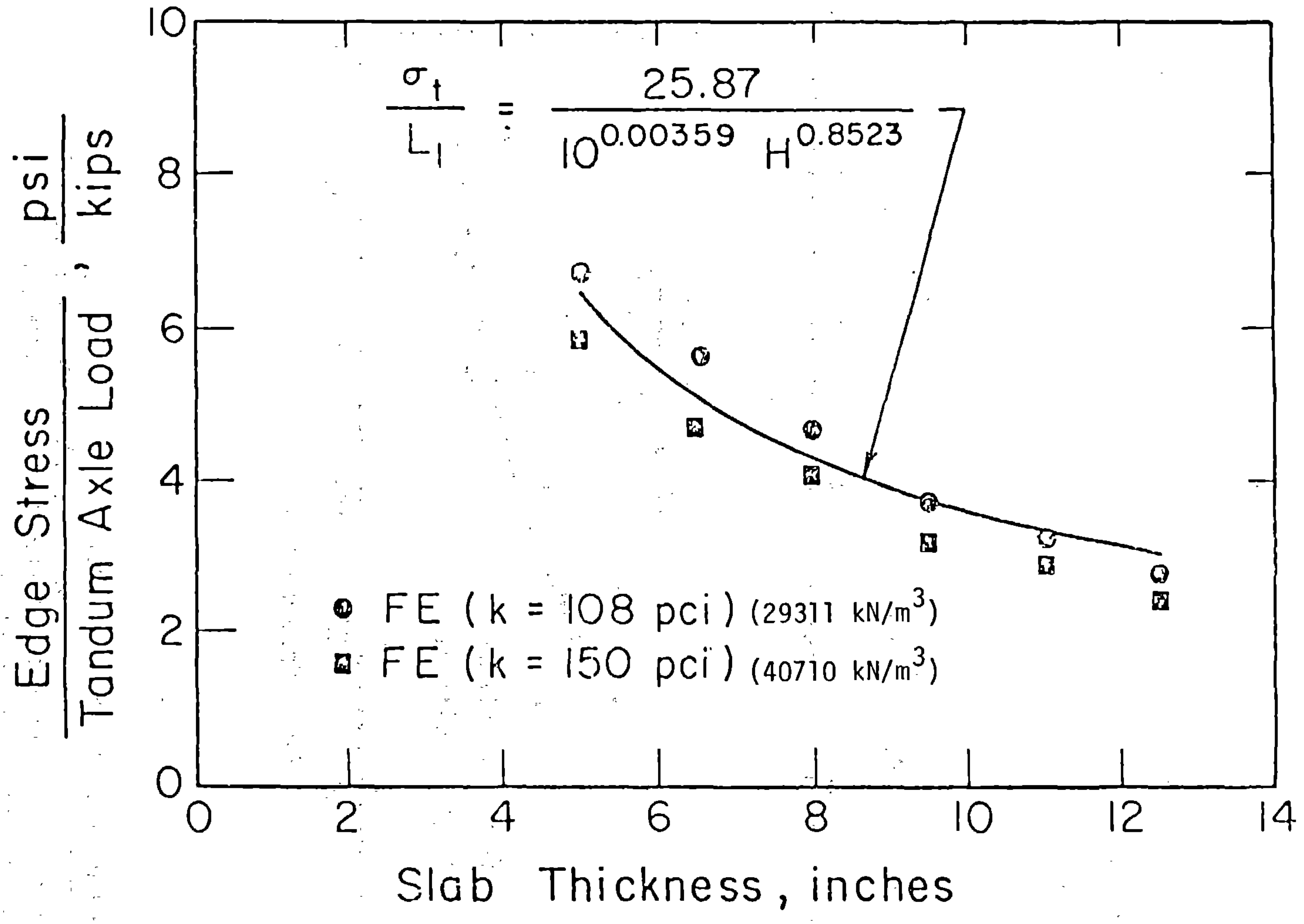


Figure 3.6. Comparison of Edge Stresses Computed with the Finite Element Program and those Measured at the AASHO Road Test for Tandem Axles (placed 20 in. [508 mm] from joint and strain measured at edge).

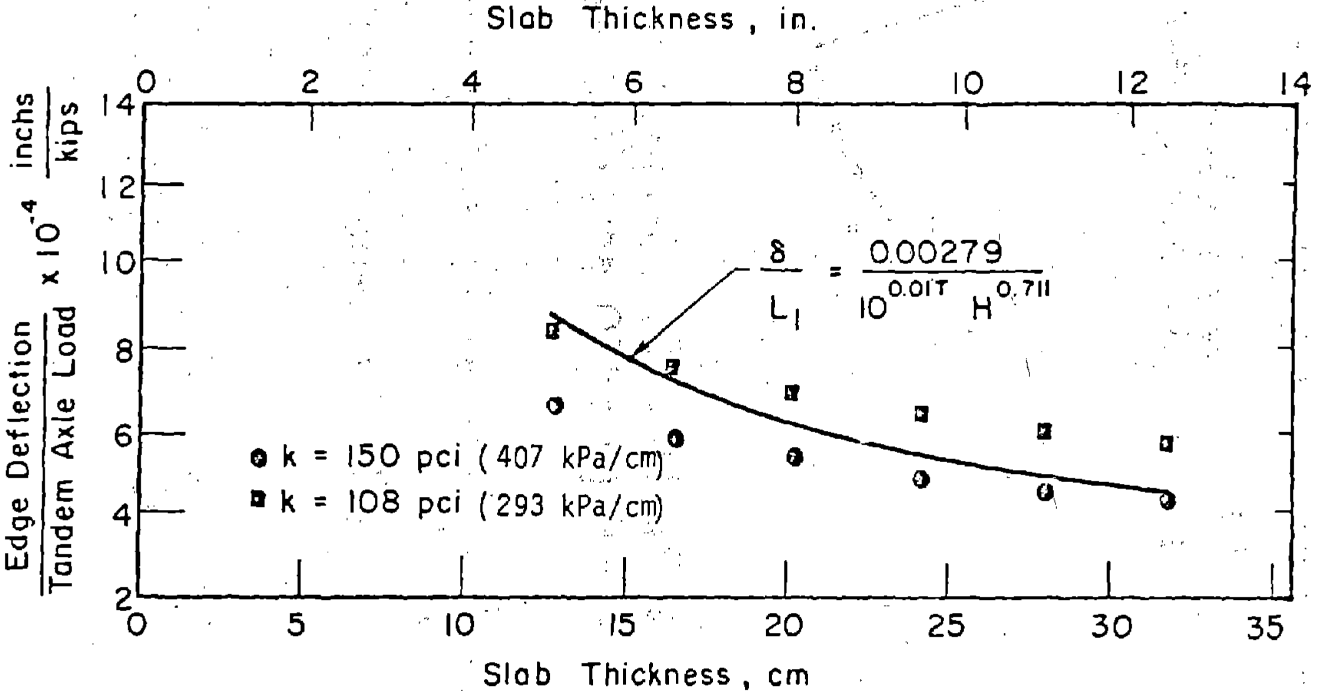


Figure 3.7. Comparison of Edge Deflections Computed with the Finite Element Program and Those Measured at the AASHO Road Test for Single Axles (Load placed 20 in. [508 mm] from joint and deflection measured at edge).

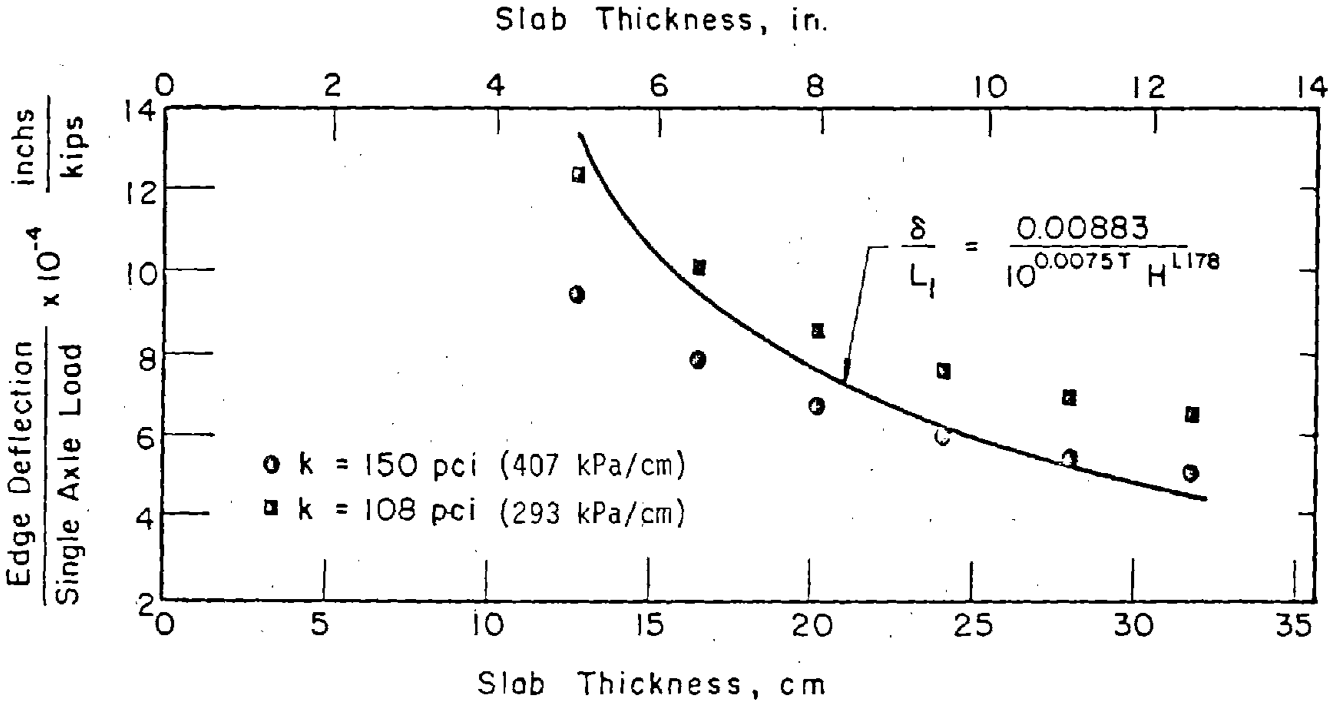


Figure 3.8. Comparison of Edge Deflections Computed with the Finite Element Program and Those Measured at the AASHO Road Test for Tandem Axles (Load placed 20 in. [508 mm] from joint and deflection measured at edge).

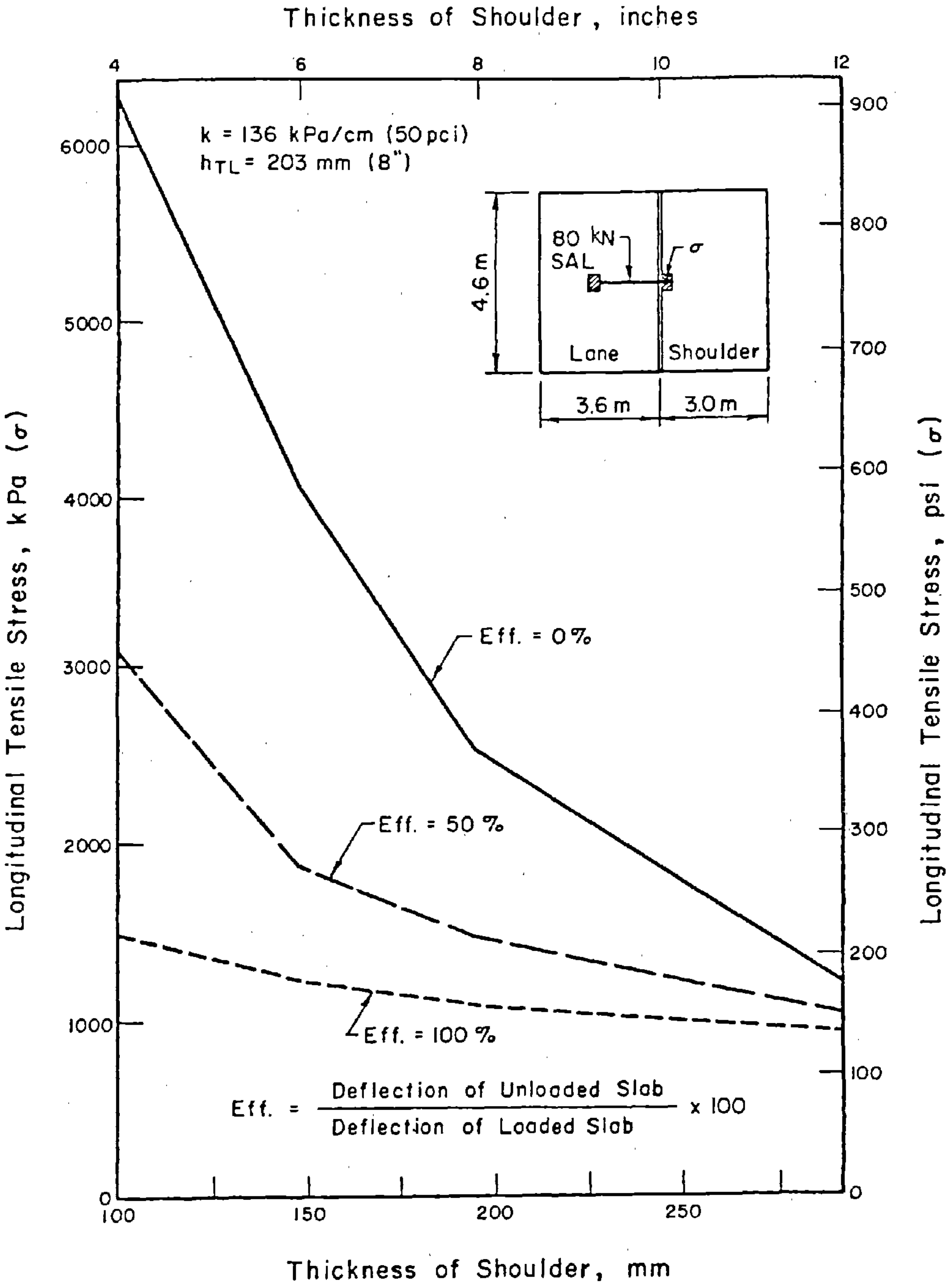


Figure 3.9. Effect of Shoulder Thickness and Lane/Shoulder Tie on Tensile Stresses at Bottom of PCC Shoulder.

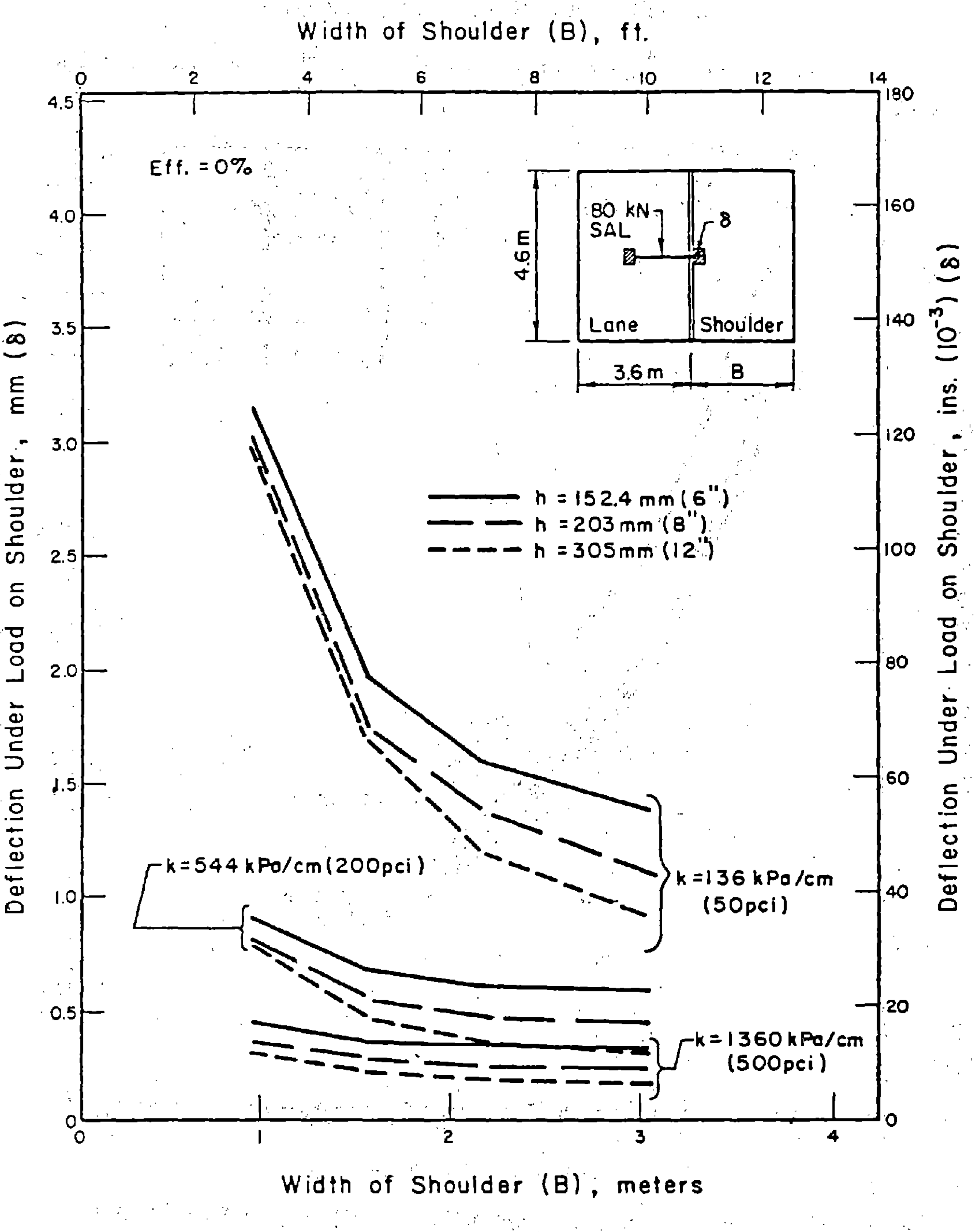


Figure 3.10. Effect of Encroachment of Truck Wheel Loads on Deflection of PCC Shoulder for Various Conditions of Support and Thickness.

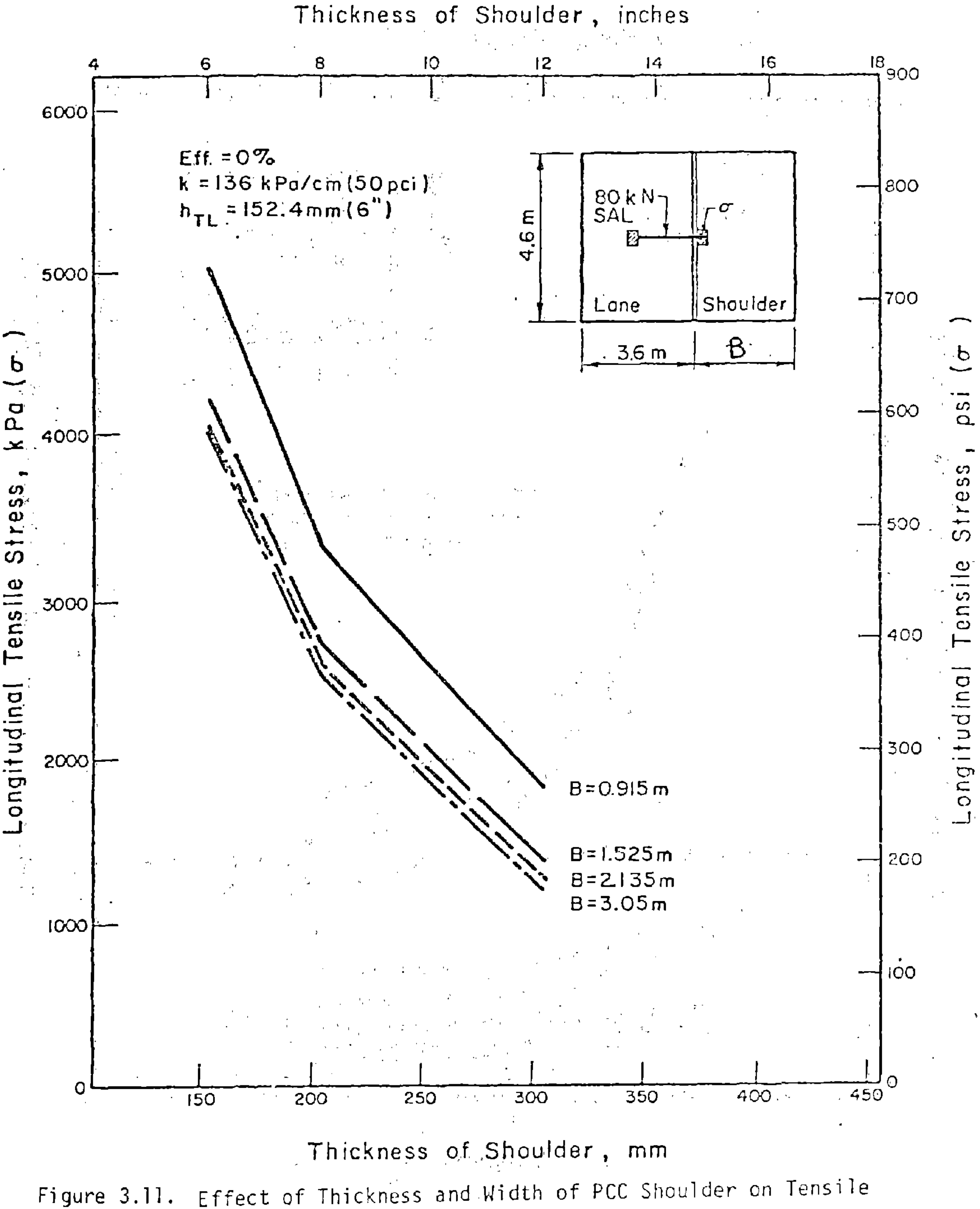
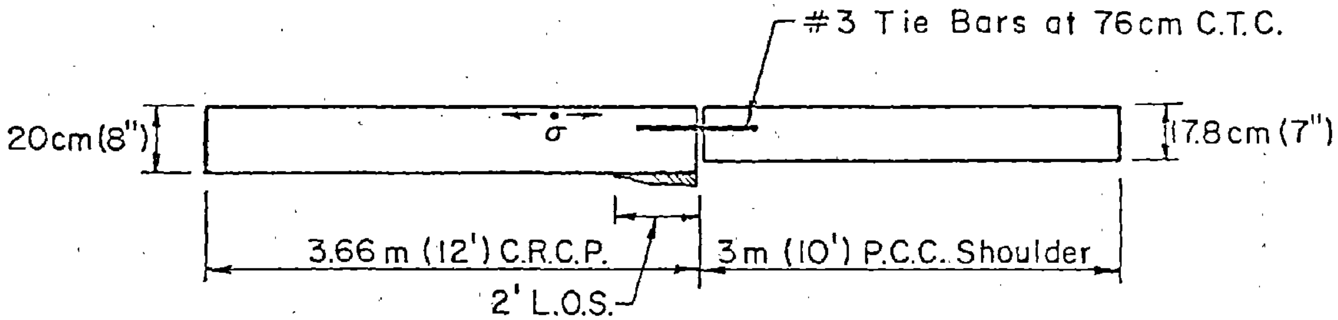
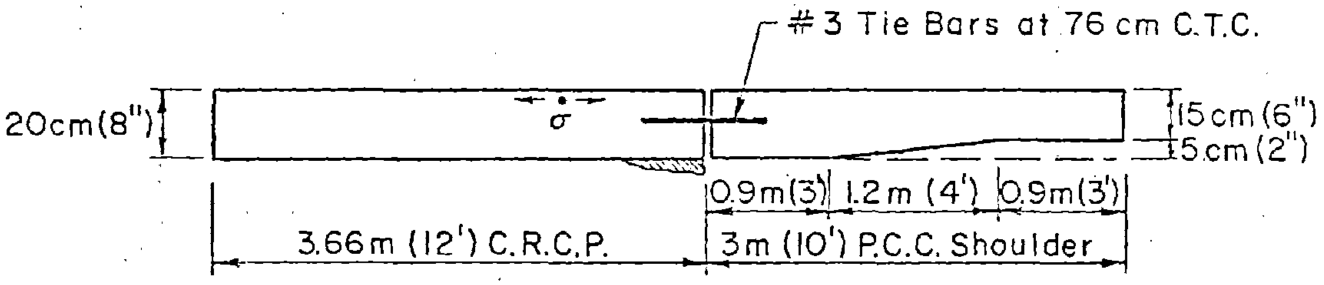


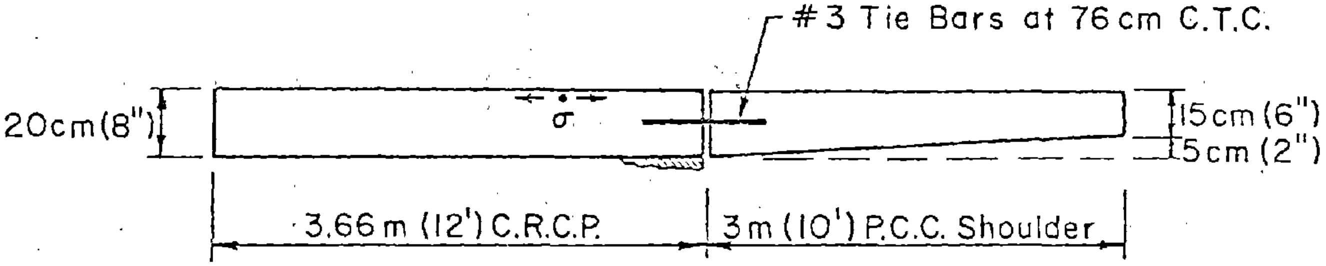
Figure 3.11. Effect of Thickness and Width of PCC Shoulder on Tensile Stresses at the Bottom of PCC Shoulder.



17.8 cm (7") Thick Shoulder



Stepwise Tapered Shoulder



Uniformly Tapered Shoulder

Section X-X

Figure 3.12. Alternative CRCP Traffic Lane/Shoulder Designs Used For Analysis.

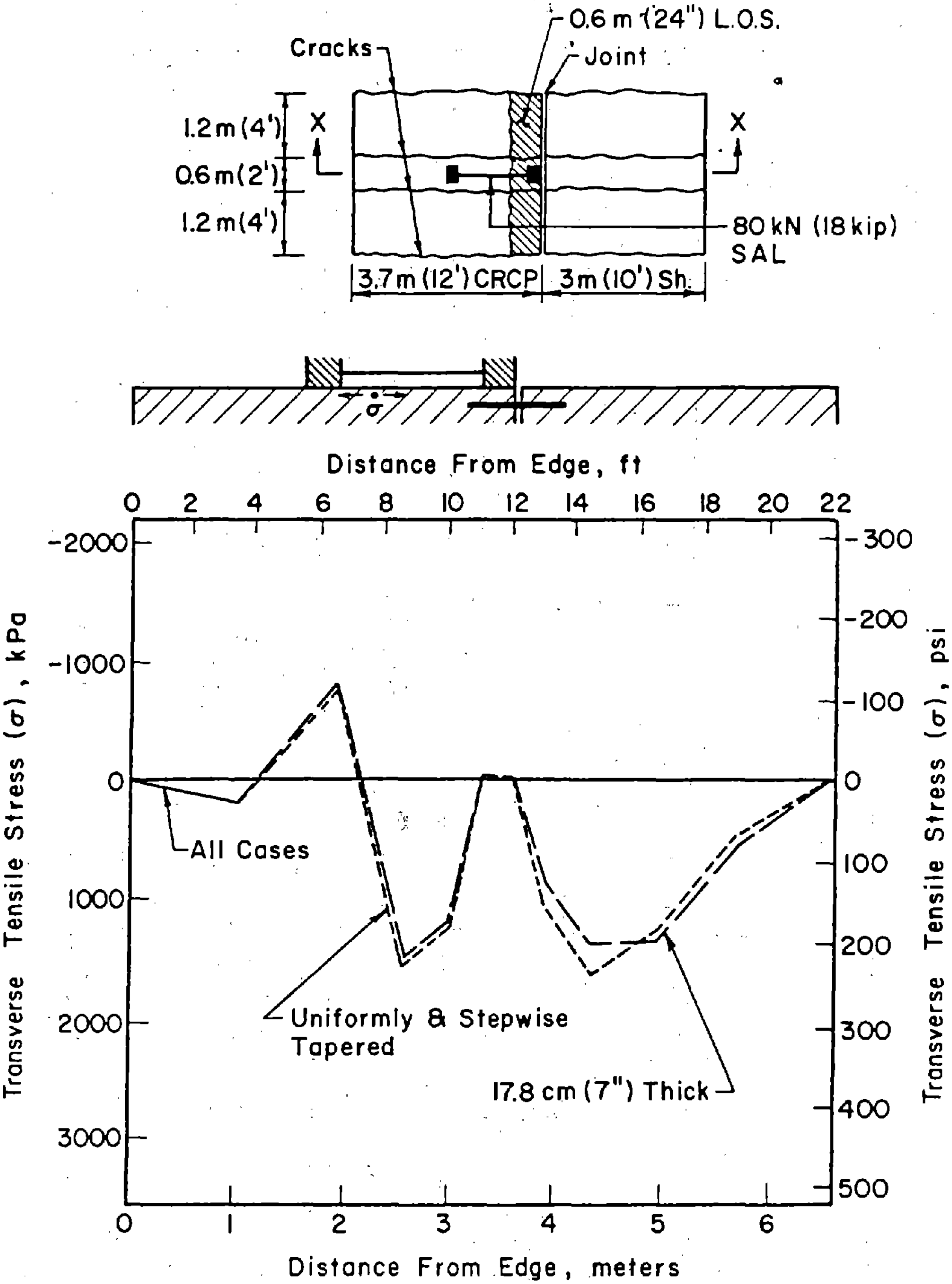


Figure 3.13. Tensile Stress at the Top of the PCC Slab and Deflections Along Section X-X Due to Mainline Traffic Loading.

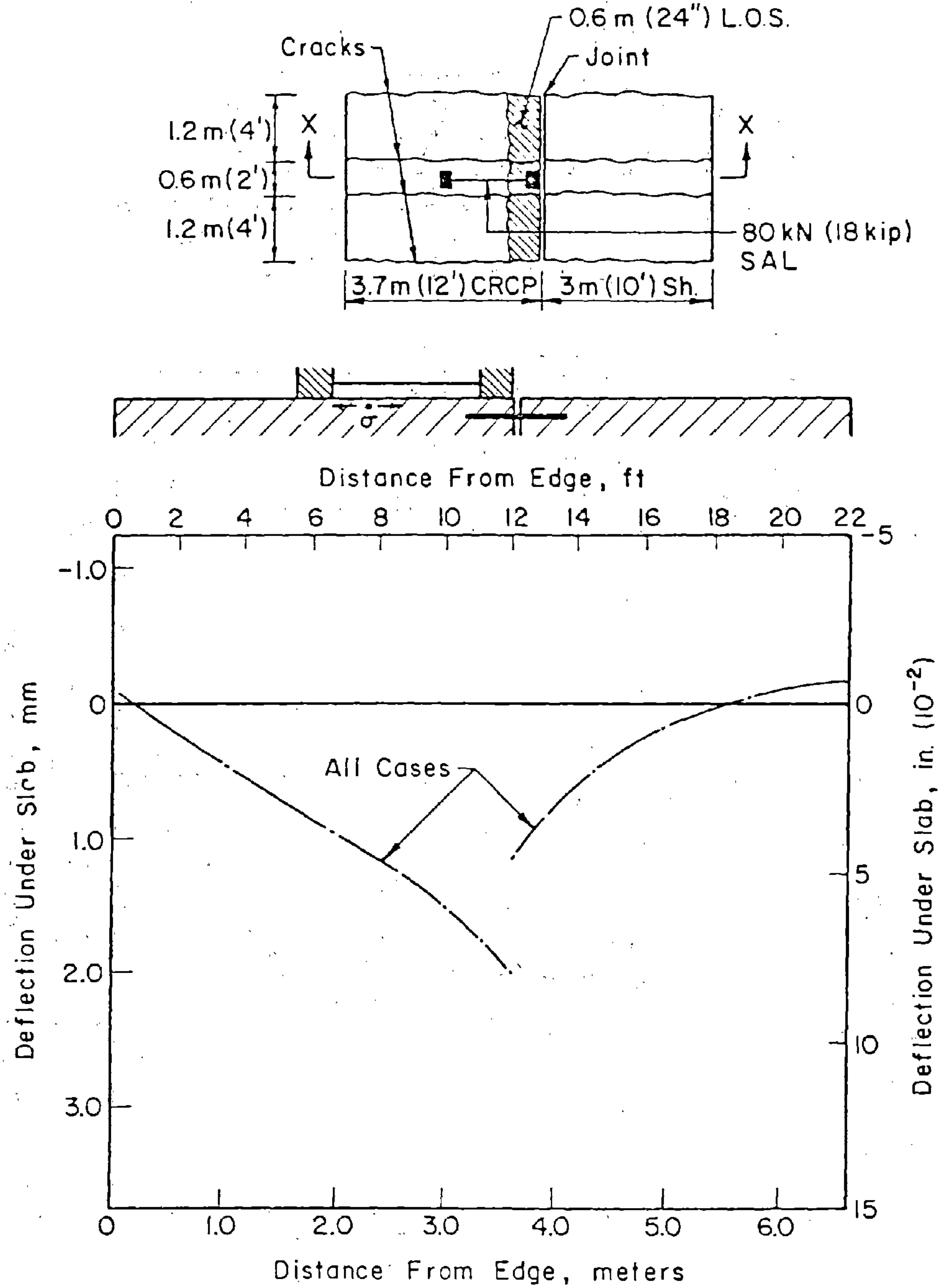


Figure 3.13. Continued.

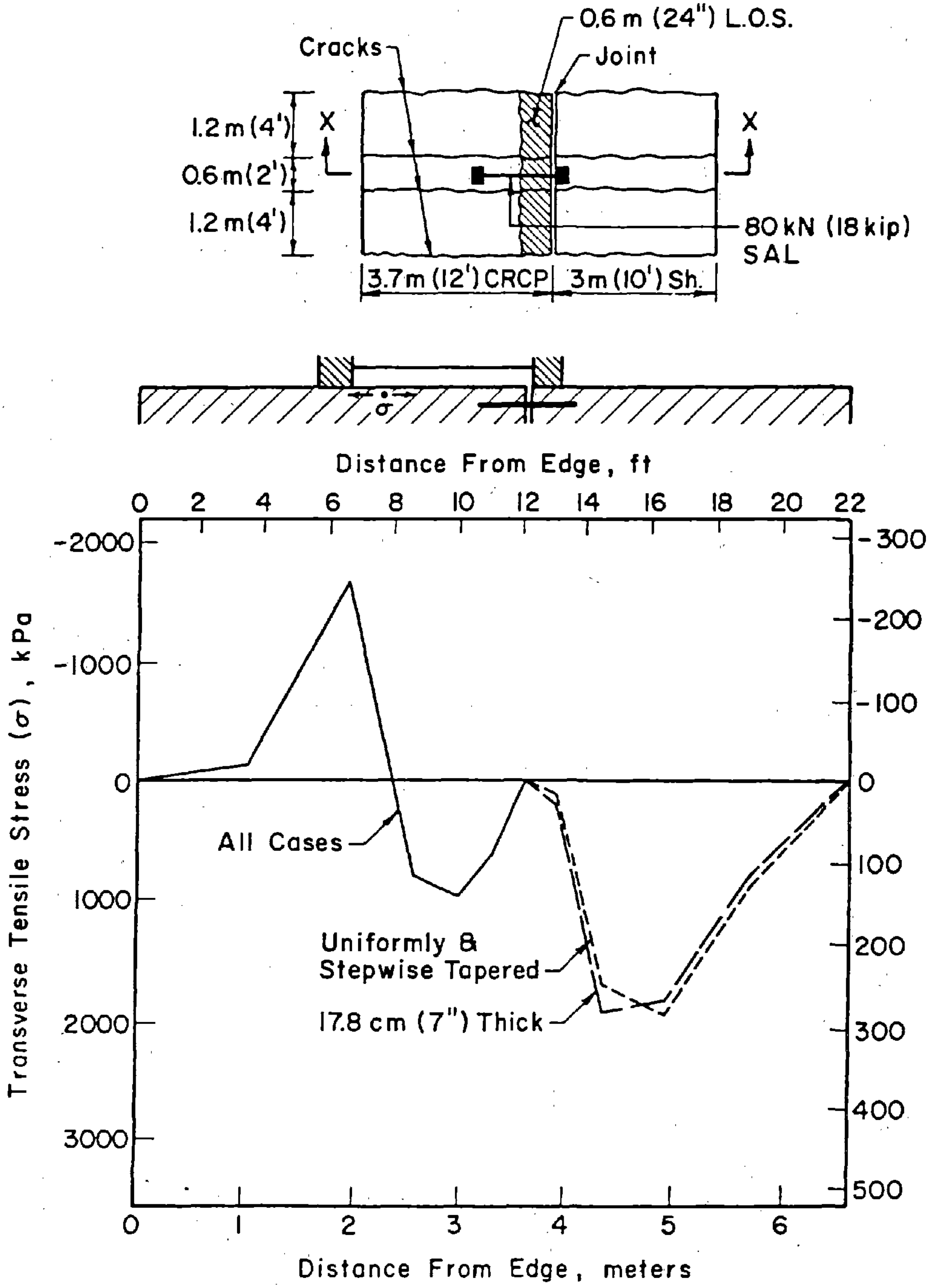


Figure 3.14. Tensile Stress at the Top of the PCC Slabs and Deflections Along Section X-X Due to Encroached Traffic Loading.

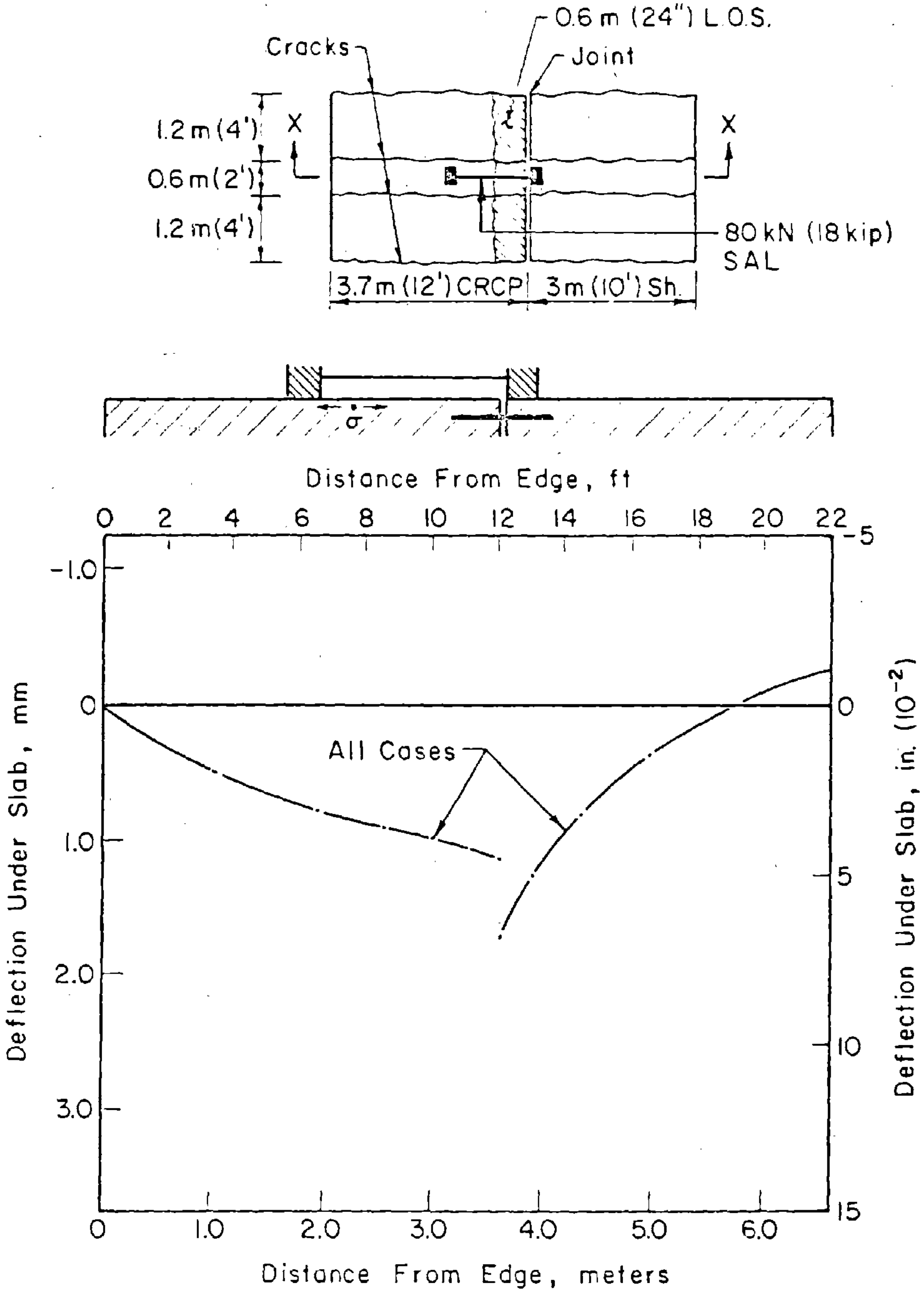


Figure 3.14. Continued.

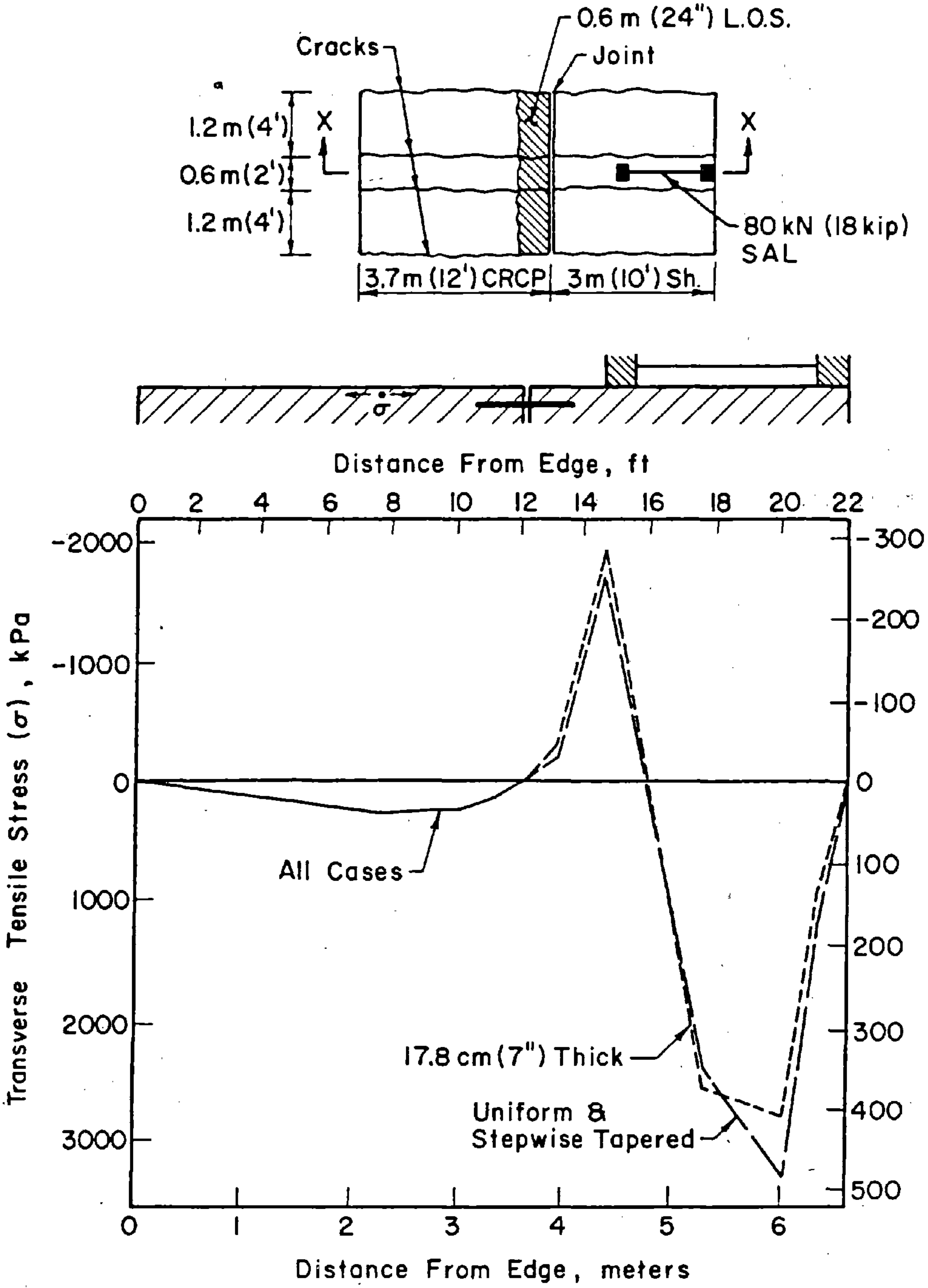


Figure 3.15. Tensile Stress at the Top of the PCC Slabs and Deflections Along Section X-X Due to Parked Traffic Loading (6 to 8 in. tapering).

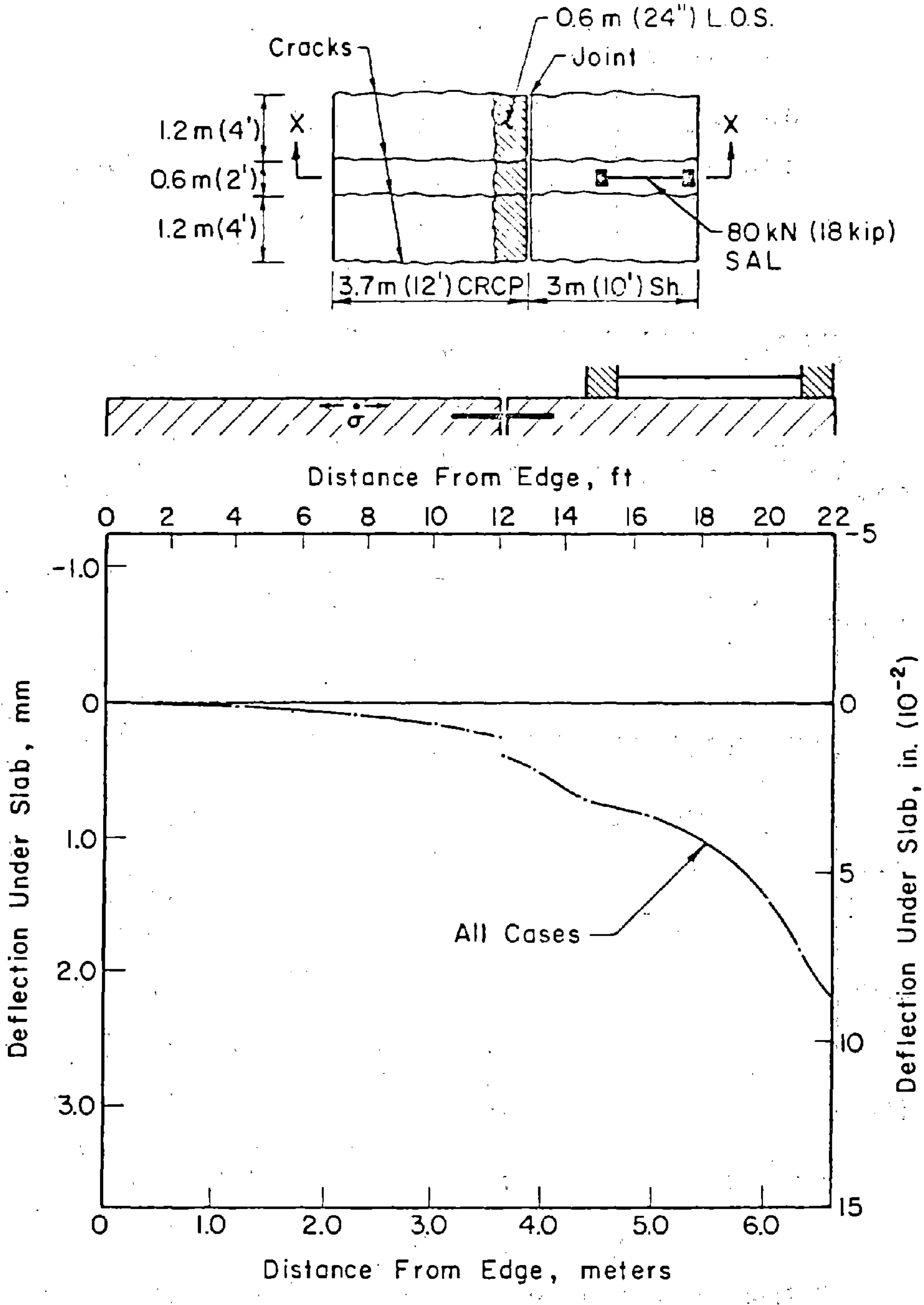
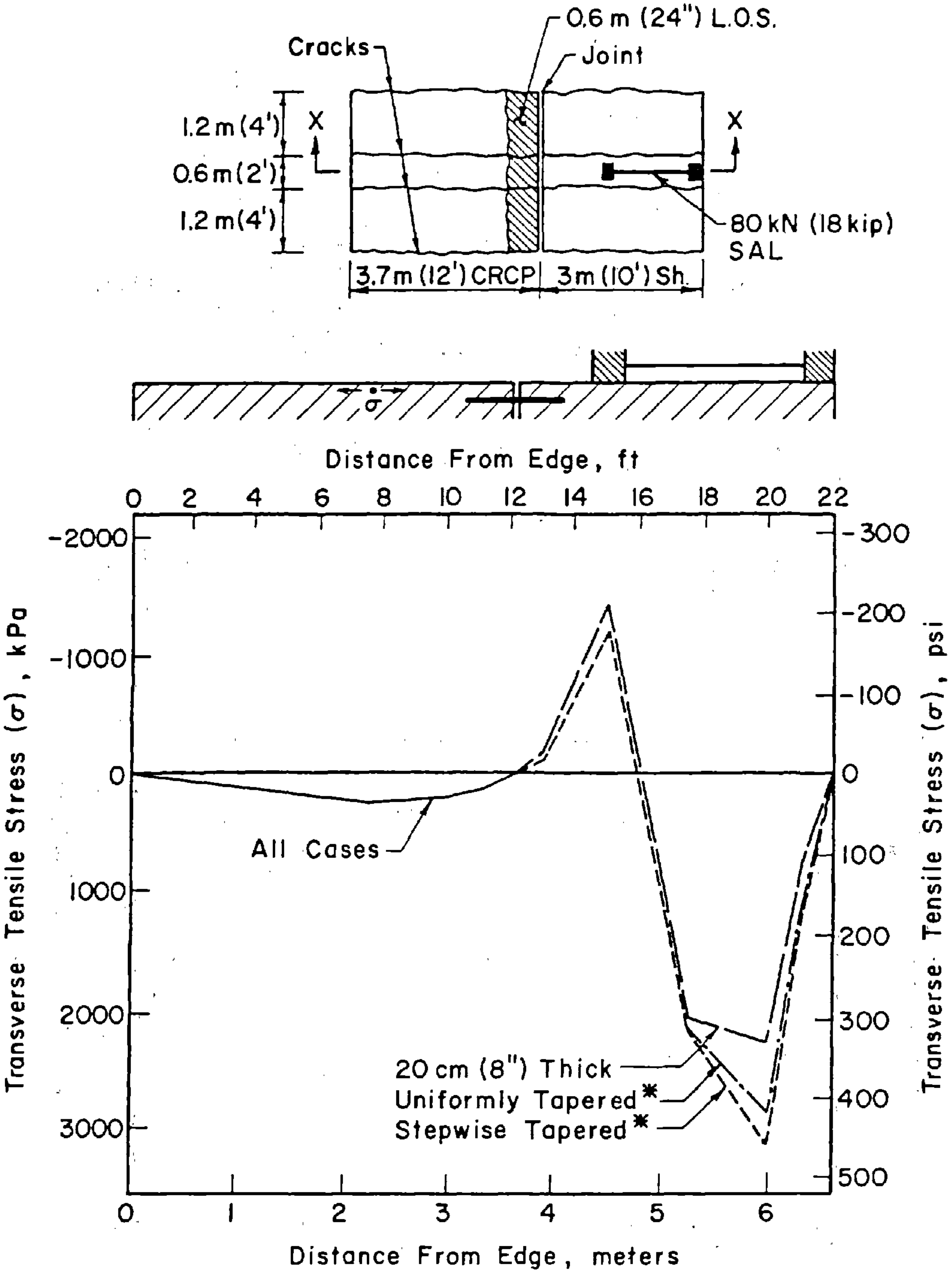
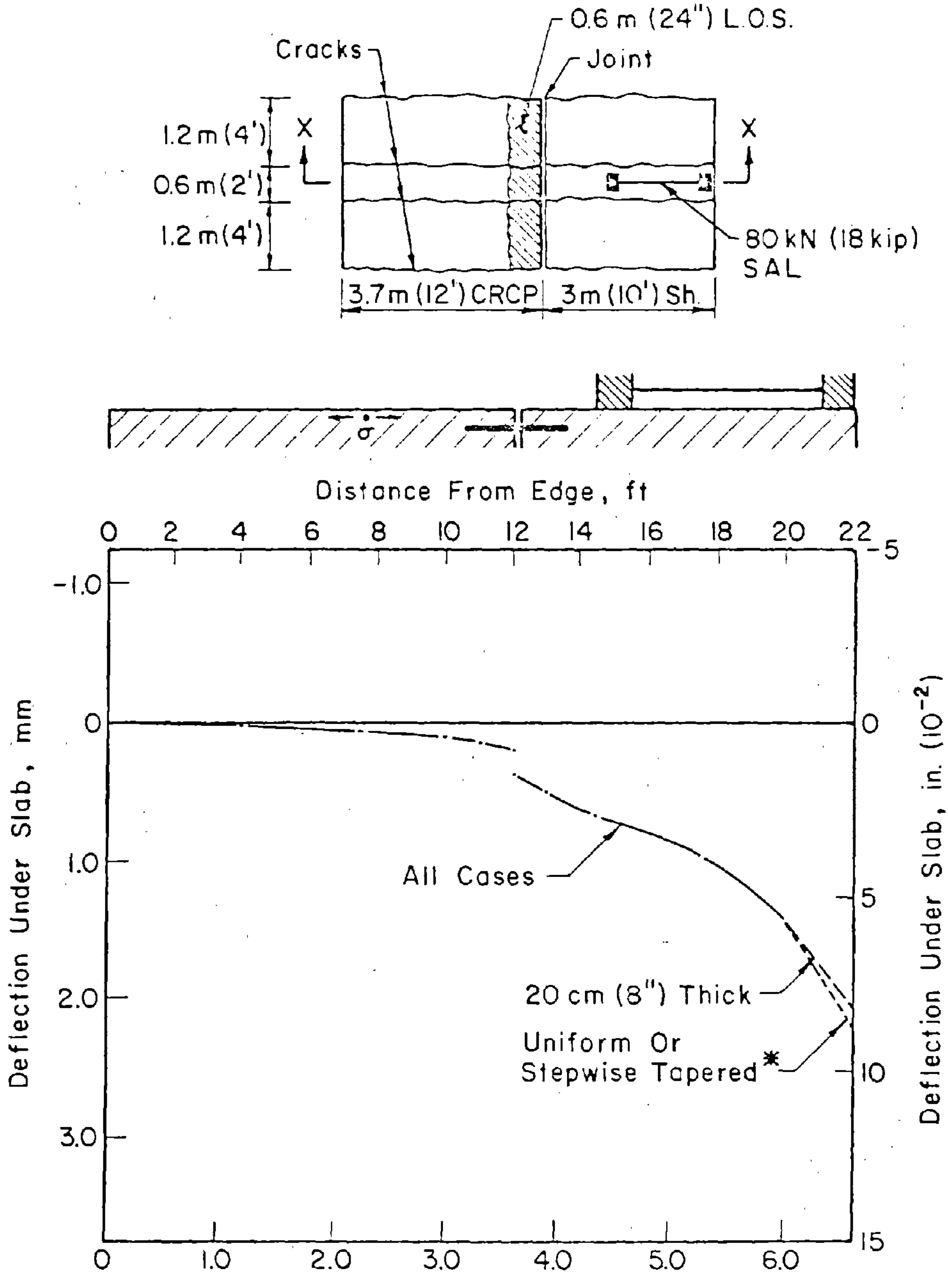


Figure 3.15. Continued.



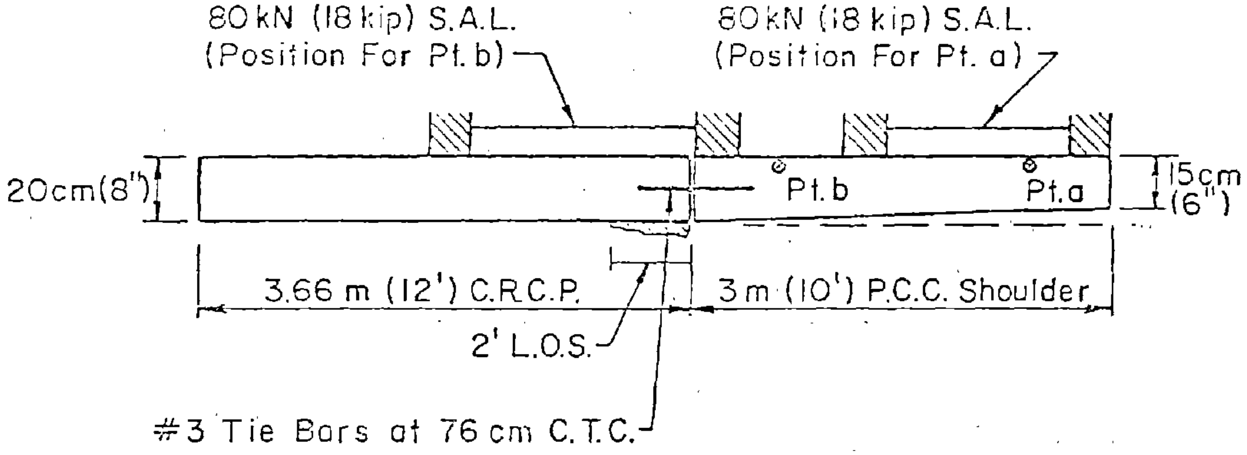
* Tapering Is 15 cm (6") At The Free Edge To 25 cm (10") At The Joint

Figure 3.16. Tensile Stress at the Top of the PCC Slabs and Deflections Along Section X-X Due to Parked Traffic Loading (6 to 10 in. tapering).

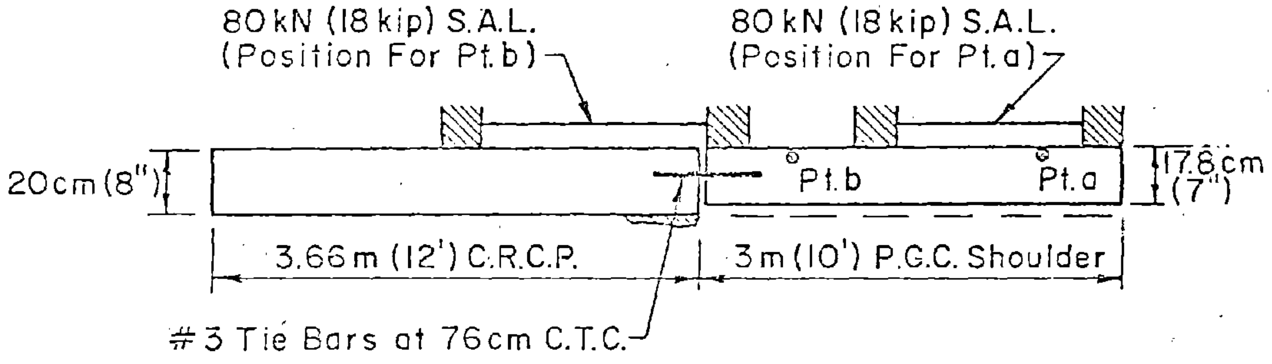


* Tapering Is 15 cm (6") At The Free Edge To 25 cm (10") At The Joint

Figure 3.16. Continued.



Position	Stress σ (psi)	N*(No. of Reps. (Until Failure)
Point a	485	2.95×10^3
Point b	250	6.87×10^9



Position	Stress σ (psi)	N*(No. of Reps (Until Failure)
Point a	410	3.18×10^5
Point b	282	9.33×10^8

* $\text{Log } N = 16.61 - 17.61 \frac{\sigma}{F_{28}}$; $F_{28} = 650$ psi

Figure 3.17. Allowable Load Applications Until Failure for the Different PCC Shoulder Designs Discussed in Figures 3.14 and 3.15.

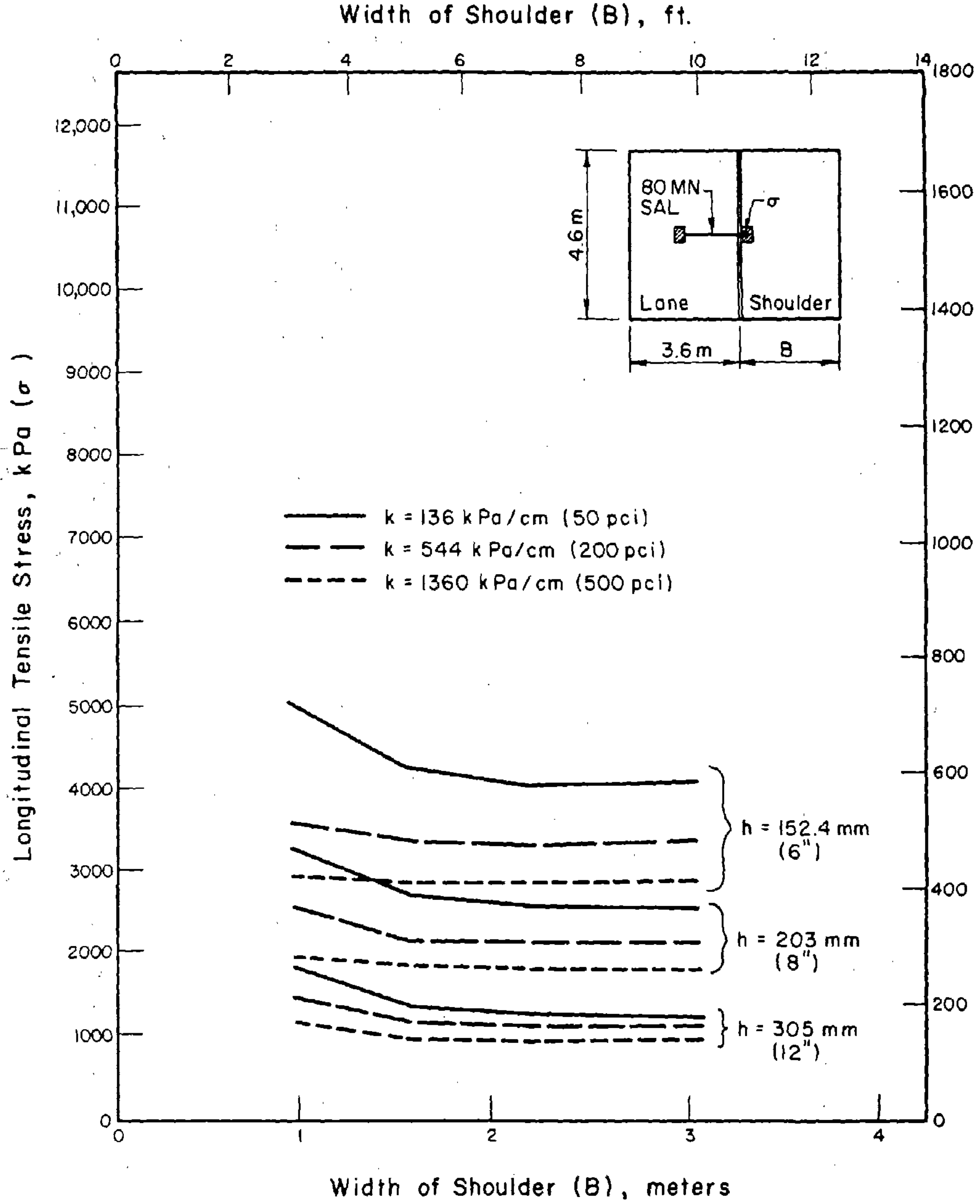


Figure 3.18. Effect of Encroachment of Truck Wheel Load on Tensile Stresses at Bottom of PCC Shoulder for Various Conditions of Support and Thickness.

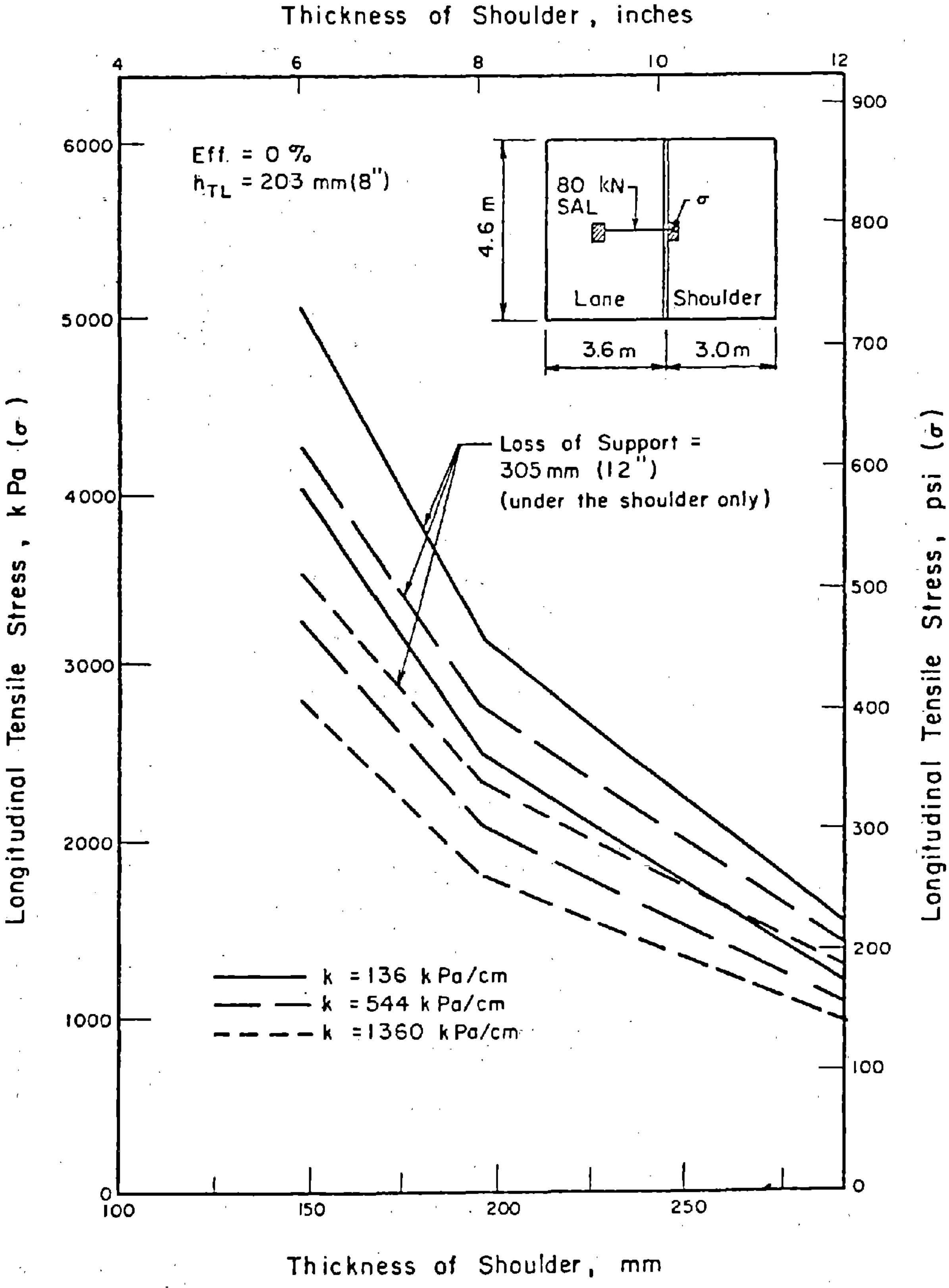


Figure 3.19. Effect of Loss of Support on Tensile Stresses at the Bottom of PCC Shoulder.

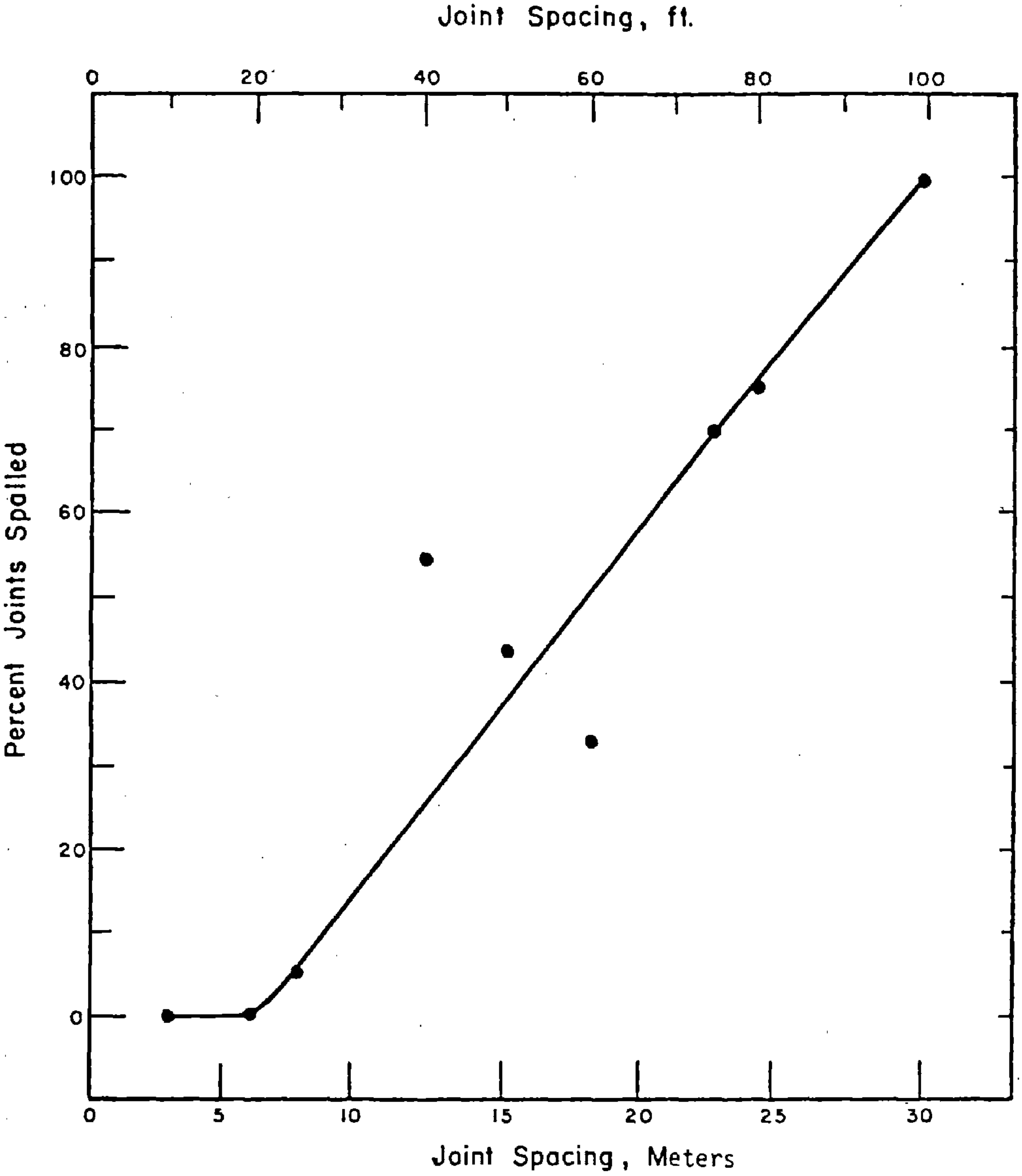


Figure 3.20. Effect of Joint Spacing of PCC Shoulder on Joint Spalling (Data from 10 year old Illinois Projects).

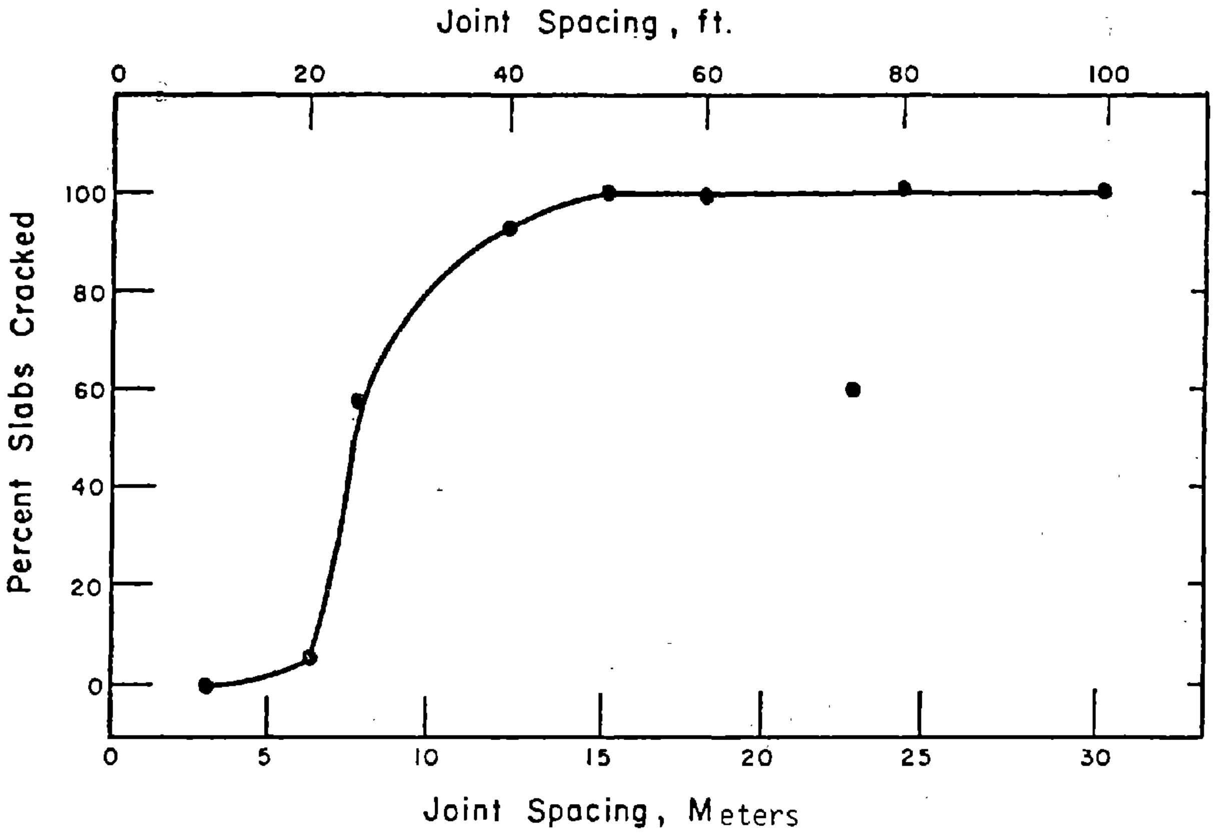


Figure 3.21. Effect of Joint Spacing of PCC Shoulder on Transverse Cracking (Data from 10 year old Illinois Projects).

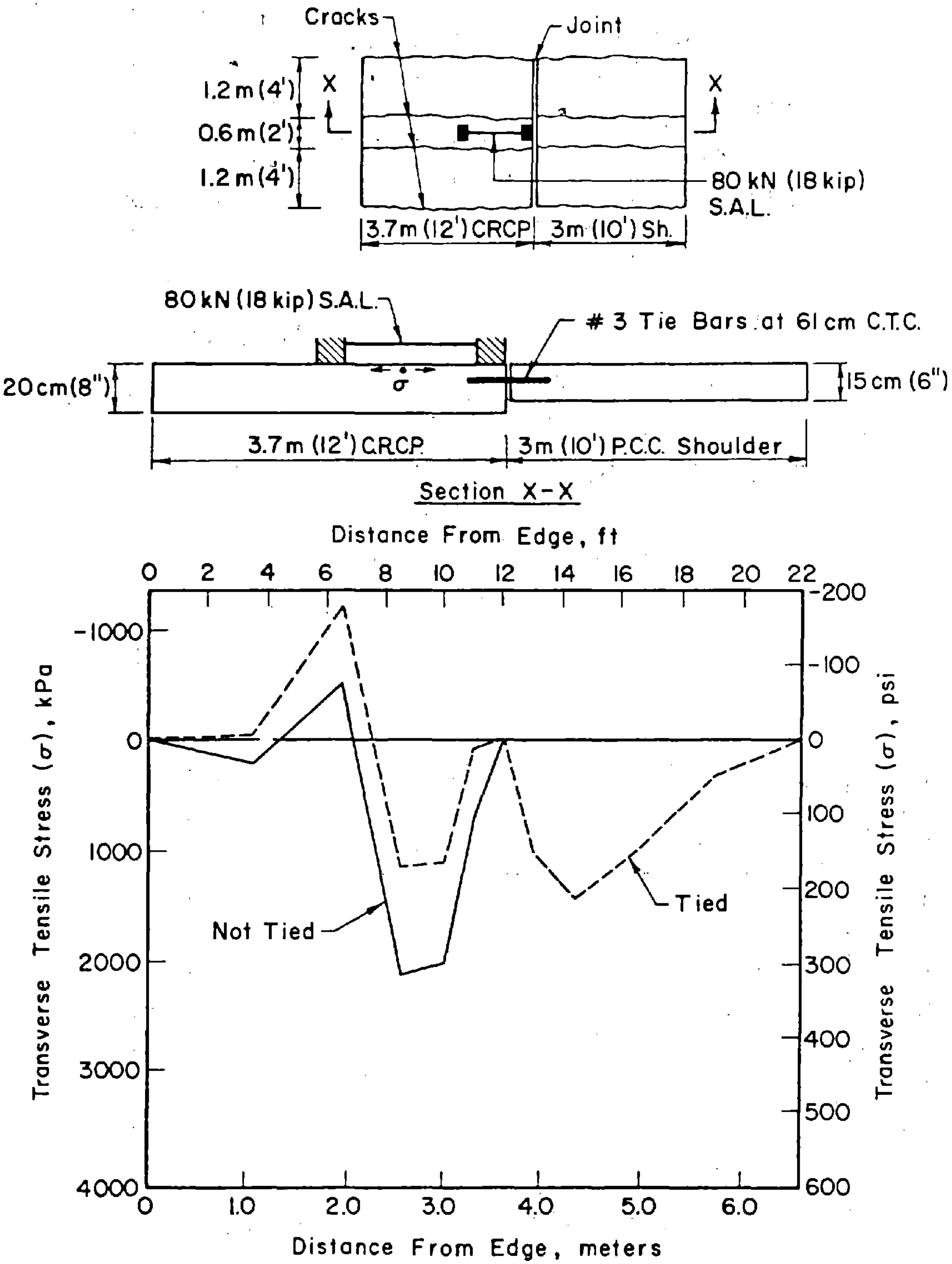


Figure 3.22. Tensile Stresses at the Top of the Slab and Deflections Along Section X-X (no loss of support).

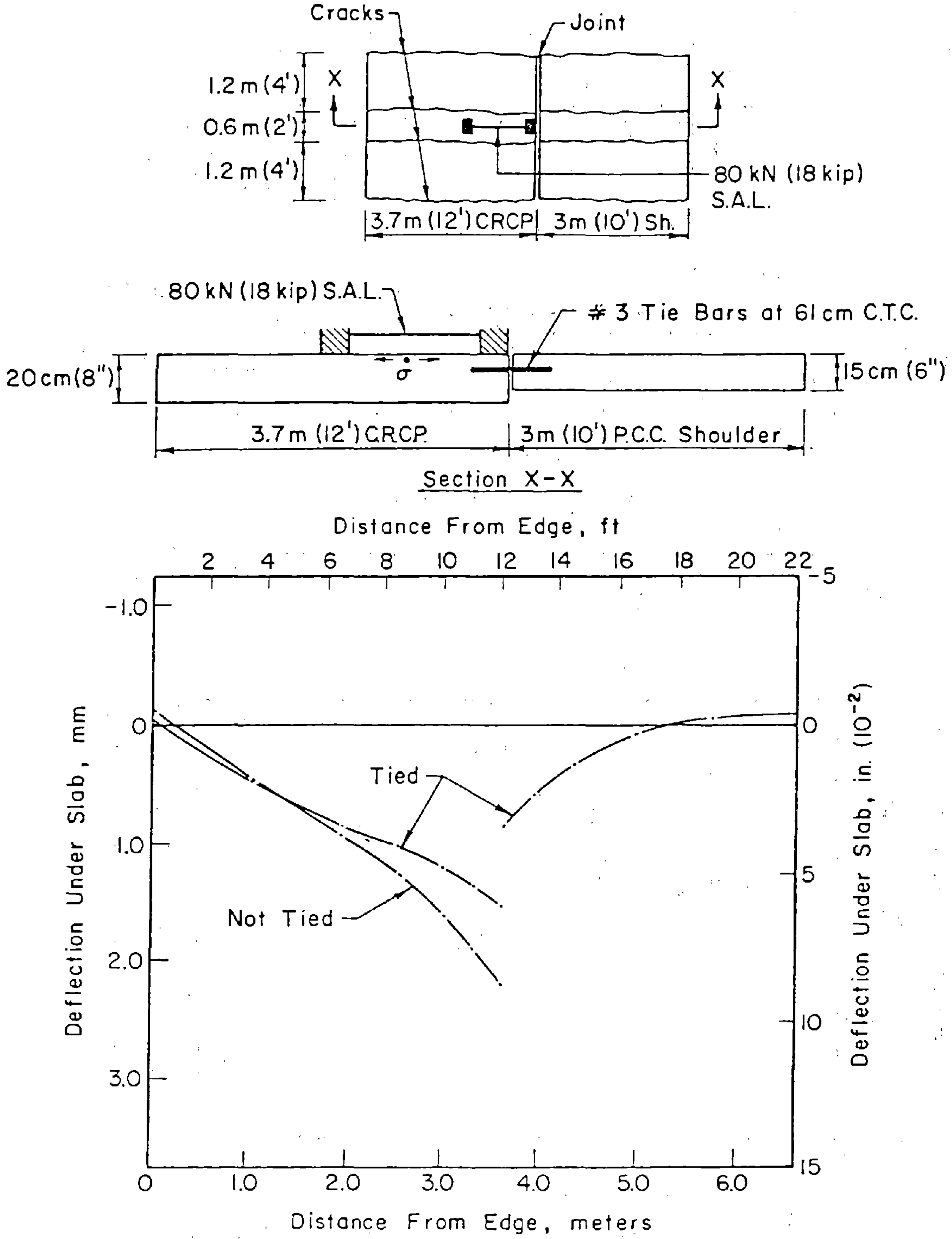


Figure 3.22. Continued.

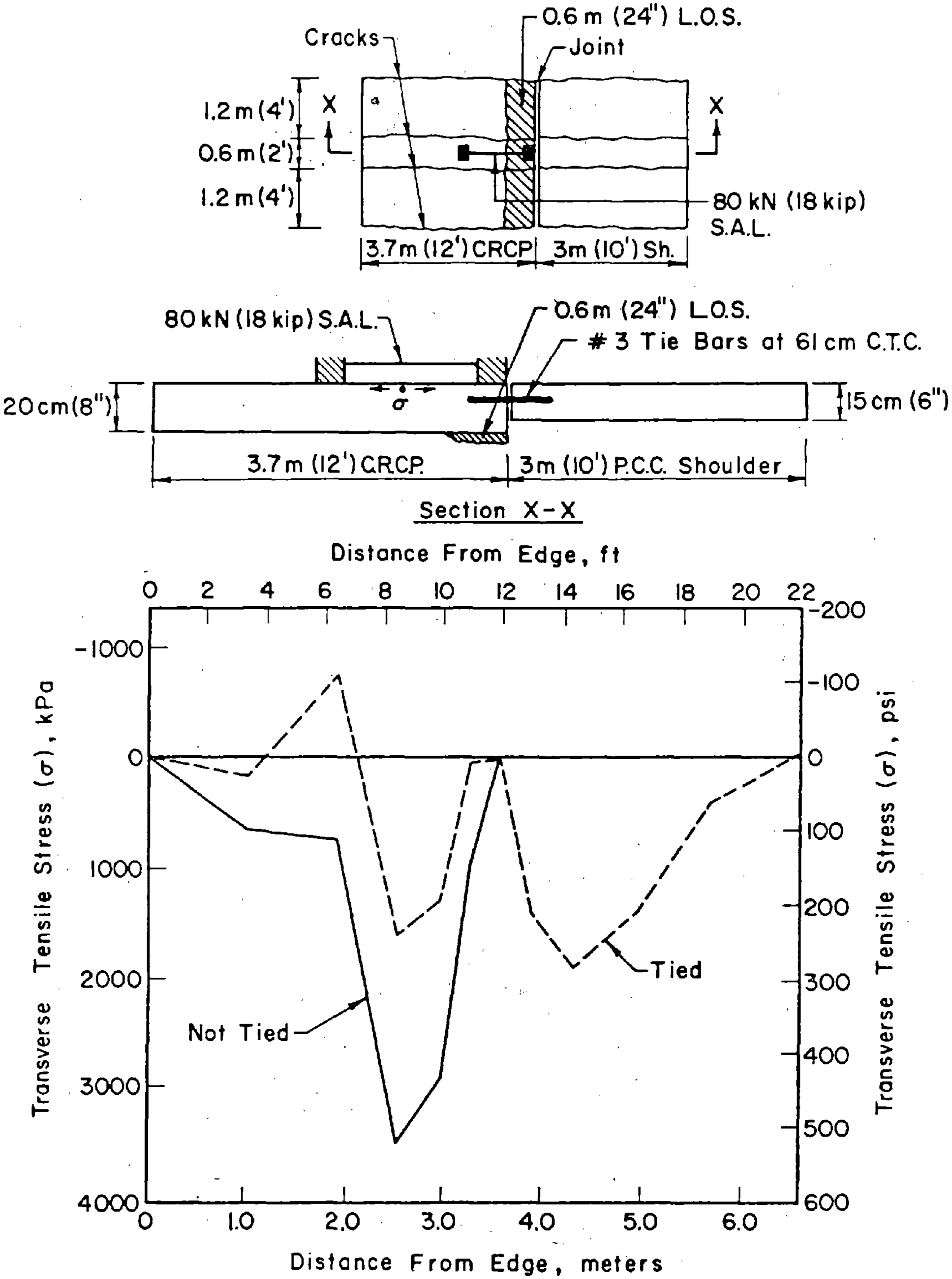


Figure 3.23. Tensile Stress at the Top of the Slab and Deflection Along Section X-X (2 feet loss of support).

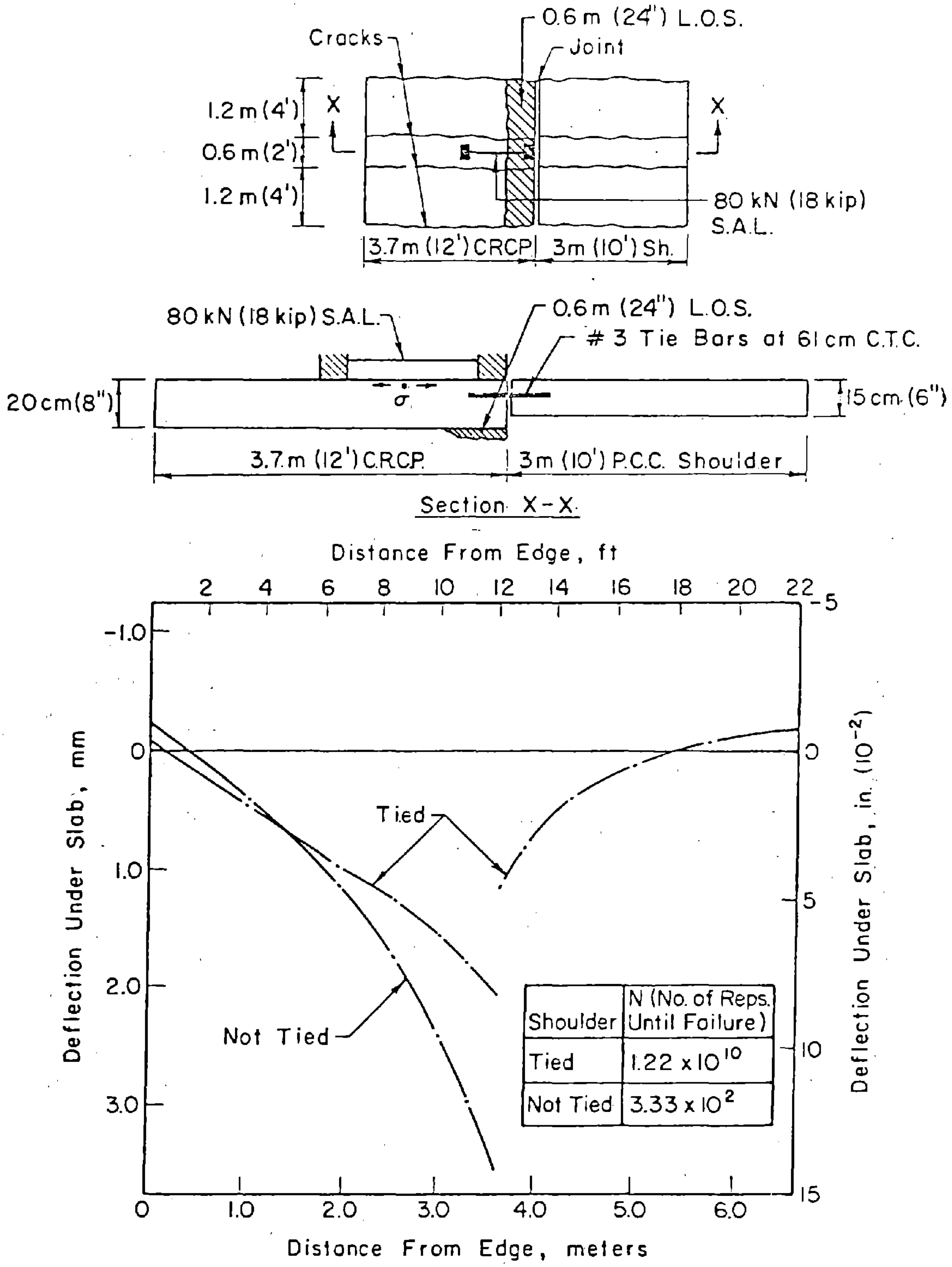


Figure 3.23. Continued.

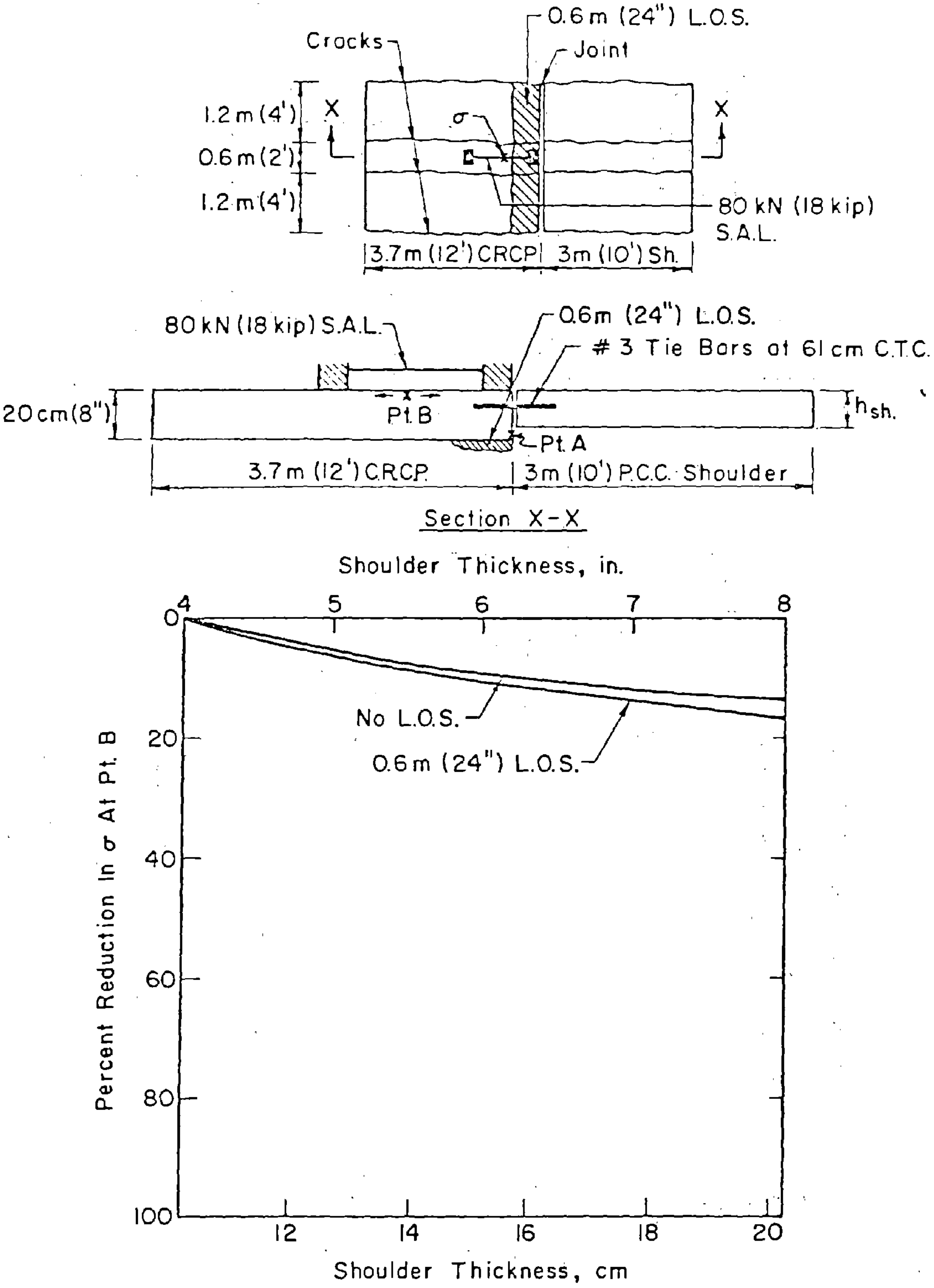
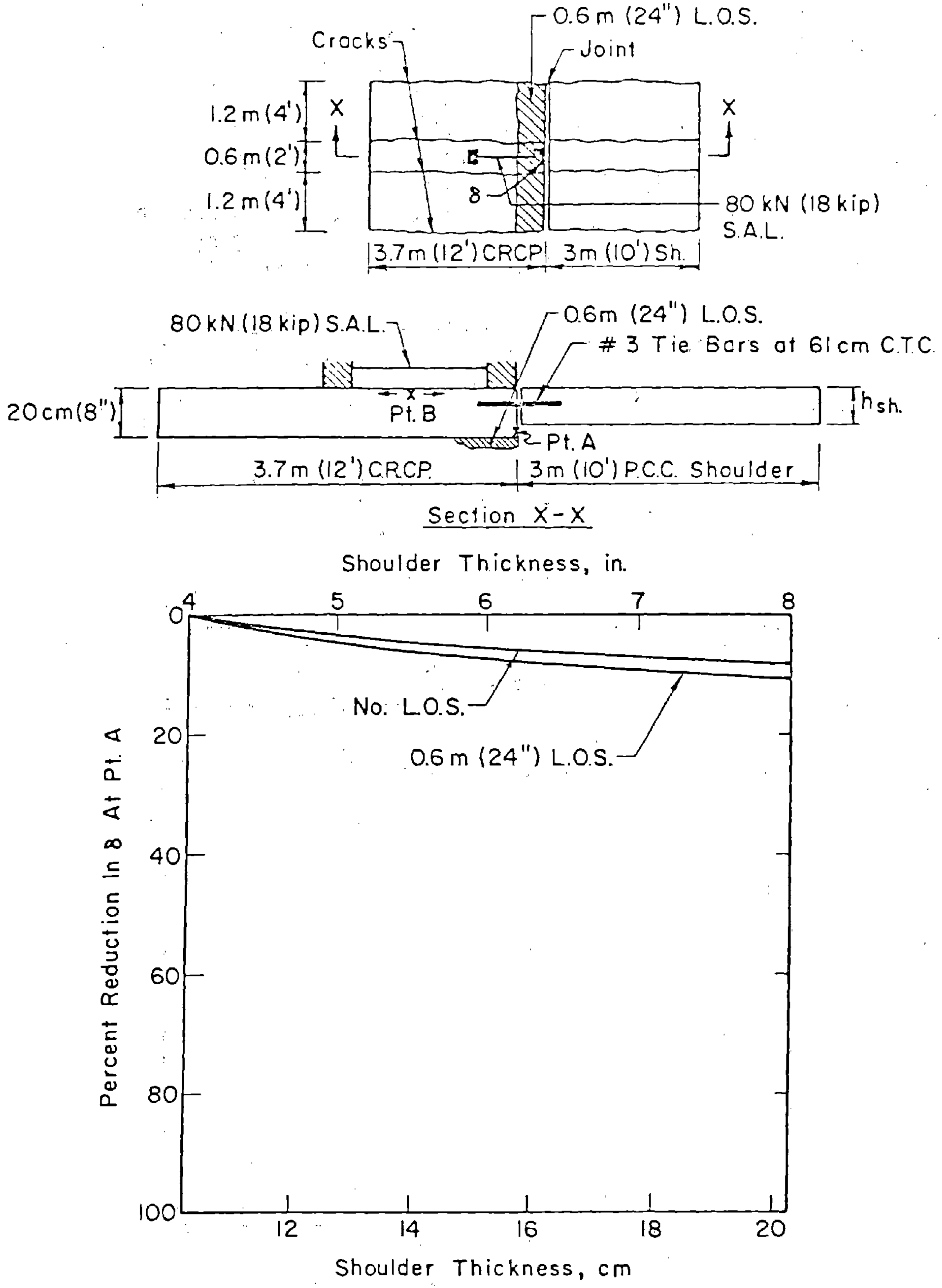


Figure 3.24. Effect of PCC Shoulder Thickness on Tensile Stress and Deflections at Points B and A, Respectively.



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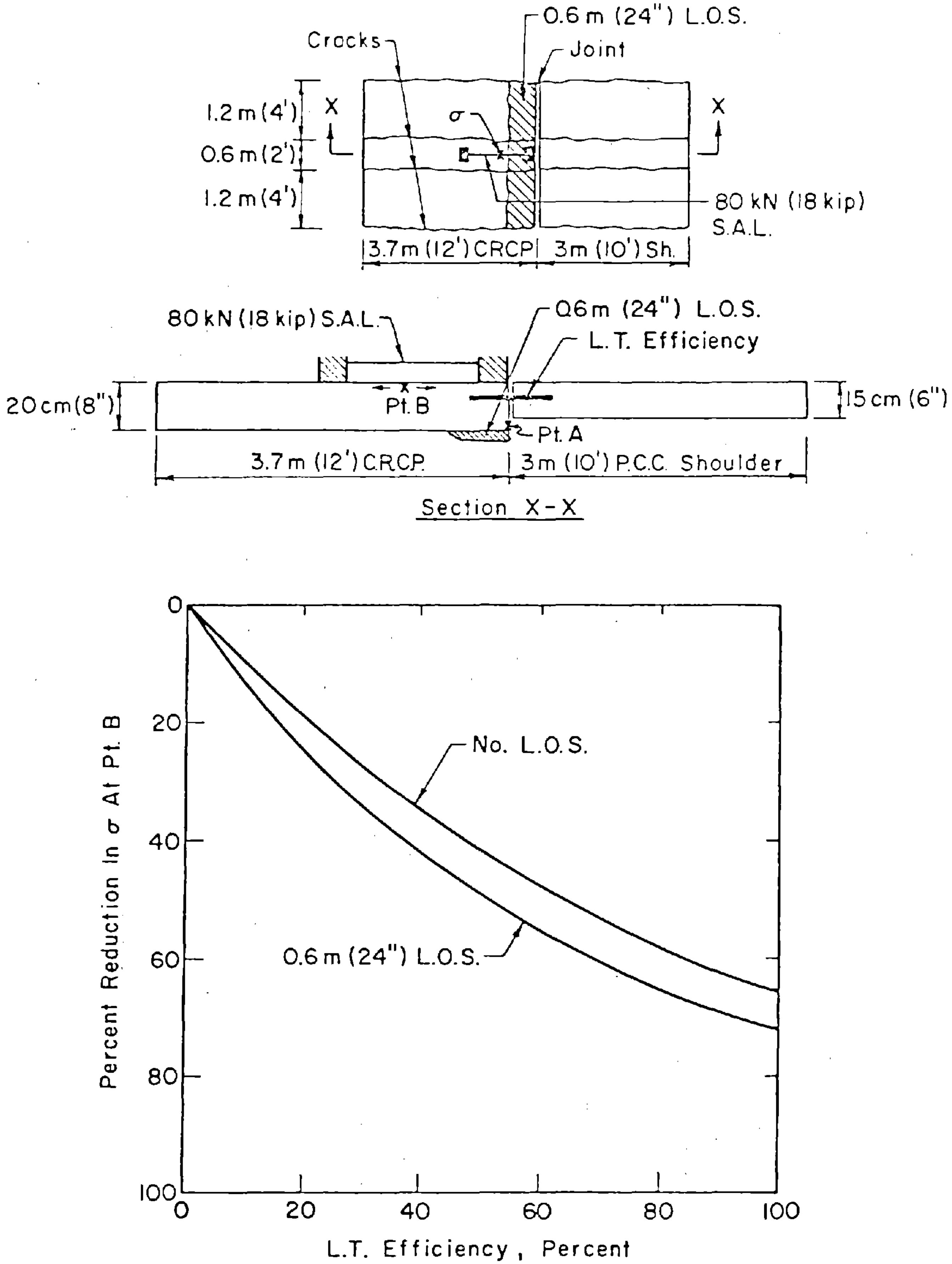


Figure 3.25. Effect of Load Transfer Efficiency on Tensile Stress and Deflections at Points B and A, Respectively.

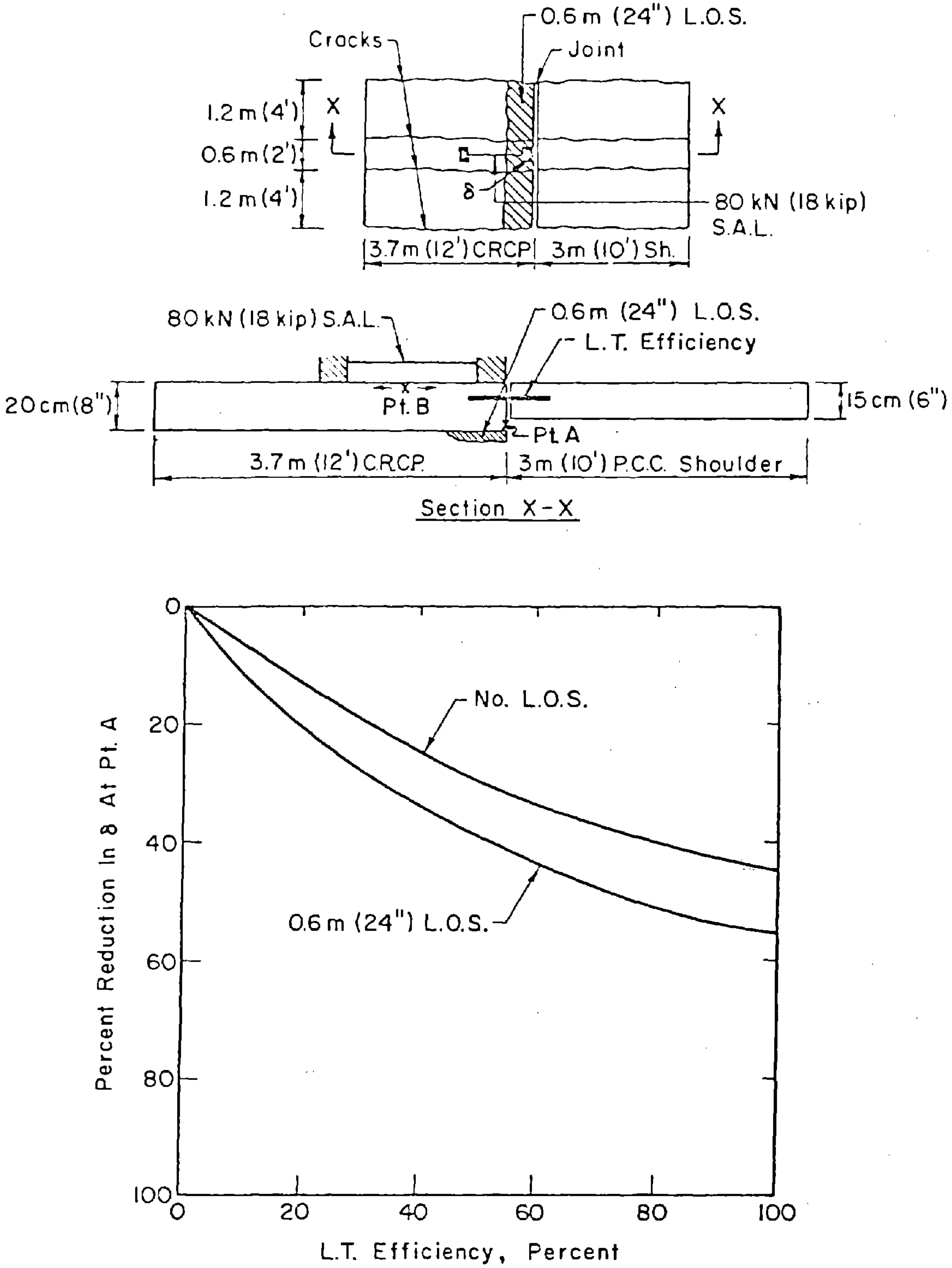


Figure 3.25. Continued.

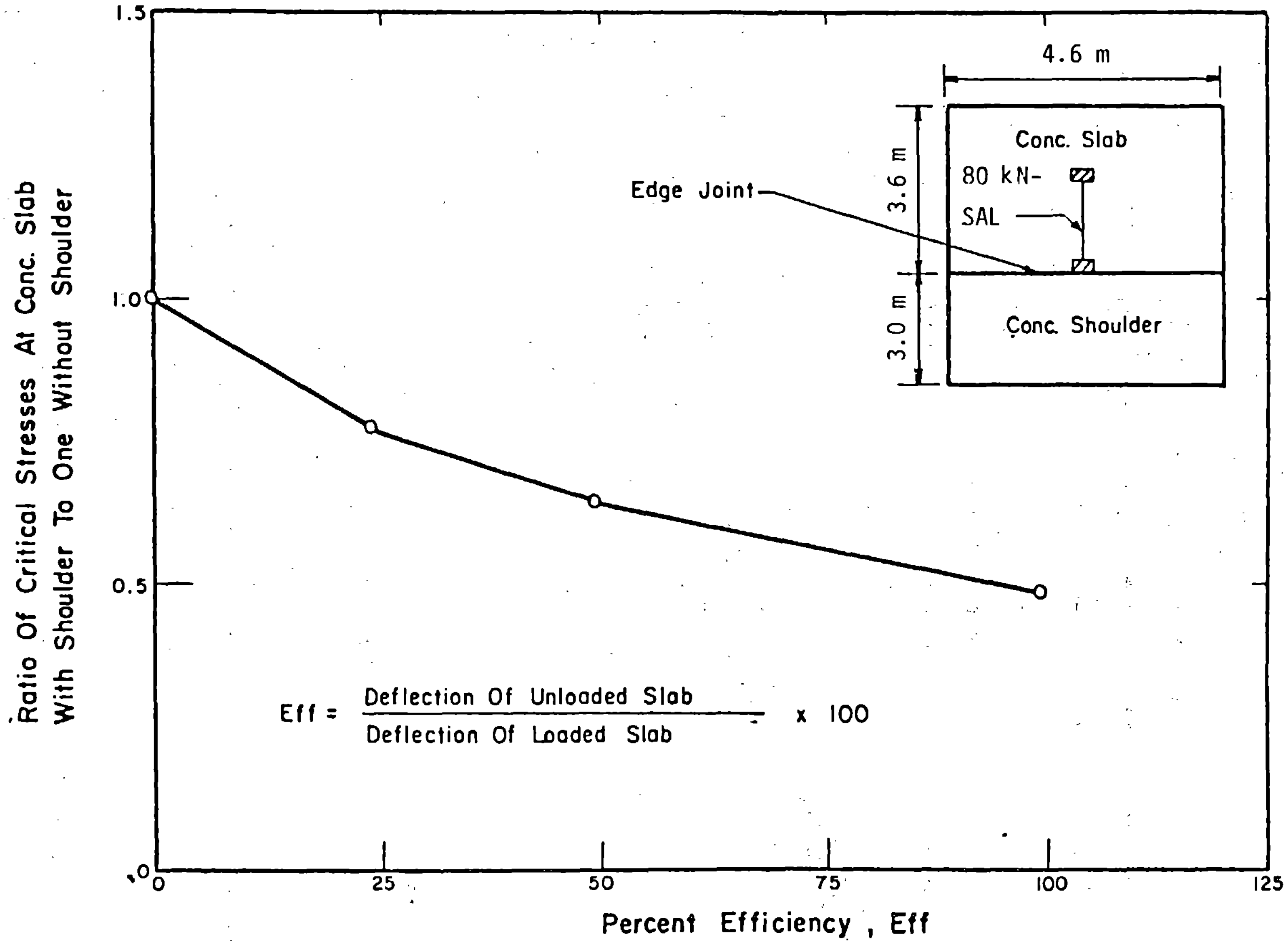


Figure 3.26. Effect of Concrete Shoulder on Critical Edge Stress for Varying Joint Load Transfer Efficiency.

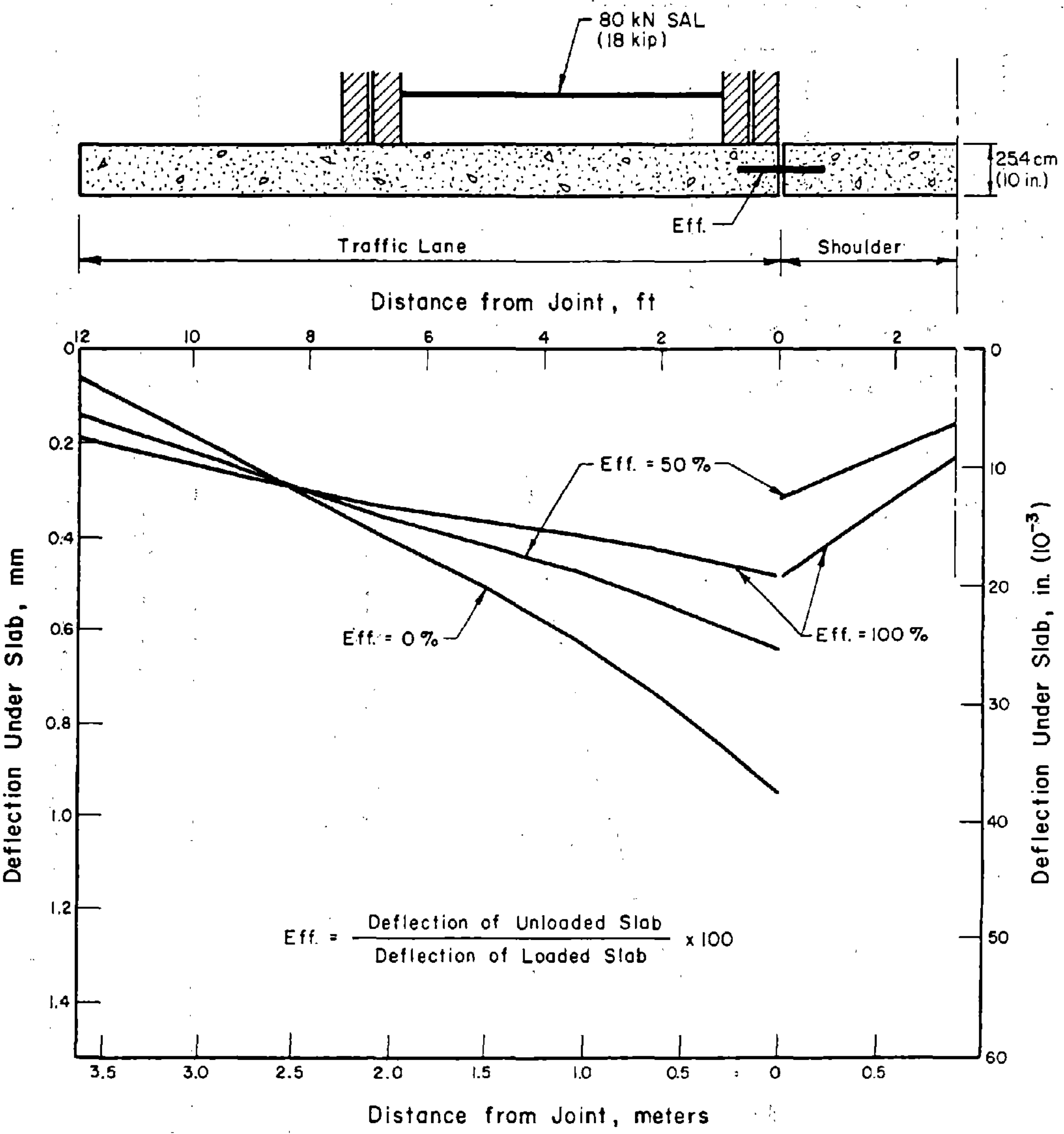


Figure 3.27. Effect of Lane/Shoulder Tie on Deflection of PCC Traffic Lane.

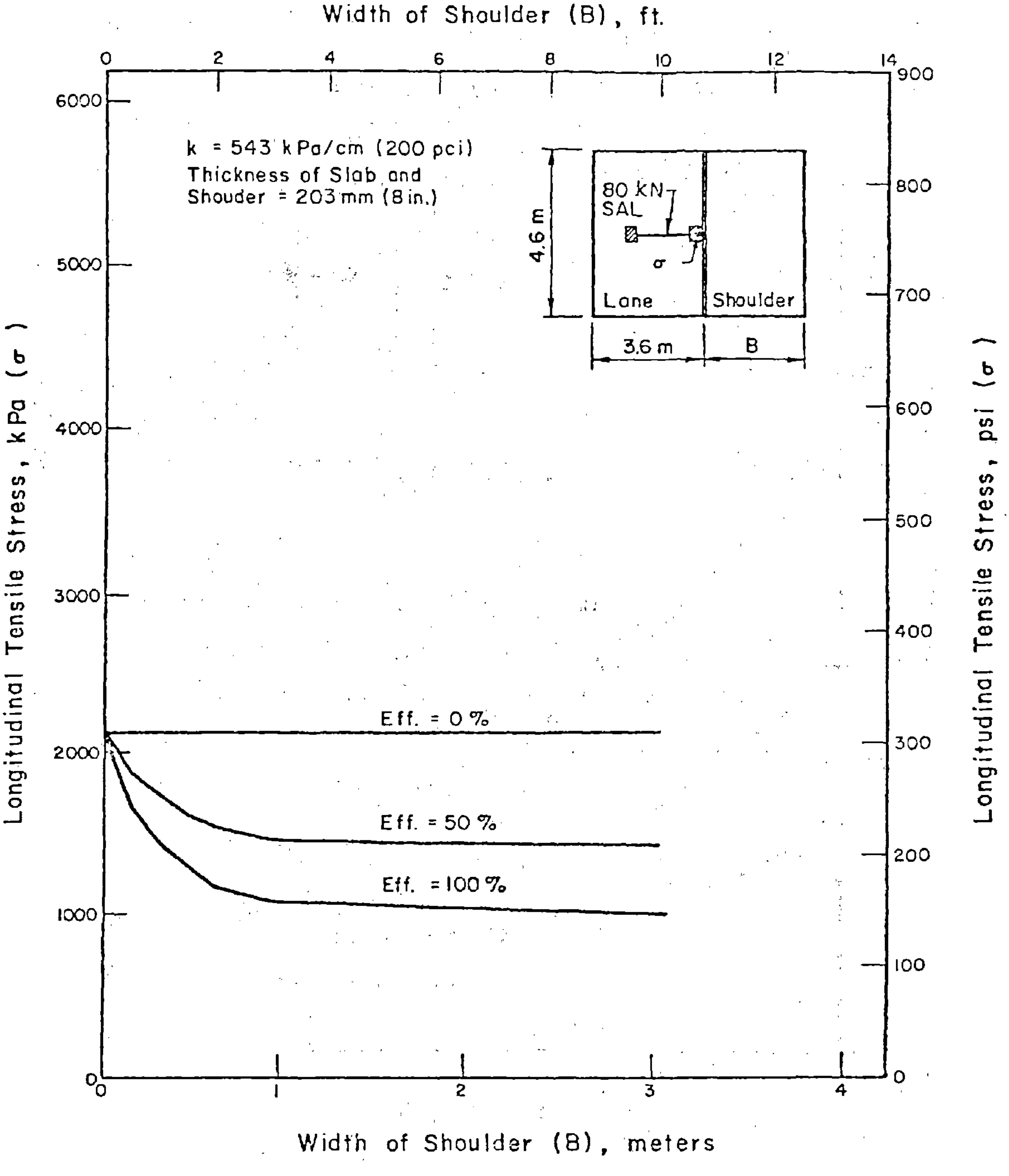


Figure 3.28. The Effect of Lane/Shoulder Tie and Width of PCC Shoulder on Tensile Stress of Traffic Lane.

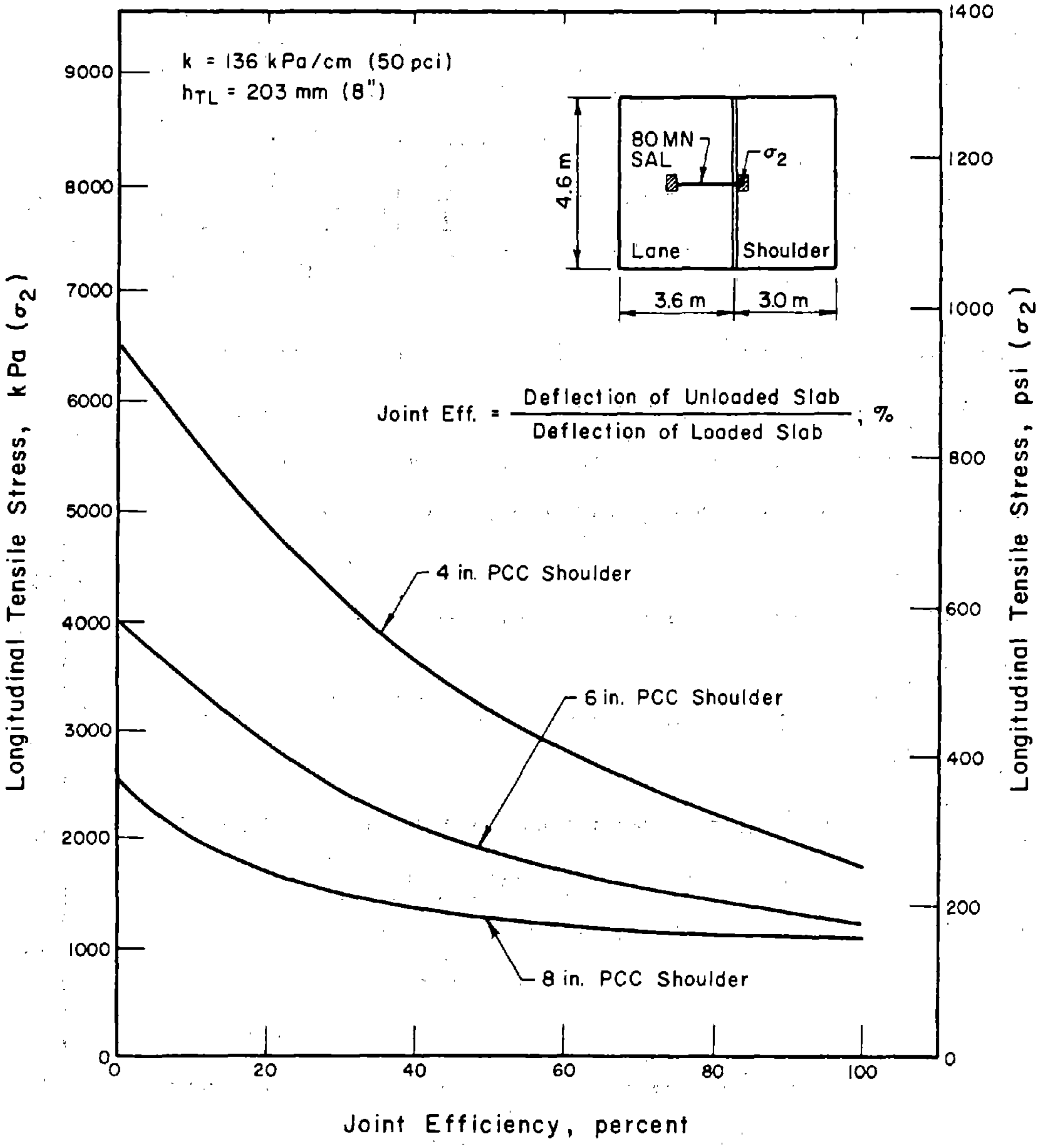


Figure 3.29. Effect of Traffic Lane/Shoulder Tie (Joint Efficiency) on Tensile Stresses in the Bottom of PCC Shoulders.

Table 3.1. Distress in Traffic Lane from Two CRCP Projects Having PCC Shoulders Along a Portion of Their Length.

Project	Age Years	Length of Project in Miles	PCC Shoulders	Edge Punchouts/mi.	Wide Cracks/mi.
I-80	9	5.7	No	6.0	7.9
		1.8	Yes	1.1	5.0
I-74	10	5.0	No	4.0	1.6
		0.8	Yes	0.0	0.0

(1 mile = 1609 m)

Table 3.2. Summary of Performance, Traffic, and Design Data from Two Illinois Experimental Projects.

TRAFFIC/ DESIGN PARAMETERS	Highway I-74	Highway I-80
1. Age, years	10	9
2. Traffic Lane Thickness	18 cm (7 in.) CRC	20 cm (8 in.) CRC
3. PCC Shoulder Thickness	15 cm (6 in.)	20 cm (8 in.) at joint, tapers to 15 cm (6 in.) at outside edge
4. Jt. Spacing	3-30.5 m (10-100 ft.)	6.1 m (20 ft.)
5. Tie	Tie bars and no tie bars #4 Bar 76 cm (30 in.) long 76 cm (30 in.) c. to c.	Anchor bars 2 in. Embedded in Traffic Lane, 15 in. shoulder
6. Mean ADTT (in adjacent truck lane)	950	2140
7. 80 KN ESAL (18-kip) in adjacent lane over life	2.7×10^6	7.0×10^6
8. Percent Slabs Cracked	0 (3.05 m Joint Spacing) 5 (6.10 m " ") 60 (7.60 m " ") 90 (12.20 m " ") 100 (15.25 m " ") 100 (18.30 m " ") 100 (24.40 m " ") 100 (30.50 m " ")	5

Table 3.3. Field Measurement Data on 10 Year Old Illinois PCC Shoulders to Determine Longitudinal Lane/Shoulder Joint Efficiency (I-74 sections described in Table 3.2).

Shoulder Design	Mean Edge* Deflection - Traffic Lane	Mean Edge* Deflection - Shoulder	Deflection Load Transfer Efficiency (%)
1 Tiebars, keyway, and Granular Subbase	0.1143 mm (0.0045 in.)	0.1118 mm (0.0044 in.)	97.8
2 Tiebars, keyway no subbase	0.1448 mm (0.0057 in.)	0.1016 mm (0.0040 in.)	70.2
3 No tiebars, keyway, with granular subbase	0.2108 mm (0.0083 in.)	0.0330 mm (0.0013 in.)	16.0

*Deflections measured with Benkleman Beam using 84.4 kN (19,000 lb) single axle. Procedure similar to that used at AASHO Road Test (Ref. 13) with outside of duals 7.5-15 cm (3-6 in.) from traffic lane slab edge and beam probe at traffic lane edge and at shoulder edge (creep speed deflection).

Table 3.4 Field Measurement Date on 9 Year Old Illinois PCC Shoulders to Determine Longitudinal Lane/Shoulder Joint Efficiency (I-80 sections described in Table 3.2).

Shoulder Design	Mean Edge[*] Deflection-Traffic Lane	Mean Edge[*] Deflection-Shoulder	Deflection Load Transfer Efficiency (%)
Tiebars, and Granular Subbase (Intermediate)	0.2311 mm (0.0091 in.)	0.0889 mm (0.0035 in.)	38.5
Tiebars, Granular Subbase (Coarse)	0.2464 mm (0.0097 in.)	0.0762 mm (0.0030 in.)	31.0
Tiebars, with No Subbase	0.2159 mm (0.0085 in.)	0.1016 mm (0.0040 in.)	47.0

[*] Deflections measured with Benkleman Beam using 121.3 kN (27,300 lb) tandem axle. Procedure similar to that used at AASHO Road Test (Ref. 13) with outside of duals 7.5-15 cm (3-6 in.) from traffic lane slab edge and beam probe at traffic lane edge and at shoulder edge (creep speed deflection).

CHAPTER 4

DEVELOPMENT OF PCC SHOULDER DESIGN PROCEDURE

This chapter discusses the development of a fatigue design procedure for plain jointed concrete shoulders. The objective of the fatigue design is to provide adequate slab thickness to control cracking of the slabs, which is one of the most serious types of distress requiring maintenance.

4.1 Critical Fatigue Location in Shoulder

Location of the critical point at which cracking initiates in the PCC slab is vital to the development of a fatigue analysis with an objective of controlling slab cracking. The location of the critical point is determined using both field and slab fatigue analysis results.

4.1.1 Initiation of Cracking-Field Results

A few road tests have been conducted where the cracking of plain jointed PCC slabs was carefully recorded. Results from the AASHO and Michigan Road tests and also observations made on in-service pavements during a previous research are presented.

The AASHO Road Test provides data relative to the initiation of cracking. Transverse cracking occurred first on 61 out of 91 plain and reinforced concrete sections and "usually began with a crack originating at a point on the edge of the pavement at least 5 feet (1.5 m) from the transverse joint" (13). Although longitudinal cracking initiated first in the other 30, it usually occurs in thin slabs 2.5 to 5.0 in. (63-127 mm) and not on thicker slabs of 6 in. (15 cm) or greater which are under consideration in this study. The location of the first crack in 31 plain jointed concrete sections is as follows:

Distance from Joint to Transverse Crack, ft	Number of Failed Sections
0-5	5
5-10	20
10-15	6

(1 ft = 0.305 m)

An example of crack initiation and progression for an 8 in. (20 cm) plain slab section is shown in Figure 4.1. The initiation of most of the cracking at the slab edge near the midpoint of the slab is apparent.

Results from the Michigan Test Road (38) also show transverse cracking to be the dominant type occurring for slabs of 8 in. (20 cm) thick having joint spacing ranging from 10 to 30 ft (3 to 9 m). Cracking per mile (1609 m) in 1955 is as follows:

	Joint Spacing, ft		
	30	20	15
Transverse	296	139	50
Diagonal	7	6	0
Longitudinal	4	20	11

(1 ft = 0.305 m)

Transverse cracking occurred much more than any other types of cracking.

Several heavily trafficked plain jointed concrete pavements were examined during the field survey as a part of the zero-maintenance pavement research project (32) and the types of cracking noted and summarized. Transverse cracking was observed in 12 pavements, corner cracking occurred in one, and longitudinal cracking occurred in three projects.

4.1.2 Initiation of Cracking-Fatigue Analysis

As a part of the research project, "Design of Zero-Maintenance Pavements" (32) that was developed at the University of Illinois, a comprehensive fatigue analysis was conducted using the finite element method and Miner's fatigue damage hypothesis to determine theoretically the critical point in the slab where cracking should initiate. Two positions in the slab were evaluated:

1. Near the transverse joint where longitudinal cracking initiates.

2. At mid-slab between the transverse joints where transverse cracking initiates.

These locations and the direction of critical stresses are shown in Figure 4.2.

A fatigue analysis showed that when the mean lateral placement (D) of the axle loads using the slab is less than 36 in. (0.9 m), the critical fatigue damage is at D = 0 or the slab edge, and, therefore, cracking should definitely initiate at the outer edge of the slab.

The fatigue analysis also showed that the magnitude of damage for the mid-slab edge position is much higher than the transverse joint position when both were subjected to the same average lane traffic. Thus, transverse cracking would theoretically be expected to occur long before longitudinal cracking occurred.

Hence, both field and analytical results indicate that for normal highway loadings and slab widths the critical fatigue damage is at the slab edge.

4.2 Development of Fatigue Damage Analysis

A comprehensive PCC shoulder fatigue damage analysis was developed based upon the following:

- The critical fatigue damage location in the shoulder is at the slab longitudinal edge midway between the transverse joints.
- Critical edge stresses caused by traffic loads are considered to cause transverse cracking.
- Load stresses are computed using a finite element program which has been shown to provide close results.
- The proportion of mainline traffic encroaching on the shoulder inner edge and/or parking on the shoulder is used in the fatigue analysis.
- Fatigue "damage" is computed and accumulated according to Miner's hypothesis (52).
- A correlation between computed fatigue "damage" and measured cracking was determined and limiting "damage" for PCC shoulder design is selected.

4.2.1 PCC Fatigue

Several laboratory studies have shown that plain PCC beams experience fatigue failure when subjected to high repetitive flexural stresses (39 through 48). Also, several road tests and many in-service PCC slabs have been observed to experience fatigue cracking when subjected to many applications of heavy truck traffic (13, 34).

Results from laboratory studies showed that the number of repeated loads that PCC can sustain in flexure before fracture depends upon the ratio of applied flexural stress to the ultimate static flexural strength or modulus of rupture. The results also showed that Miner's damage hypothesis, which assumes linear accumulation of damage, does not give exact prediction of failure of PCC. However, data from recent tests indicate that the inaccuracy of MIner's hypothesis is not very significant compared to the large variability in strength and fatigue life that is typical of PCC (49). Hence, it was concluded that Miner's hypothesis represents the cumulative damage characteristics of concrete in a reasonable manner (49).

Fatigue data were obtained during a previous study for plain PCC beams from three studies (40, 49, 60). A R-N plot of 140 tests from these studies is shown in Figure 4.3. The plot shows a large scatter of data, and the data from the three studies generally overlay each other. A least square regression curve was fit through the data as shown (Curve 1) (32).

$$\text{Log}_{10} N = 17.61 - 17.61 (R) \tag{4.1}$$

where:

N = number of stress applications to failure of beam.

R = ratio of repeated flexural stress to modulus of rupture.

Standard error = 1.4 (of log N).

This equation is a mean regression curve in that it represents a failure probability of 0.5 or 50 percent. Hilsdorf and Kesler (42), for example, established curves for various probabilities of failure based upon their data, and the curve for a probability of 0.05 or 5 percent is plotted in Figure 4.3 (Curve 2). The fatigue curve used in design by PCA is also shown in Figure 4.3 (Curve 3) which is much lower than the $P = 0.05$ curve for lower stress ratios.

The applicability of these laboratory fatigue results from beam specimens to the fatigue of actual pavement slabs under field conditions has never been established. Many differences, such as age of slab, thickness variation, variation of PCC strength, etc., exist between laboratory and field conditions that probably result in different fatigue responses. The complexities due to these differences are so great and available information is so limited that any laboratory curves used to estimate the fatigue damage in field slabs must be "calibrated" based on field data as presented in Section 4.3. Additional research on PCC slab fatigue is greatly needed.

The concrete fatigue curve used for design purposes was the same one used in the zero-maintenance design for plain jointed concrete by Darter (32):

$$\text{Log } N_d = 16.61 - 17.61\ (R) \qquad (4.2)$$

This expression provides a safety margin of one decade of load applications as shown in Figure 4.3 (Curve 4), and represents probability of 24 percent. This curve will also be used in this research.

4.2.2 Shoulder Truck Traffic

Truck traffic on shoulders consists of moving encroachments near the longitudinal joint, parked trucks with wheel loads near the outside edge, and use as an additional traffic lane. One of the most important factors that affects the lateral distribution of truck traffic in the outside traffic lane is the existence of shoulders, and whether the shoulder is paved. The encroachment of truck traffic onto the shoulder depends mainly on the lateral placement in the adjacent traffic lane. Available evidence (32) indicates that when there is a paved shoulder and no lateral obstructions, there is a definite tendency of trucks traveling on the outer lane, to shift several inches (cm) towards the slab edge. Data collected by Taragin (51) in 1956 for 12 ft (3.6 m) concrete traffic lanes found that the mean lateral distance of mainline truck distribution to be 11 in. (28 cm) from the edge when paved shoulders are used and 25 in. (63.5 cm) when gravel or grass shoulders are used. This lateral shift towards the slab edge increases the number of truck encroachments onto the shoulder accordingly.

Similarly, there are some important factors that affect the amount of parked trucks along a given highway section. Factors such as the geometric layout of the section, its location relative to a weighing station, and its proximity to an interchange all affect the amount of parked trucks.

In addition, and as discussed in Chapters 1 and 2, PCC shoulders are sometimes used for regular traffic as a detour around a closed lane or as an additional lane during peak traffic hours. Then, consequently, these conditions will have an effect on the structural and geometrical adequacy of PCC shoulders and, therefore, must be considered in design.

For a PCC shoulder to perform its functions, the truck traffic used in design should be based on the actual future uses of the shoulder under its local conditions along the project. This is a very crucial factor in shoulder design.

4.2.3 PCC Fatigue Computation

A fatigue analysis procedure was developed based upon the results of previous sections to provide a method of estimation of traffic "damage" that could result in cracking of the slab. The basic fatigue design philosophy for plain jointed concrete shoulders is that linear cracking must be controlled. This is possible through direct consideration of traffic loadings, joint spacing, lane/shoulder tie, shoulder width and, foundation support or loss of support. Fatigue "damage" is investigated at two critical locations in the concrete shoulder, the inner edge as well as the outer edge. These two locations are very important in design, as was discussed earlier and therefore must be analyzed separately in the design procedure.

The major steps in the fatigue analysis are as follows:

1. Determine axle applications, at each of the two critical edge locations, in each single and tandem axle load group.

2. Select trial slab/subbase structure, lane/shoulder load transfer, PCC variability, PCC shoulder width, and other required factors.

3. Compute the fatigue damage occurring at each of the shoulder edges for a given year using the Miner's accumulative damage hypothesis (52) and sum yearly over the entire design period.

$$\text{DAMAGE} = \sum_{j=1}^{j=p} \sum_{i=1}^{i=m} \frac{n_{ij}}{N_{ij}} \tag{4.3}$$

where:

DAMAGE = total accumulated fatigue damage over the design period occurring at either of the slab edges.

n_{ij} = number of applied axle load applications of the i^{th} magnitude for the j^{th} year.

N_{ij} = number of allowable axle load applications of the i^{th} magnitude for the j^{th} year determined from PCC fatigue curve.

i = a counter for magnitude of axle load, both single tandem axle.

j = a counter for years over design period.

m = total number of single and tandem axle load groups.

p = total number of years in the design period.

The fatigue damage is computed at each of the slab longitudinal edges because results from field observations of many jointed concrete pavements and analytical fatigue analysis (Sec. 4.1) showed the midpoint between the transverse joints at the slab edge to be the critical point where cracking initiates.

Applied Traffic, n_{ij}: The n_{ij} is computed using the traffic data for the year under consideration. It is computed using the following expression:

$$n_{ij} = (ADT_y)(T/100)(DD/100)(LD/100)(A)(365)(P/100)(C/100)(CON) \quad (4.4)$$

where:

ADT_y = average daily traffic at the end of the specific year under consideration.

T = percent trucks of ADT.

DD = percent trucks in direction of traffic lane adjacent to shoulder.

LD = lane distribution factor, percent trucks in design lane in one direction.

A = mean number of axles per truck.

P = percent axles in the i_{th} load group.

C = percent of total axles in the truck traffic lane that park on or otherwise use the adjacent PCC shoulder (used for computing the fatigue damage at the outer edge), <u>or</u>

= percent of total axles in the traffic lane that encroach on or otherwise use the adjacent PCC shoulder (used for computing the fatigue damage at the inner edge).

CON = 1 for single axles, 2 for tandem axles.

Allowable Traffic, N_{ij}: The N_{ij} is computed from PCC fatigue considerations (as was discussed earlier in Section 4.2.1). The loading stress is computed at either of the two edges of the shoulder for a given axle load (single or tandem) using the finite element model discussed earlier (Sec. 3.2). The stress models were derived using multiple stepwise regression techniques from a factorial of data obtained from the finite element program over a wide range of the design variables:

Shoulder Slab Thickness (H1): 6, 8, 12 in. (15, 20, 30 cm)
Traffic Lane Slab Thickness (H2): 8, 10, 14 in. (20, 25, 36 cm)
Shoulder Width (B): 3, 5, 7, 10 ft. (.9, 1.5, 2.1, 3 m)
Stress Transfer Efficiency Between Shoulder and Traffic Lane (EFF): 0, 50, 100 percent (See Sec. 3.2 for definition)
Foundation Modulus (K): 50, 200, 500 pci (13.5, 54.2, 135 MN/m^3)
Loss of Support (ERODE): 0, 12 in. (0.30 cm) (along the inner shoulder edge).

The finite element computed stresses for all possible combinations of these factors were obtained and individual equations were derived for traffic load stress (STRT) at each of the shoulder edges due to loading condition at the edge under consideration.

The regression equations determined for these stresses are as follows:

Load Stress for single axle load at the outer edge of the shoulder:

$$\begin{aligned} STRT = {} & [LOAD/(18.0\ H1^{2})][116.36335 + 0.64672\ H1 + 17.6412\ H1^{0.5} \\ & + 15.6341\ K^{0.25} - 63.74884 \log_{10} K - 2.4917\ H1 \\ & - 37.44179\ K^{-0.25} \log_{10} B + 6.50848\ K^{-0.25}\ H1 \\ & - 115.5093\ K^{-0.25}\ H1^{0.25} - 0.00123\ BK + 5.00214\ B/H1] \end{aligned} \quad (4.5)$$

Load Stress for tandem axle load at the outer edge of the shoulder:

$$\begin{aligned} STRT = {} & [LOAD/(36.0\ H1^{2})][-12.1686 + 12.36292\ H1^{0.5} - 2.09608\ H1 \\ & - 31.73886\ K^{-0.25} \log_{10} B + 4.87304\ H1K^{-0.25} \\ & - 96.50225\ K^{-0.25}\ H1^{0.25} - 0.00096\ BK + 0.031011\ H1^{2} \\ & + 6.75862\ H1^{0.75}/K^{0.25} - 0.06193\ B(\log_{10}(H1^{3}/K))^{3} \\ & + 4.11229\ B/H1 + 140.71457\ K^{-0.25}] \end{aligned} \quad (4.6)$$

Equations 4.5 and 4.6 are valid only when the width of the PCC shoulder (B) is less than 7 feet (2.1 m); in this case only one wheel (the wheel at the edge) of the axle load is applied due to the geometry of the shoulder (the other wheel is still on the mainline slab). When the width of the shoulder (B) is 7 feet (2.1 m) or more, under which both wheels of the axle load are applied on the shoulder slab simultaneously, the effect of the other wheel on the critical edge stress should be considered. Previous studies (32) had shown that the other wheel will increase the edge stress by 5 to 15 percent over that caused by one wheel. Therefore an average increase of 10 percent in the stress obtained by Equations 4.5 and 4.6 is used for that condition. Then,

Load Stress for $B \geq 7.0$ ft (2.1 m):

$$STRT = 1.10 \times STRT \text{ (Eqs. 4.5 or 4.6)} \quad (4.7)$$

Load Stress for Single Axle Load at the Inner Edge:

$$\begin{aligned}
\mathrm{STRT} = {} & [\mathrm{LOAD}/18.0\ \mathrm{H1}^{2})][78.06105 + 0.6472\ \mathrm{H1} + 17.6412\ \mathrm{H1}^{0.5} \\
& + 10.51771\ \mathrm{H2}^{0.5} + 15.6341\ \mathrm{K}^{0.5} - 63.74884\ \log_{10}\mathrm{K} \\
& + 144.41502\ (\mathrm{EFF} + 1)^{-2} + 0.63417\ \mathrm{H1H2} \\
& - 37.44179\ \mathrm{K}^{-0.25} \log_{10}\mathrm{B} + 0.81356\ \mathrm{H1H2K}^{-0.25} \\
& - 40.8387\ \mathrm{K}^{-0.25}\ \mathrm{H1}^{-0.25}\ \mathrm{H2}^{0.5} - 0.00274\ \mathrm{ERODE\ H1H2} \\
& - 0.00123\ \mathrm{BK} + 0.08268\ \mathrm{H1\ ERODE} - 0.35561\ \mathrm{H1H2\ EFF} \\
& + 0.0012\ \mathrm{BK\ EFF} - 135.56133\ (\mathrm{EFF} + 1)^{-1.5} \\
& - 0.12128\ \mathrm{ERODE\ EFF} - 0.94563\ \mathrm{H1H2}\ (\mathrm{EFF} + 1)^{-1} \\
& + 5.00214\mathrm{B}/\mathrm{H1} + 0.0425\ (\mathrm{H2\ EFF}/\mathrm{H1})^{5}]
\end{aligned} \tag{4.8}$$

Load Stress for Tandem Axle Load at the Inner Edge:

$$\begin{aligned}
\mathrm{STRT} = {} & [\mathrm{LOAD}/(36.0\mathrm{H1}^{2})][-57.69734 + 12.3629\ \mathrm{H1}^{0.5} \\
& + 37.03882\ \mathrm{H2}^{0.25} + 140.71457\ \mathrm{K}^{-0.25} \\
& - 75.80695\ (\mathrm{EFF} + 1)^{-0.67} + 59.34409\ (\mathrm{EFF} + 1)^{-2} \\
& + 0.5065\ \mathrm{H1H2} - 31.73886\ \log_{10}\mathrm{BK}^{-0.25} + 0.60913\ \mathrm{H1H2K}^{-0.25} \\
& - 34.1187\ \mathrm{K}^{-0.25}\mathrm{H1}^{0.25}\mathrm{H2}^{0.5} - 0.0012\ \mathrm{H1H2\ ERODE} \\
& - 0.00096\ \mathrm{BK} - 0.00001\ \mathrm{BK\ ERODE} + 0.06195\ \mathrm{H1\ ERODE} \\
& + 0.031011\ \mathrm{H1}^{2} + 6.75862\ \mathrm{H1}^{0.75}/\mathrm{K}^{0.25} - 0.29443\ \mathrm{H1H2\ EFF} \\
& + 0.00102\ \mathrm{BK\ EFF} - 0.06193\ \mathrm{B}(\log_{10}(\mathrm{H1}^{3}/\mathrm{K}))^{3} \\
& - 0.76851\ \mathrm{H1H2}\ (\mathrm{EFF} + 1)^{-1} - 0.01283\ \mathrm{H2\ ERODE\ EFF} \\
& + 4.11229\ \mathrm{B}/\mathrm{H1} + 0.03\ (\mathrm{H2\ EFF}/\mathrm{H1})^{5}]
\end{aligned} \tag{4.9}$$

where:

LOAD = total load on single or tandem axle, pounds
H1 = PCC shoulder thickness, inches
H2 = traffic lane slab thickness, inches
B = width of the shoulder, feet
EFF = load transfer efficiency between shoulder and traffic lane, percent.
K = modulus of foundation support (top of subbase, pci)
ERODE = erodability of support along shoulder slab edge, inches

Standard estimate of error based on 504 data points:

Single axle of STRT = 16.0 psi (110 kPa)
Tandem axle of STRT = 12.9 psi (89 kPa)

These standard estimates of error are believed to be acceptable when compared to the other uncertainties involved.

A computer program, called JCS-1, was developed to compute the accumulated fatigue damage over the design life of the PCC shoulder. This data can be used to evaluate and design a plain jointed concrete shoulder considering fatigue damage.

4.3 Limiting Fatigue Consumption

The fatigue analysis that has been developed considers directly the effects of traffic loadings, shoulder width, traffic lane/shoulder tie and the loss of foundation support (i.e., pumping). However, there are several factors that are not considered due to insufficient information. One of the most important factors may be the use of PCC fatigue curves obtained from small beams to estimate the fatigue life of large fully supported pavement slabs. Traffic loading conditions also differ considerably between laboratory and field. Other inadequacies could be cited; however, the point to be made is that the final accumulated fatigue "damage" based on Equations 4.5 through 4.9 computed for a pavement slab must be correlated with measured slab cracking before a limiting fatigue consumption can be selected with confidence for design.

According to the Miner's hypothesis, a material should fracture when the accumulated "damage" equals 1.0. Even if Miner's hypothesis were exact, variability of material strengths, loads, and other properties would cause a variation in accumulated "damage" ranging from much less than 1.0 to much greater.

In order to determine a limiting fatigue damage value to be used in the design procedure, a fatigue analysis using the expression shown in Eq. 3.4 was used on many in-service pavements. The field data from 27 projects needed for the analysis were obtained by Darter for the Zero-Maintenance design project (32). The cracking index of these pavement sections was also obtained. From the analysis on the sections having 15 to 20 ft (4.6 - 6.1 m) joint spacing, the curve shown in Figure 4.4 was developed. The data used for the curve were from plain jointed concrete pavements located in various states. The designer, with the use of this curve, can select a limiting design fatigue damage value to limit the cracking of the pavement slabs, or once the fatigue damage value is computed for a given design, the cracking index over the design period can be estimated.

As was discussed earlier in Chapter 3, during the field survey conducted on I-74, it was found that about 60 percent of the 25 foot (7.6 m) shoulder slabs had transverse cracking. The level of these cracks, however is of low-medium severity, and therefore, did not affect the performance of the PCC shoulder and it is tolerated by the highway users. The cracking index for this amount of cracking is 25 ft/1000 ft^2 (0.08 m/m^2). Using Figure 4.4, the corresponding fatigue damage is between 10^1 and 10^2. The amount of transverse cracking is much lower (0-5%) for the 10-20 ft slabs and is the reason shorter slabs are recommended in this research. This means that shorter slabs under similar environmental and traffic conditions can carry much more traffic before they reach the cracking index of the 25 foot slabs. It is believed that the highway user will tolerate a higher level of cracking index when driving on the shoulder than that found on the shoulders of the two projects surveyed. Therefore, a cracking index of 35 ft/1000 ft^2 (0.08 m/m^2) is recommended to be used as a design limiting criteria for PCC shoulders on heavily trafficked highways (this corresponds to a fatigue damage of 10^3 from Fig. 4.4). Recommended fatigue damage values for high, medium, and low traffic volume pavement shoulders are as follows:

Low Traffic Volume = 10^{+5} (Crack Index $\approx$ 60)
(ADT of the mainline $<$ 2000)

Medium Traffic Volume = 10^{+4} (Crack Index $\approx$ 48)
(2000 $<$ ADT $<$ 20,000)

High Traffic Volume = 10^{+3} (Crack Index $\approx$ 35)
(ADT $>$ 20,000)

A computer program was written to provide fatigue data for use in design. The program is designated JCS-1 (Jointed Concrete Shoulders-1) and is written in FORTRAN computer language for the IBM-360 digital computer. The program can be adapted for usage on other computers with only minor modifications. The computer processing time for a design problem is about 9 seconds for analyzing a range of shoulder thicknesses. The storage requirement for the program is 40,000 bytes (storage area). An input guide, sample input/output, flow chart, and program listing are given in the Appendix. The designer must specify trial structural designs, determine the required inputs, run the JCS-1 computer program, and analyze the output fatigue data. The program is written to analyze any one or a combination of shoulder thickness, mainline slab thickness, shoulder width, and mainline/shoulder tie and provide outputs for each combination, while holding all other inputs constant.

The designer can therefore examine a range of shoulder designs for a given traffic, and foundation support with only one run of the program. A complete detailed example of PCC shoulder structural design is given in Chapter 5.

4.4 Structural Design Inputs

The PCC shoulder design procedure requires the selection and/or determination of several important factors related to the PCC shoulder slab, traffic, foundation support, and traffic lane/shoulder tie. Specific guidelines for the determination of each required input are provided in this section.

4.4.1 PCC Shoulder Design Life

The actual shoulder life in years over which it is desired to provide structural low-maintenance performance is input. This time period may range from 1 to 40 years. Normally, the design life would range from 15 to 40 years for new construction. In certain instances, such as rehabilitating the traffic lane by constructing PCC shoulder adjacent to it, a shorter interval may be desired. This interval depends mainly on the remaining design life of the traffic lane. The computer program developed cannot accept a fraction of a year, such as 20.5 years. Only whole years should be input.

A design life can be separated into two or more analysis periods if conditions warrant. For example, consider a PCC shoulder under design for 20 years. If it is expected that legal load limits will increase significantly after 10 years, the program could be run for the first 10 year period with one axle load distribution, and then the program could be re-run for the next 10 years with a modified axle load distribution, and other necessary changes in input parameters.

4.4.2 PCC Slab Properties

Slab Thickness: Any number of either traffic lane or shoulder trial slab thickness can be selected for analysis. Based upon the results of this trial, other combinations of traffic lane/shoulder thicknesses can be tried if needed until the limiting design criteria are met (maximum fatigue damage). The range of the traffic lane slab thickness that was used to develop the design procedure is between 8 and 14 inches (20 and 35 cm). For the PCC shoulder the thickness range between 6 and 12 inches (15 and 30 cm). The computer program is set up so that the designer can input several combinations of traffic lane/shoulder slab thicknesses and obtain results for each combination by adding appropriate cards at the end of the original data deck to specify other trial thickness combinations as indicated in Appendix A input guide. Since both traffic lane and shoulder slab thicknesses are inputs, this computer program could be used for either new construction of PCC shoulder adjacent to new PCC traffic lane (which should be designed using different procedures) or rehabilitation of an existing PCC traffic lane by constructing PCC shoulder adjacent to it.

Shoulder Slab Width: Shoulder slab width is an important input because of its effect on the structural behavior of the shoulder under traffic loading. Its importance extends to the geometric layout of the whole highway pavement and its safety standards. If the geometric layout of the highway imposes a certain shoulder width such as 10 feet (3 m) then this width should be input in the computer program. On the other hand, if the shoulder width is to be chosen from the shoulder structural behavior standpoint, then any number of shoulder widths can be analyzed until the limiting design criteria are met. The range of the shoulder width that was used in development of the design procedure was 3 to 10 ft (0.9-3.0 m). The computer program is set up so that the designer can input several shoulder widths in combination with any slab thicknesses as was discussed in the preceding section and on the same slab thickness cards added at the end of the original data deck as will be shown in Appendix A input guide.

Mean PCC Modulus of Rupture: The mean modulus of rupture at 28 days as determined by the test procedure specified in AASHO Designation T-97, using third point loading, is the basis for determining concrete flexural strength. Current practice for conventional pavements indicates that this value ranges from 600 to 750 psi (4140 to 5170 kPa). Alternate designs using a range of concrete strengths may be developed to compare the economics of designs. Agencies use compressive strength to determine the modulus of rupture from compressive strength. This relationship was derived from strength correlation studies (32):

$$FF = 10.0\ (CS)^{0.5} \qquad (4.10)$$

where:

FF = modulus of rupture, 3rd point loading, psi

CS = compressive strength, psi

Coefficient of Variation of PCC Modulus of Rupture: The modulus of rupture of the concrete varies from point to point in the slab and this variation has significant effect on pavement performance (53, 54). Therefore, it is important to consider this variability in structural design where a high degree of reliability must be obtained. The coefficient of variation is defined as follows:

$$\text{Coefficient of variation (\%)} = \frac{\text{standard deviation}}{\text{mean modulus of rupture}} \times 100 \qquad (4.11)$$

Many transportation agencies have studied the quality control of concrete and have information available for their construction procedures and specifications. Field data indicate that the coefficient of variation ranges from approximately 5 to 25 percent for excellent to poor quality control, respectively. A mean of about 12 percent can be considered typical for highway paving, and most projects range between 10 and 15 percent. It is recommended that construction control be adequate to limit the coefficient of variation of concrete to 15 percent or less.

The 28 day mean modulus of rupture (F_{28}) adjusted for concrete variability that is used in design, is obtained from the following expression:

$$F_{28} = FF\left(1 - C\,\frac{F_{cv}}{100}\right) \qquad (4.12)$$

where:

FF = mean modulus of rupture of the PCC at 28 days, 3rd point loading, psi

F_{cv} = coefficient of variation of modulus of rupture, %

C = 1.03, a constant representing a confidence level of 85%

4.4.3 Traffic

Traffic data are needed to estimate the number of applications of single and tandem axles for each load group that will use the PCC shoulder throughout the design period. These data are used in PCC shoulder fatigue analysis.

The prediction of traffic for design purposes must rely on information from past traffic, modified by factors for growth and other expected changes. Most states accumulate past traffic information in the format of the Federal Highway Administration W4 loadometer tables, which are tabulations of number of axles observed within a series of axle load groups. These tabulations are in a convenient form for use in fatigue analysis. Special consideration must be given to heavy axle loads that are outside legal limits (overloads). The effect of the overloads on the life of the concrete shoulder is very serious and must be fully considered in PCC shoulder structural design.

Average Annual Daily Traffic (ADT) at Beginning of Design Period: The average annual number of vehicles (trucks and automobile) that use the highway daily in both directions at the beginning of the design analysis period, when the highway is open to regular traffic is input.

Average Annual Daily Traffic (ADT) at End of Design Period: The average annual number of vehicles that use the highway daily in both directions at the end of the design period. The average daily traffic is assumed to increase uniformly from the beginning to the end of the analysis period.

Percent Trucks of ADT (T): The number of trucks expressed as a percent of ADT over the entire design period is required. If pickups and panel trucks are included in this percentage, their effect must be included in the axle load distribution.

Percent Trucks in Heaviest Traveled Lane (LD): The lanal distribution of trucks varies with many factors including number of lanes, urban/rural location, traffic volume, and percent trucks. This parameter can be best estimated through manual vehicle counts on the existing or similar highways in the area. The approximate lane distribution can be estimated using the following equations for the various types of highways. These equations were developed by Georgia DOT (55), and were independently checked at a few locations and found to give reasonable predictions with measured data:

a. Four lane rural

$$LD = 96.39 - 0.0004V \tag{4.12}$$

b. Four lane urban

$$LD = 95.76 - 0.0005V$$

c. Six lane urban

$$LD = 60.76 - 0.0004V + 1.3174T$$

where:

LD = percent total trucks in one direction in heaviest traveled lane (i.e., 100 percent indicates all trucks in heaviest traveled lane).

V = traffic volume in one direction (use average ADT over design period/2)

T = percent trucks of ADT

d. Eight and ten lane urban freeways have lane distribution values ranging from approximately 40 to 60 percent.

<u>Percent Directional Distribution (DD)</u>: The percent of trucks in one direction is normally 50. This parameter converts the two-directional truck traffic to one-directional truck traffic.

<u>Mean Axles Per Truck (A)</u>: This parameter can be computed using data from manual counts of W4 loadometer tables by dividing the total number of truck axles that pass over a section of the highway (single axle plus tandem axles which are counted as one axle) by the number of trucks that pass the same section. The value of mean axles per truck ranges from 2.1 to 3.0 depending upon the traffic mix. When pickups and panels are excluded, it ranges from about 2.5 to 3.0 with a mean of 2.75 for major highways.

<u>Trucks That Use the Shoulder</u>: The number of trucks that use the shoulder is an important factor for PCC shoulder design. Shoulder usage should be estimated from traffic surveys on either the highway under design or a highway of similar design and traffic. There are three types of traffic that use PCC shoulders: <u>encroached traffic</u>, <u>parked traffic</u>, and <u>regular</u> traffic.

a. Encroached Traffic: Is the part of the mainline traffic that encroaches on the shoulder occasionally and then merges back to the mainline. The encroached traffic travels normally in the vicinity of the mainline /shoulder joint and within a transverse distance of 12 in. (30.5 cm) on the shoulder. The percent trucks that encroach on the shoulder should be obtained as a part of a field survey in the area where the PCC shoulder is to be constructed. A stretch of several miles is recommended for such a survey. Trucks should be selected at random and followed by observers over the selected distance. Records are made of the time the truck travels on the shoulder to determine the longitudinal distance for each encroachment (by using the average truck speed which would be approximately the same as the observer vehicle's speed). The following information should be obtained from the shoulder field survey:

- Average number of encroachments per truck (NE) in the surveyed stretch (LS)
- Average longitudinal distance on the shoulder per encroachment, miles (ED)

The above information can be used to compute the number of load applications on the shoulder edge near the lane/shoulder joint in terms of percent of mainline truck traffic as follows:

(1) Obtain the ADT, T, and LD for the design section. Compute the average daily truck volume in the lane next to the concrete shoulder (LTT). LTT = ADT x T x LD.

(2) Determine the total number of daily truck encroachments in the surveyed stretch by multiplying the average number of encroachments per truck (NE) times the average daily lane truck traffic in one direction (LTT)(Step 1).

(3) Determine the total encroachment distances in the surveyed stretch by multiplying the total number of encroachments (step 2) by the average longitudinal distance on the shoulder per encroachment (ED) (obtained from the survey) in miles.

(4) Then the number of encroachments for a given point (or section of ED length) in the surveyed stretch is obtained by dividing the total encroachment distances in the surveyed stretch (step 3) by the length of the surveyed stretch (LS).

(5) Hence, the proportion of encroaching trucks on the shoulder (PET) is the ratio of the number of encroachments for a given point (step 4) over the average daily truck traffic in one direction (step 1).

$$\text{PET} = \frac{\text{LTT} \times \text{NE} \times \text{ED}}{\text{LS} \times \text{LTT}} \tag{4.13}$$

This expression can be reduced to the following:

$$\text{PET} = \frac{\text{NE} \times \text{ED}}{\text{LS}} \tag{4.14}$$

where

NE x ED = Average length of total encroachments per truck in the surveyed stretch, miles

LS = Length of surveyed shoulder stretch, miles

The NE x ED and LS are inputs to the computer program. Various calculations show the PET may vary over ranges of approximately 0.01 to 0.08 (1 - 8 percent) of the adjacent lane truck volume.

This above procedure was used on I-75 at Perry, Georgia (2). Out of all the trucks that use the highway, approximately 2.4 percent encroach on the outside shoulder. The truck wheels were found to be concentrated primarily within about 12 in. (30.5 cm) of the longitudinal joint with an average transverse encroachment distance of 7.1 in. (18 cm). This tends to justify the use of the full percentage of encroached truck traffic for structural PCC shoulder design.

Taragin (56), as a part of a study by the Highway Research Board to determine the relative effects of different magnitudes and configurations of axle loads on PCC pavements, also reported that an average of 2.5 percent of the mainline truck traffic encroached on the outside shoulder of the test section to the extent of 12 inches (30.5 cm).

The above studies were conducted with either unpaved or different types of paved shoulders other than PCC in service. This suggests that the above percentages could be different when PCC shoulders are in service. The location of the shoulder stretch under design could also affect this percentage. These factors make the traffic survey of the local condition of the highway a necessity.

b. Parked Traffic: Is the percent of mainline truck traffic that parks on the shoulder for emergency reasons or otherwise. This input may be estimated for the design section based upon traffic counts on similar highways. It varies greatly along a given project depending on geometric and interchange conditions. A much higher proportion of trucks typically park near to ramps at interchanges. If this occurs, specific design sections should be selected.

As for encroaching traffic, it is necessary to compute the number of expected load applications that will occur along the outer shoulder edge in the selected design section. This is computed as follows:

(1) A length of project must be selected that is representative of the design section (DL).

(2) The ADT, T, and DD in the section must be determined.

(3) The mean length that a truck drives on the shoulder during a typical stop is determined from actual observations (PL).

(4) The mean number of trucks that actually used the shoulder in the design section for parking is determined by visual counting over a typical 24 hour period. It should be noted that most parking occurs during the very early morning hours and therefore this period of time must be included.

(5) The percentage of trucks that park on the shoulder is then computed. The design section is divided conceptually into "subsections" of length PL. It is assumed that probability of a truck to park on each "subsection" is equal to P, where

$$p = \frac{1}{DL/PL} .$$

Thus, the percentage of total truck traffic in one direction that parks on any random "subsection" (PPT) is computed as

$$PPT = \frac{N \times p \times 100}{ADT \times T \times DD} \tag{4.15}$$

where N = average number of parked trucks/day

Preliminary surveys and calculations show that the PPT may range from percentages of 0.0005 to 0.005.

The total of the proportion of encroached as well as parked truck traffic is used as an input for encroached traffic percentage due to the fact that any truck has to encroach in order to park on the shoulder.

c. Regular Traffic: If it is anticipated that the PCC shoulder would be used by regular traffic at any stage of its design life, then this extra amount of traffic should be counted for as a part of the shoulder design traffic. The amount of traffic at both edges of the PCC shoulder should be increased accordingly. The ultimate case is to design the shoulder as an extra lane by considering its traffic to be similar to the mainline outer lane truck traffic. The outer and the inner edges of the PCC shoulder would carry such traffic and, therefore, the percent of encroached and parked truck traffic in the computer program should be adjusted accordingly.

Axle Load Distribution: The average percent of total load applications occurring within specified load groups (usually 2000 pounds (8.9 kN) range) must be estimated for the entire design analysis period. If a legal load limit change is expected, it should be included in the analysis. Most important by far is the distribution of loads in the heavy axle loads groups (i.e., above 18,000 pound (80 kN) single and 32,000 pound (142 kN) tandem). Results from field surveys and interviews (35) indicate that for nearly all major highways, a significant percentage of axles are above the legal limits. Estimates indicate that the total percentage of axles above these values is 3 to 20 percent. The results also indicate that the data from loadometer stations do not usually give accurate estimates of the overload distribution due to enforcement, and an accurate estimation of the upper load distribution can only be obtained from spot weight studies or from police enforcement tickets.

It is, therefore, recommended that spot weight studies be conducted on the existing or similar highways to establish the existing distribution, and then that this distribution be modified to account for any anticipated legal load increases or other load changes over the design period.

4.4.4 Foundation Support

Modulus of Foundation Support: The finite element model used in this research uses the assumption that the subgrade acts as a dense liquid which is the same assumption made by Westergaard. The k-value, representing the modulus of subgrade reaction, can be determined by running a plate bearing test using a 30 in. (76 cm) plate. Details of this test are given in ASTM designations D1195 and D1196 or AASHO Designation T-221. The k-value of the subgrade can also be estimated from soil classifications (57). A set of curves were developed at the University of Illinois (35) based on the AASHO classification system.

If a subbase is used in the design, the k-value on top of the subbase must be determined. Using a subbase stiffens the foundation. Curves have been developed using the elastic layer theory relating the k-value of the subgrade to the k-value on top of the subbase for various materials and thicknesses in Reference 32 for unstabilized granular, asphalt stabilized, and cement stabilized materials.

Erodability of Foundation: The amount of erosion of the subbase at any time is expressed as the width in inches of a rectangular strip parallel to the PCC shoulder inner edge (longitudinal joint) that has no contact with the pavement slab. The erodability in inches at the end of the design period is input into the computer program. The erodability at the beginning of the design period is assumed to be zero in the program. The amount of erodability at any time after the pavement is opened to traffic is linearly interpolated between the initial and final erodability factors.

The erodability of the subbase will depend on many factors, including subbase type, available moisture, settlement of subsurface drainage, etc. Subbases that are densely graded and contain considerable amount of fines may pump significantly in a wet region. An erodability of up to 12 in. (30.5 cm) under the inner edge of the shoulder is considered to be a reasonable amount which is equivalent to a settlement of a subsurface drain, for example.

4.4.5 Traffic Lane/Shoulder Tie (Joint Efficiency)

Properly-tied PCC shoulders to either new or existing concrete pavement serve to stiffen the traffic lane and thereby decrease the deflection and consequent pumping near the longitudinal joint. The method of tieing the PCC shoulder to the mainline concrete pavement is a primary factor in determining the magnitude and the extent of the load transfer efficiency across the longitudinal joint throughout the design life. Therefore, some recommended methods for constructing tied concrete shoulders to both new and existing traffic lanes are discussed.

Provision of adequate load transfer when providing a PCC shoulder for an existing slab can be accomplished through closely spaced tiebars. Holes are drilled in the edge of the existing slab. This could be done with a tractor mounted drill that can drill several holes in the side of a mainline slab at one time. Tiebars are installed in the holes with epoxy or a non-shrinkage cement grout. The length of placing the bars into the slab should be adequate to develop full bond strength, but not less than 9 in. (23 cm) to avoid spalling over the base.

Malleable tiebars of small diameter (#4 or #5) and spacing (12-24 in. (0.3-0.6 m)) midway across the slab depth are preferable to stiffer short bars with large spacing intervals. This will substantially reduce the possibility of stress concentrations above the tiebar which will cause the joint to spall in the vicinity of the bar and the eventual breakage of the slab and the loss of the load transfer. The possibility of upward heave or drop-off of the shoulder in the area between the bars will also be substantially reduced when a short tiebar spacing is used (< 24 in. (60 cm) is recommended) since there will be more steel to hold the lane/shoulder together. A shoulder upward heave and spalling of the lane concrete problems were experienced in Pennsylvania and New York where two-piece tie bolts 60 in. (152 cm) center to center, were used to tie a 6 in. (15 cm) concrete shoulder with the existing mainline pavement.

On I-80 in Illinois the shoulders were tied to the mainline slab (smoother edge) with No. 4 hooked bolts of 15 in. (37.5 cm) in length (embedded in the shoulder), turned into a 2 in. (5 cm) snapoff expanding end anchors set into the edge of the mainline slab at 30 in. (75 cm) intervals with a pneumatic hammer. Recent measurements of this project showed that the traffic lane/shoulder joint deflection efficiency was poor and ranged from 31-47 percent. The joint had opened an average of about 3/8 in. (10 mm) and many of the bars had spalled the concrete directly over the bar in the traffic lane (where the 2 in. (5 cm) snap-off expanding and anchors were set). Some of the bars were set within 2 in. (5 cm) of the surface which also contributed to the spalling and loss of load distribution transfer. It is believed that placement of bars at slab mid-depth would minimize any potential spalling.

The practice of not placing tiebars within 30 in. (75 cm) of the transverse shoulder joint results in loss of load transfer along 60 in. (150 cm) of traffic lane. On one CRCP project in Indiana (I-65), several edge punchouts have occurred within this area because of no load transfer. Based upon results from the I-74 and I-80 projects in Illinois, tiebars may be placed much closer to the transverse shoulder joint, such as one-half the normal tiebar spacing without any problems.

In the case of new construction, tiebars can be inserted into the plastic concrete near the rear of the slip form paver. Bent bars can be installed by mechanical or manual means. The bent portion can be straightened later to tie the shoulder to the mainline. A 3 piece tie bolt can be used in which the one half and the coupler are inserted in the traffic lane by machine, and then the other half is screwed into the coupler before the shoulder is added (6, 8, 58). A keyway can also be formed in addition to the tiebars to provide for additional load transfer capability.

A keyed joint with tiebars was used in the construction of the experimental shoulder sections built on I-74 in Illinois. The extent of load deflection transfer efficiency on I-74 is still quite high (70-100 percent) after 10 years in service. This shows that with proper joint design and construction a high efficiency can be attained over a long period of time (i.e., more than 70%).

It was also found in the field survey conducted as a part of this research on I-74 (see Section 3.3.1) that a joint opening of up to 1 in. (25 mm) is experienced on keyed joints where no tiebars are used. This opening results in complete loss of joint efficiency along with an upward heave or a drop-off in the PCC shoulder.

The following tentative recommendations are provided for longitudinal design efficiencies for various types of joints. These values represent approximate efficiencies after 10-15 years of heavy traffic loadings. The estimates of deflection joint efficiencies are based on the data from inservice measurements and engineering. The joint stress efficiencies are determined from Figure 3.2 (this is the value used in the design computer program).

Joint Type	Deflection Efficiency - %	Stress Efficiency - %
Tied and Keyed	70-100	30-100
Tied Butt		
30 in bar spacing	60-80	25-42
12-24 in bar spacing	70-95	30-75
Non-Tied	0-20	0-5

These values are tentative only and need further verification.

The longitudinal joint between traffic lane and shoulder should be provided with a sealant reservoir and sealed with an effective sealant. This will reduce the possibility of foreign materials to collect inside the joint and consequently reduce the potential of the joint to spall, and also minimize the amount of deicing salt to penetrate to the tiebars. There was significant corrosion of tiebars on I-80 after 11 years which shows the necessity of either a good seal or provision of corrosion-resistant tiebars to insure a long-term structural adequacy of the bar in transferring the load across the joint (if pavement is subjected to deicing salts).

Cross-slope of the bottom surface of the concrete shoulder should be great enough to permit drainage away from the longitudinal shoulder/pavement joint and avoid pocketing water at this critical location. This will directly contribute to a more effective and lasting load transfer system across the joint.

Finally, for plain jointed concrete pavements, the shoulder joint pattern should match the traffic lane, although intermidiate joints may be placed if the traffic lane joint spacing is greater than 20 ft (6.1 m). Intermediate contraction joints must be placed where the traffic lane is jointed reinforced concrete with long joint spacing. None of the transverse shoulder joints require dowels, unless the shoulder is to be used as a regular traffic lane.

4.5 Selection of Alternative Trial Designs

The designer must specify trial structural designs, determine the required inputs, run the JCS-1 computer program, and analyze the output fatigue data at the two PCC shoulder critical locations. The program is written to analyze any one or a combination of shoulder thickness, mainline slab thickness, shoulder width, and load transfer efficiency across the longitudinal joint and to provide outputs for each combination, while holding all other inputs constant. The designer can therefore examine a range of combinations of the above four factors for a given traffic and foundation support with only one run of the program.

An example of fatigue results has been plotted in Figure 4.5 for design of PCC shoulder of a major highway as will be described in Chapter 5. Trial slab thicknesses of 5, 6, 7, 8 and 9 in. (12.5, 15, 17.5, 20, and 22.5 cm) were analyzed, and the data as obtained from the JCS-1 program is plotted as shown, to select minimum slab thickness based on limiting fatigue damage criteria. The minimum slab thickness allowed for a limiting fatigue damage of 10^{+3} is 7.3 in. (18.5 cm). Slab of any less thickness would exceed this limit. For example, if a 6.5 in. (16.5 cm) slab were constructed, a fatigue damage of over 10^{7} would occur at 20 years design period and hence would not be acceptable for structural design.

The program requires the input of a specific structural section as well as shoulder width, material properties, foundation, and traffic inputs. Parameters which are fixed for a given design situation include: mainline slab thickness (in case of rehabilitation), traffic, and foundation support factors. Parameters which can be controlled by the designer and their typical ranges include:

a. PCC slab - shoulder slab thickness (6 to 12 inches (15 to 30 cm))
    mainline slab thickness (in case of new construction
      8 to 14 inches (20 to 36 cm)
    shoulder width (3 to 10 feet (0.9 to 3 m))
    modulus of rupture (600-900 psi (4140-6200 kPa))

b. Load transfer across the mainline/shoulder joint

c. Subbase - type (granular or stabilized)
    - thickness (4 to 24 inches (10 to 61 cm))

There are many possible alternatives that can be developed that meet the PCC shoulder limiting design criteria and several should be examined so that the least cost design that is also compatible with mainline pavement and subsurface drainage requirements can be selected.

4.6 Structural Design Verification

Complete verification of the design procedure requires construction of the recommended designs in various climatic regions and observation of their performance over the structural design life. In lieu of this costly and time consuming procedure, a reasonable verification can be obtained by comparing the design of the two experimental plain jointed concrete shoulder projects built in Illinois (I-74 and I-80) with the new design, using JCS-1 computer program, of the same projects. The new design period would be set equal to the existing life of the projects under consideration, the design inputs would be the as-built construction data and the traffic applied to the project since its construction. Thus, the two projects are used to provide a partial verification of the procedure. The following steps were followed for each project:

1. As-built construction data for both the mainline pavement and the shoulder (material strength, geometry, mainline/shoulder tie, thicknesses, etc.) were obtained from IDOT. Traffic data over the life of the project were also obtained.

2. The foundation including subbase and subgrade and the mainline/shoulder tie and the shoulder width were kept the same as the existing projects, and all other necessary inputs to the structural design procedure were determined.

3. The new design slab thickness was compared with the actual slab thickness of the shoulder. Conclusions were made upon this comparison.

The results from each of the projects is discussed in the following:

1. I-74 (near Peoria, Illinois): The existing shoulder is 10 years old with PCC shoulder slab thickness of 6 inches (15 cm), mainline CRCP slab thickness of 7 inches (18 cm), shoulder width of 10 ft (3.05 m). The load transfer system used across the traffic lane/shoulder joint consists of #4 tiebars 30 in. (76 cm) long with 30 in. (76 cm) bar spacing. The foundation that supports the shoulder is 5 in. (12.5 cm) of granular subbase on top of a fine-textured subgrade.

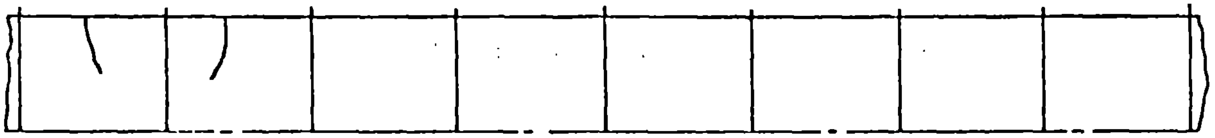
The 10 and 25 ft (3 and 7.6 m) long shoulder slabs did not require maintenance so far and are performing quite satisfactorily. The thickness of shoulder slab provided by the structural design procedure developed in this research was 6.0 in. (15.0 cm) with fatigue controlling the thickness as shown in Figure 4.6. As could be seen, the existing shoulder slab thickness is compatible with the one provided by the new design procedure. Thus, the new design procedure would be expected to provide a PCC shoulder that will last for at least 10 years with a minimum maintenance required.

2. I-80 (near Joliet, Illinois): This pavement is 9 years old, it has an 8 in. (20 cm) CRC mainline pavement tied to a PCC shoulder with slab thickness of 8 in. (20 cm) at the inner edge that tapers to 6 in. (15 cm) at the outside edge of the shoulder. The shoulder width is 10 ft (3.05 m) and the joint spacing is 20 ft (6.1 m).

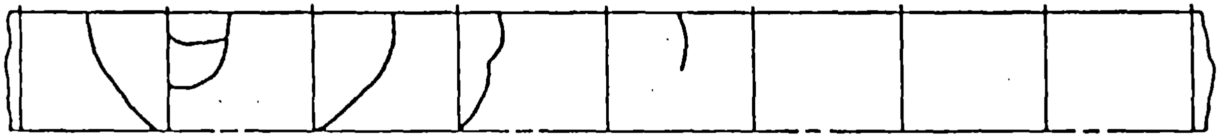
Similar to those on I-74, the shoulder slabs did not require any maintenance and are in a very acceptable condition. The existing structure of this PCC shoulder was redesigned (Figure 4.7) using the new design procedure and found to be compatible with the existing structure. Thus, here also the new design procedure is expected to provide a PCC shoulder that will last at least 9 years with a minimum maintenance required under the same traffic and otherwise conditions that exist on I-80.

Overall, while it is desirable to obtain additional data for further verification, the available results show that the new design procedure gives design that is compatible with the existing design practices that have provided long-term no-maintenance performance.

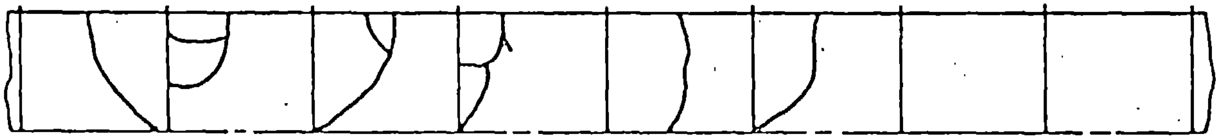
The design inputs and the assumptions that were used in re-designing the above two projects will be discussed in detail in Chapter 5 when a PCC shoulder is designed, using the new design procedure, under typical conditions (such as those on I-74 and I-80), as a PCC shoulder design example.



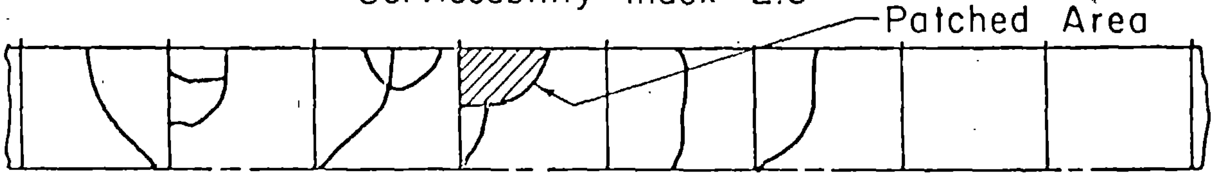
Cracking Index, 9 ft. Per 1000 Square Feet
Serviceability Index 4.0



Cracking Index, 42 ft. Per 1000 Square Feet
Serviceability Index 3.2



Cracking Index, 62 ft. Per 1000 Square Feet
Serviceability Index 2.9



Cracking Index, 92 ft. Per 1000 Square Feet
Serviceability Index 1.5

Figure 4.1. Initiation and Progression of Cracking in an 8.0 in. (203 mm) Non-reinforced Section on 3.0 in. (76 mm) Granular Subbase, 30-kip Single Axle Load, AASHO Road Test (32). (133 kN)

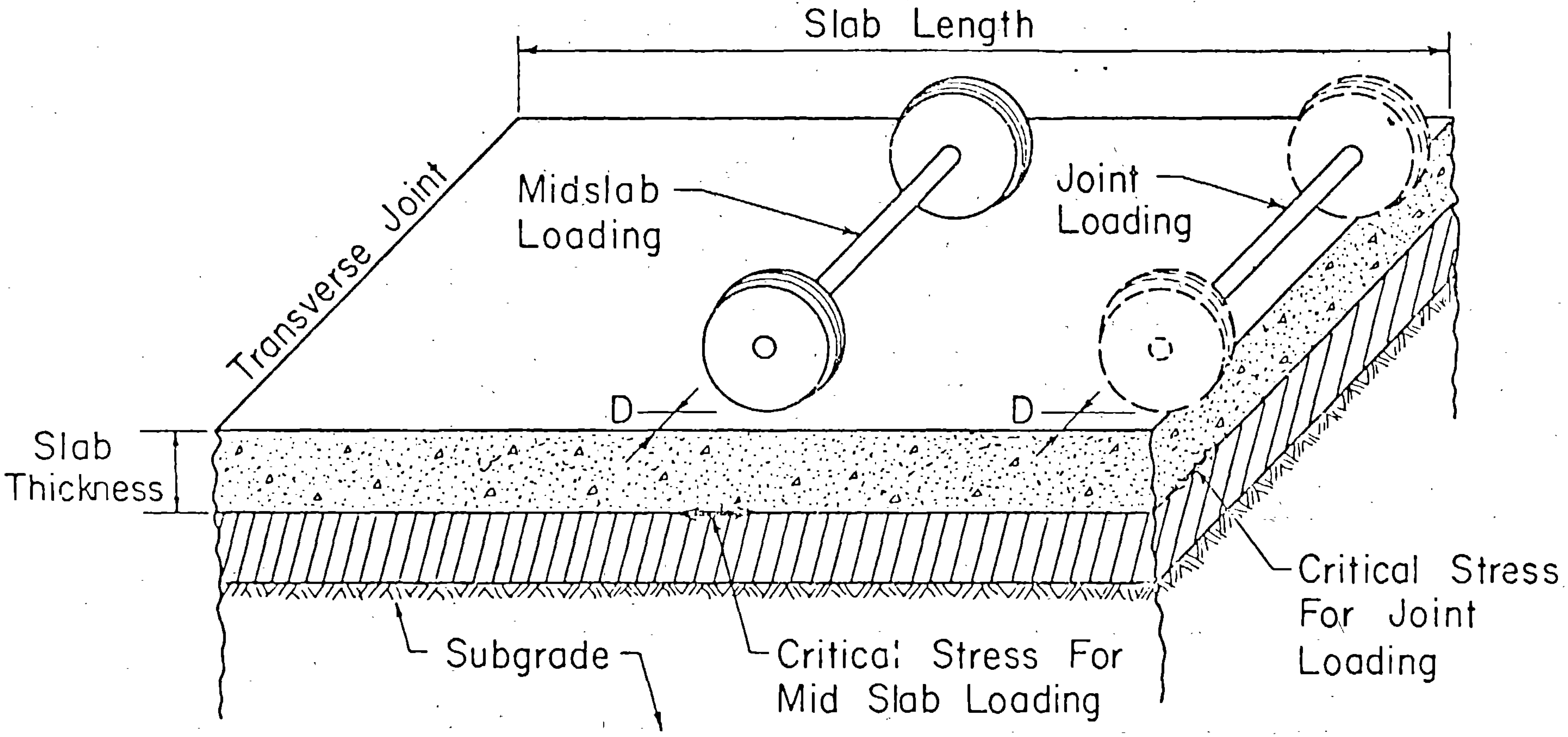


Figure 4.2. Illustration of Load Positions and Stresses Considered in Fatigue Analysis of Critical Points in Slab (32).

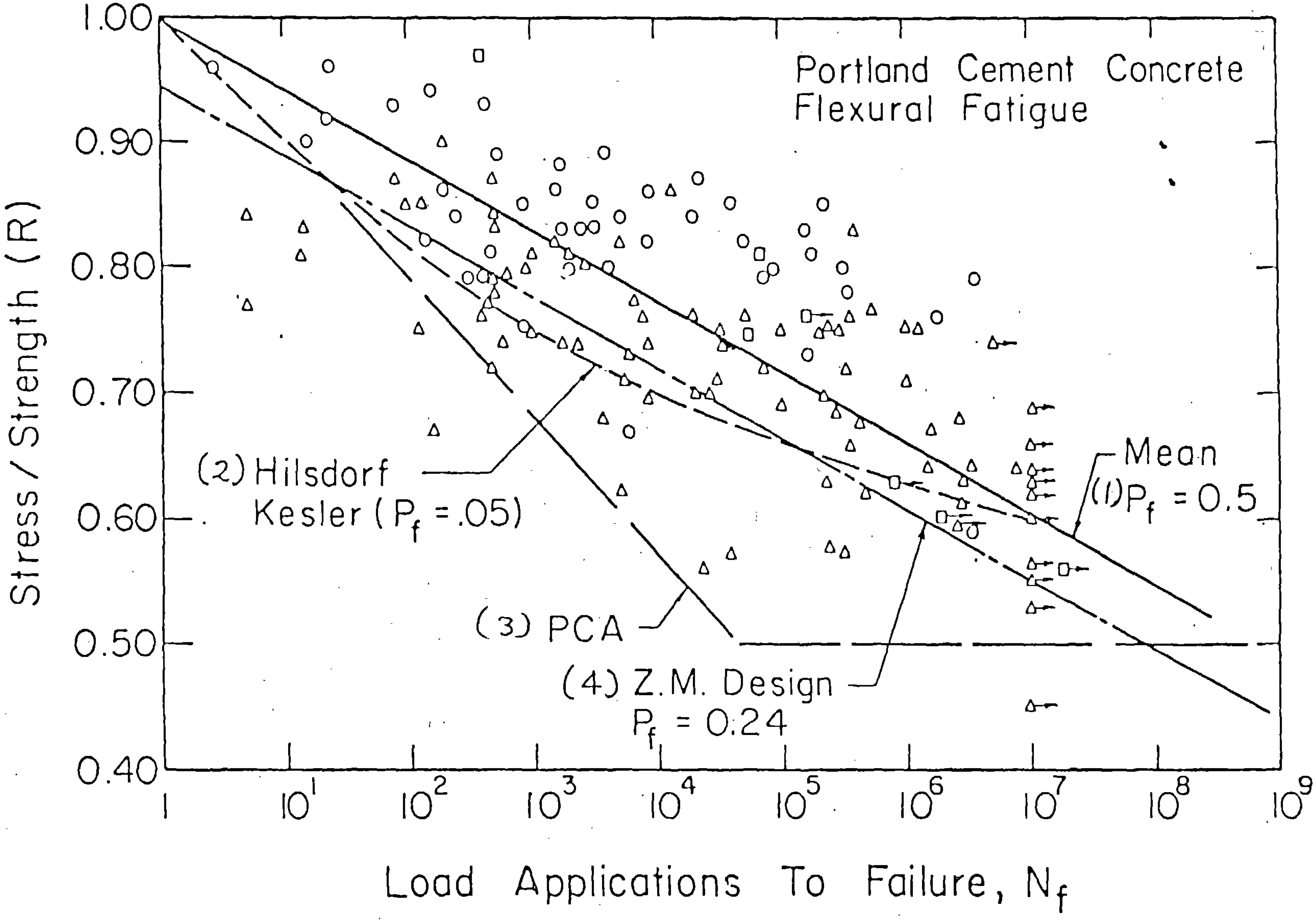


Figure 4.3 PCC Flexural Fatigue Data with Various Curves (32).

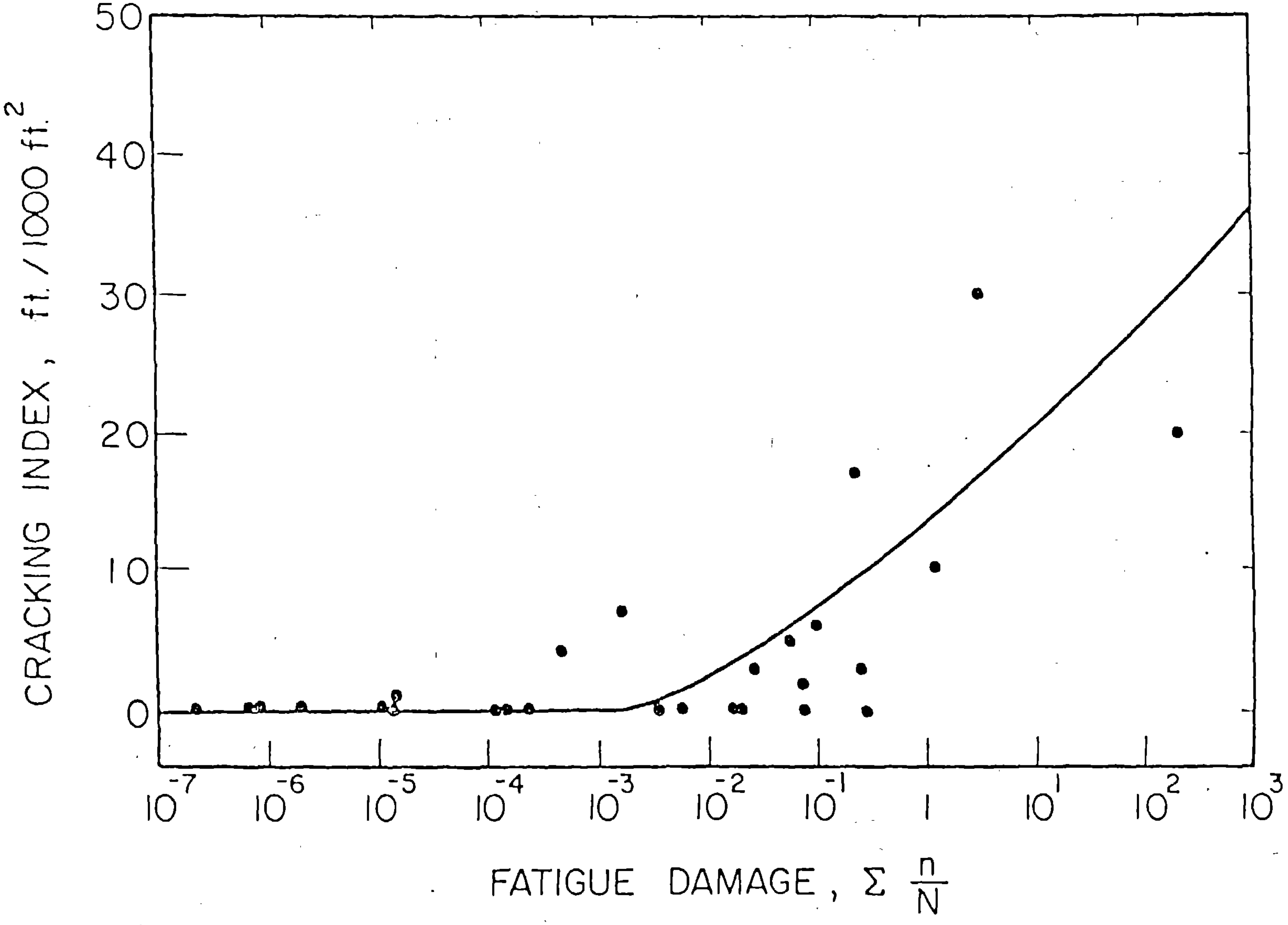


Figure 4.4. Cracking Index vs. Computed Fatigue Damage Developed For In Service Pavements.

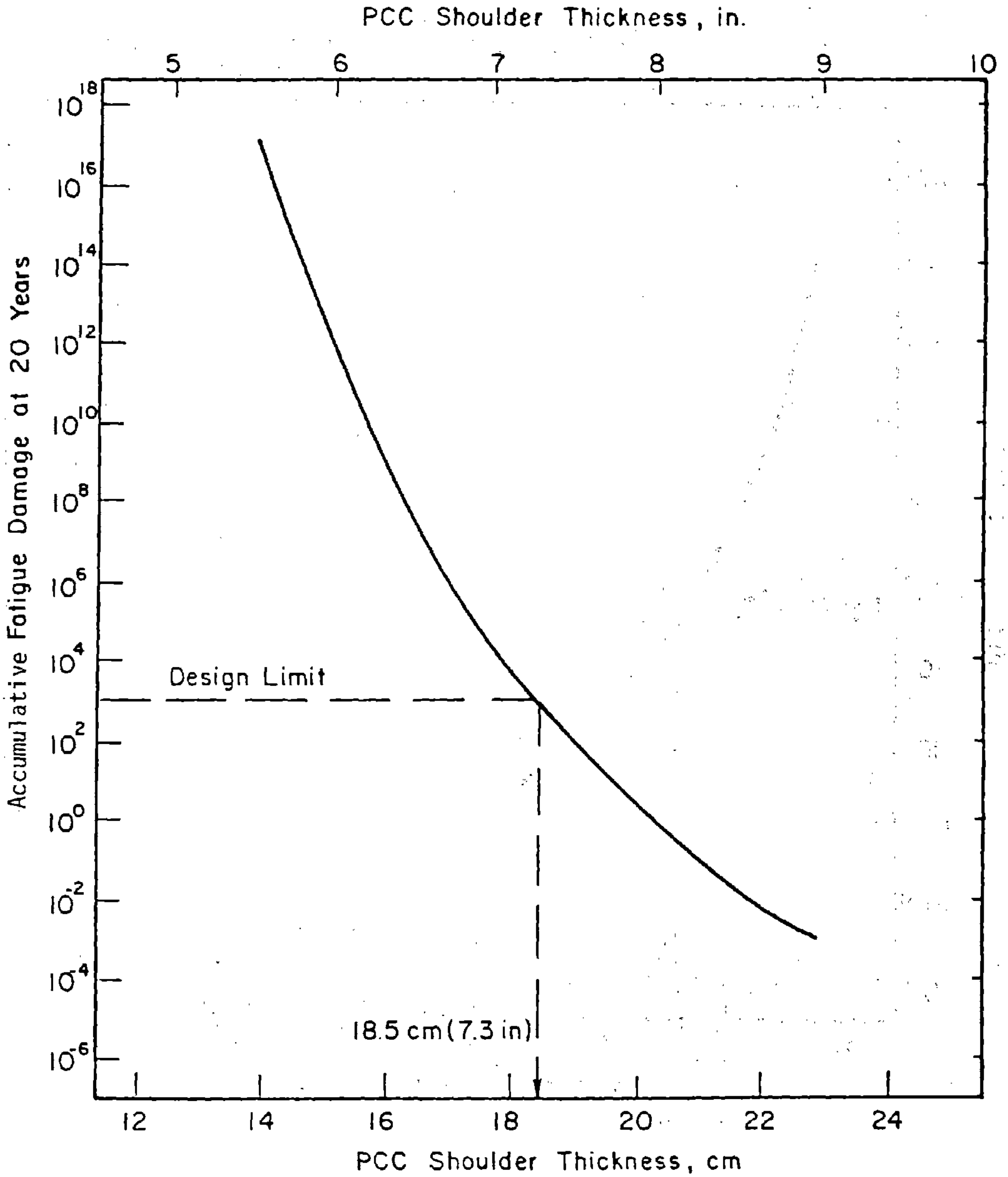


Figure 4.5. Fatigue Damage Plot Used to Determine PCC Shoulder Design Thickness.

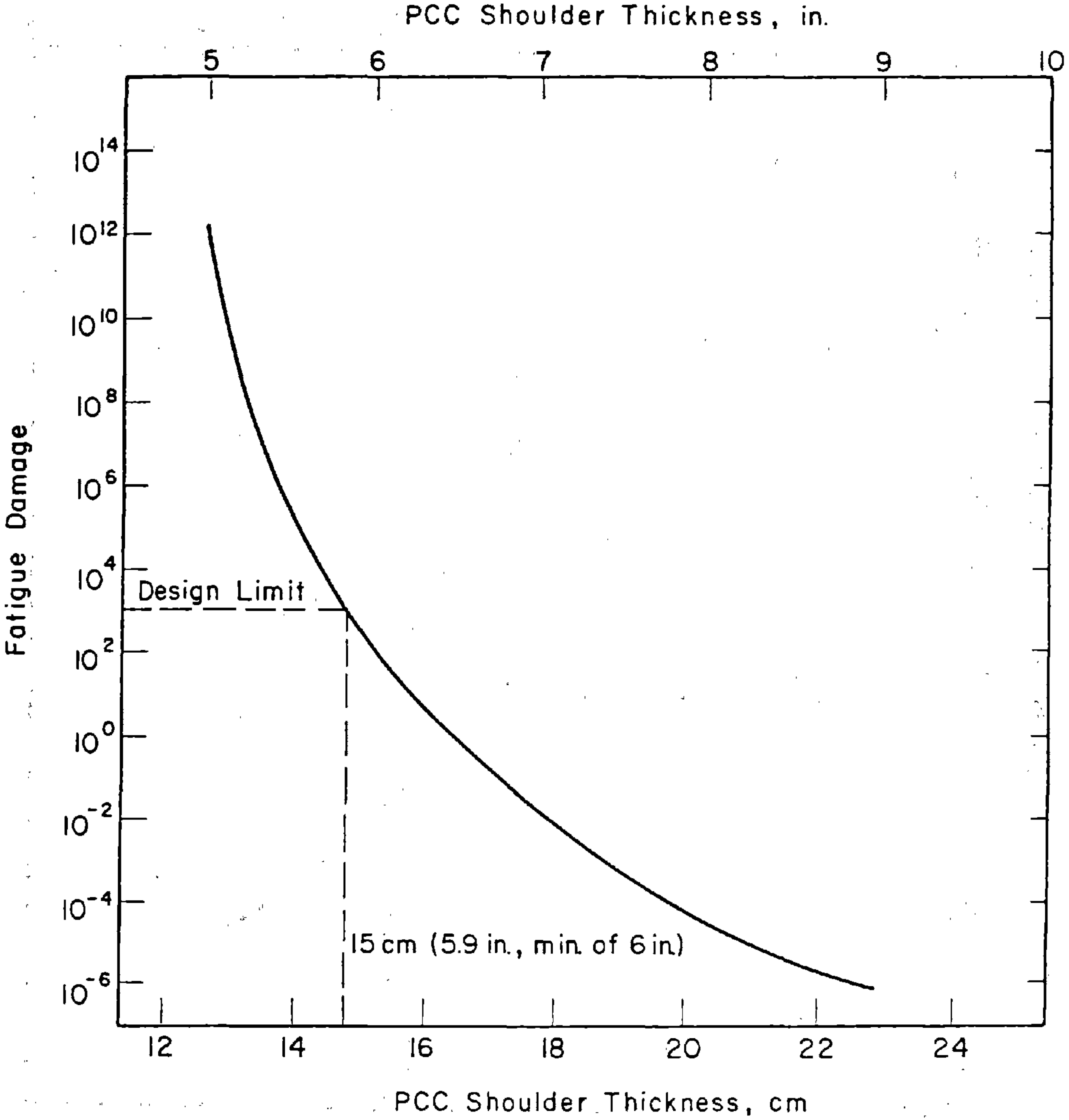
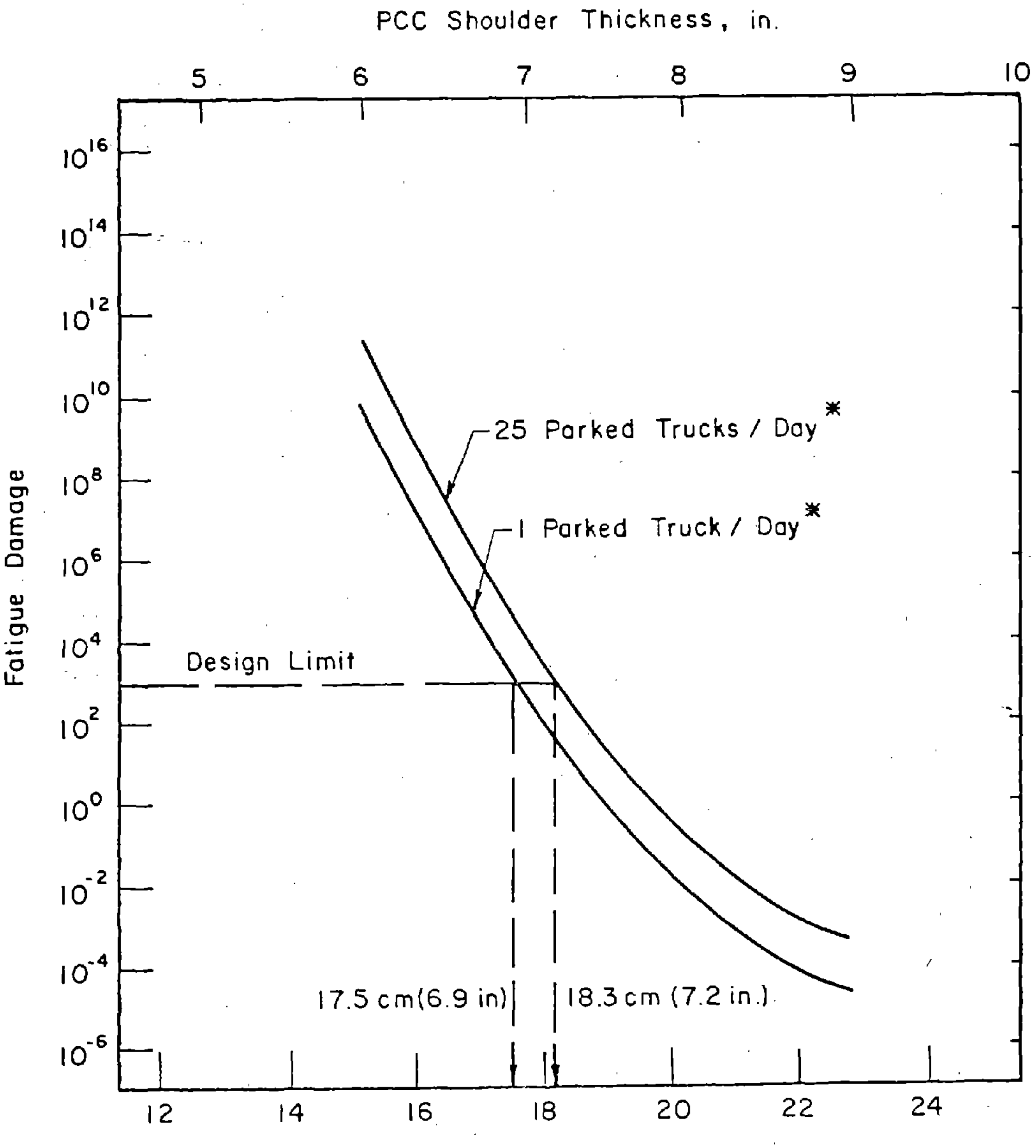


Figure 4.6. Structural Re-design of PCC Shoulder on I-74, Near Peoria, Illinois.



*For details see Section 5.1.3.

Figure 4.7. Structural Re-design of PCC Shoulder on I-80, Near Joliet, Illinois.

CHAPTER 5

SHOULDER DESIGN EXAMPLE

This design example is for a PCC shoulder located on a stretch of I-80 near Joliet, Illinois. The existing paved shoulder has reached a point of severe deterioration requiring complete reconstruction. Moreover, the mainline is an 8 in. (20 cm) CRC pavement that is experiencing excessive edge deflections due to the combined effect of heavy truck traffic and the loss of support at the vicinity of the outer edge of the pavement due to the excessive pumping of fine materials from under the CRC slab. Edge punchouts have occurred to the extent that major rehabilitation of the pavement is needed before deterioration becomes excessive. Construction of a PCC shoulder was selected as a method of rehabilitation to replace the existing deteriorated shoulder and to improve the performance of the adjacent traffic lane through edge support. The desired shoulder design period is 20 years. Details on selection of structural design inputs, interpretation of the computer program output, and selection of structural design are described. A sensitivity analysis of some of the design parameters is given in Section 5.5, to illustrate their relative effects on the design.

The design life, shoulder slab properties, traffic, foundation support, and traffic lane/shoulder tie are determined as recommended in Chapter 4.

5.1 Structural Design Inputs

5.1.1 Design Life

The desired period of the PCC shoulder life is 20 years. However, the pavement should perform for several additional years beyond 20 with routine maintenance before major rehabilitation is needed.

5.1.2 Slab Properties

1. Slab Thickness: Trial thicknesses of 5, 6, 7, 8, and 9 in. (12.5, 15, 17.5, 20, and 22.5 cm) are chosen for the shoulder slabs to provide a range of results which should encompass the appropriate slab thickness. The adjacent CRCP traffic lane is 8 in. (20 cm) thick.

2. Slab Width: A shoulder slab width of 10 feet (3 m) is standard practice for use on Interstate highways to accomodate emergency stops and other uses by the traveling vehicles.

3. The PCC shoulder slab length is not an input variable for the design procedure. Recommended length is 15 ft (4.6 m) as was previously discussed (Section 3.3).

4. Mean PCC Modulus of Rupture: The mean modulus of rupture, third point loading, at 28 days curing that will be used in this design example is 750 psi (5171 kPa).

5. Coefficient of Variation of PCC Modulus of Rupture: An average coefficient of variation of 10 percent for the PCC used in the shoulder construction will be used in this design.

5.1.3 Traffic

1. Average Daily Traffic at Beginning of Design Period: The initial ADT in both directions, as was obtained from the traffic data of the highway, is estimated to be 17,100 vehicles.

2. Average Daily Traffic at End of Design Period: The final ADT after 20 years is estimated from the transportation planning studies to be 39,100 vehicles. The increase over the 20 year period is expected to be reasonably linear.

3. Percent Trucks of ADT: The average percent of trucks including panels and pickups, is obtained to be 21 percent for the highway. This percentage will be used over the entire 20 years period.

4. Percent Trucks in Most Heavily Traveled Lane: The percentage of trucks in the most heavily traveled lane (outer lane) is calculated using the 4-lane rural equation, as recommended in Section 4.4.2, as follows:

$$\begin{aligned} LD &= 96.39 - 0.0004V \\ &= 96.39 - 0.0004\left(\frac{17{,}000 + 39{,}100}{2}\right) \\ &= 96.39 - 0.0004\,(28{,}100) \\ &= 85.15\% \end{aligned}$$

5. Percent Directional Distribution: Travel is approximately equal in each direction, and therefore, a value of 50 percent traffic in the design direction is selected.

6. Mean Axles Per Truck: Traffic data of the highway show an average of 2.6 axles per truck (including pickups and panels).

7. Percent Trucks That Use the Shoulder:

a. Encroached traffic: For this design example, a 10 mile (16.1 km) shoulder stretch was surveyed and an average length of total encroachments per truck over the length of the surveyed stretch was 0.24 miles (0.39 km) (obtained by multiplying the NE = 4.8 by the ED = 0.5 mi. as described in Section 4.4.3). This provides 2.4 percent trucks encroaching on the shoulder (0.24/10 x 100). This estimate was obtained by following behind randomly selected trucks and recording the length of their encroachment over the 10 mile (16.1 km) section.

b. Parked traffic: The percent trucks parked on a specific slab of the shoulder is estimated as follows: The surveyed shoulder stretch is 2 miles (3.2 km). Observations indicate that a truck drives on the shoulder an average distance of 200 ft (61 m) during a typical stop. Results from brief surveys of the project area show that the number of parked trucks could range from 1 to 25 with a mean of about 9 per day. This range is used in design as an example. Following the procedures in Section 4.4.3, the percent of parked trucks of total truck traffic in one direction is computed as follows:

1 Parked Truck/day

$$PPT = \frac{N \times p \times 100}{ADT \times T \times DD}$$

$$= \frac{1 \times \frac{1}{10560/200} \times 100}{28100 \times .21 \times 0.5}$$

$$= 0.00064 \text{ percent}$$

25 Parked Trucks/day

$$PPT = 0.00064 \times 25 = 0.016$$

8. Axle Load Distribution: The axle load distribution was established from weighings of axle loads at a loadometer station near the project. This distribution is shown in Table 5.1. This axle load distribution should be modified if conditions indicate future legal load changes during the 20 year period.

5.1.4 Foundation Support

The shoulder will be placed on embankment materials mostly fine-textured. The soil is an AASHO Classification A-6 and A-7-6 materials.

The materials are principally relatively thin glacial drift of Wisconsian age overlaying dolomitic limestone bedrock (6). The k-value on top of the subgrade is estimated using Reference 32. An 8 in. (20 cm) layer of opengraded granular materials was evaluated as a subbase for the shoulder concrete slab. The k-value on top of the subbase is estimated using Reference 32 to be about 200 pci (54.2 MN/m^3).

The initial erodability of the shoulder foundation is zero and the final erodability is estimated to be 8 in. (20 cm) for the granular subbase.

5.1.5 Traffic Lane/Shoulder Tie

As was discussed in Section 4.4.5, tiebars could be installed in the existing mainline pavement and the new PCC shoulder to provide some load transfer across the joint. For this example, a load transfer system consists of tied-butt joint with #4 tiebars, 30 in. (76 cm) long, placed 18 in. (46 cm) center to center will be used to provide the load transfer across the longitudinal joint.

An average value of 80% (based on deflection) will be used for the load transfer efficiency of this joint to account for the effect of millions of repeated loads applied near the joint (as recommended in Section 4.4.5). The degree of load transfer efficiency, which is defined as the ratio of the deflection of the unloaded slab over that of the loaded slab at the joint is not necessarily the same degree of the efficiency when it is defined as the ratio of the flexural stress experienced by both slabs at the joints. The finite element model used in the analysis does not take this factor into consideration. Thus, an adjustment for the difference between the two efficiencies is needed. A more comprehensive FE model (59) which accounts for the difference between the two efficiencies is used to establish an adjustment curve which can be used in design. Figure 3.2 is plotted to show the relationship between the Load Transfer efficiency based on deflections and that based on stresses and used for adjustment. Thus, for this design example, with 80% LT efficiency (based on deflection) and using Figure 3.2 for adjustment, 42% LT efficiency (based on stress) is obtained and will be used for design.

5.2 Interpretation of Program Outputs

The program outputs a complete listing of inputs and results for each trial design configuration (trial slab thickness for this example). Trial analysis were run for 5, 6, 7, 8, and 9 in. (12.5, 15, 17.5, 20, and 22.5 cm) PCC shoulder slabs placed on the granular subbase. A listing of program inputs for the 9 in. (22.5 cm) PCC slab trial is shown in Table 5.2. The inputs should be carefully checked to eliminate any possible errors.

Results of the fatigue damage accumulated during each year of the shoulder design life, as printed out for 9 in. (22.5 cm) slab, are shown in Table 5.3. The total fatigue damage during the whole design period is also printed in the same table. The results are shown for two different locations of the shoulder slab; due to parked traffice (at the outer edge) and due to encroached traffic on the shoulder (at the inner edge). A summary of the results for 5, 6, 7, 8, and 9 in. (12.5, 15, 17.5, 20, and 22.5 cm) slabs is given in Table 5.4 which will be used to select the design structure in Section 5.3.

5.3 Selection of Structural Design

The results given in Table 5.5 are plotted as shown in Figure 5.1. The minimum design slab thickness at the inner and outer edge of the shoulder are determined as indicated (although the inner edge thickness is shown as 5.1 in. (13.0 cm), a minimum of 6 in. (15 cm), as recommended in Section 3.3 will be used):

Outer edge minimum thickness = 7.3 in. (18.5 cm) due to parked traffic

Inner edge minimum thickness = 6.0 in. (15.0 cm) due to encroached traffic with 80% LT Eff. across the joint

Therefore, for this design life, slab properties, traffic, foundation support, and traffic lane/shoulder joint load transfer conditions, a structural design thickness would be 7.3 in. (18.5 cm) minimum of PCC over an 8 in. (20 cm) of open-graded granular subbase.

By decreasing the volume of shoulder parked traffic in the 2-mile (3.2 km) surveyed stretch from 25 trucks per day to only one truck per day as discussed earlier in Section 5.1.3, the structural design thickness of the PCC shoulder would be reduced to 7.0 in. (17.8 cm) as shown in Figure 5.3.

The previous structural design selections (Figure 5.1) were obtained for a specific subbase, shoulder width and concrete strength. There are other alternatives, however, which could be analyzed in order to obtain the most economical structural design. A summary of a few alternatives is shown in Table 5.5. The other design inputs were held constant for each of these alternatives as a single parameter was varied as shown. Required thickness varies from 6.0 in. to 7.4 in. (15.0 to 18.8 cm) depending upon the values of the design parameters controlled by the designer. Each alternative should be further designed and economic analysis conducted to determine the most economical alternative.

5.4 Final Design Selection Relative to Cost

A complete cost analysis of the alternative designs that meet the limiting criteria must be conducted. Since low shoulder structural maintenance is expected over the 20-year design period, the cost analysis can be based upon the first cost of the pavement. The design alternative providing the lowest initial construction cost should be chosen as the optimum structural design alternative.

5.5 Sensitivity Analysis

A sensitivity analysis is conducted to illustrate the effect of changes in several of the design parameters on required shoulder slab thickness and to show the reasonableness of the design procedure. The average conditions are set as described in the design of the example project, and then one parameter at a time is varied over a range that might exist in actual situations. Shoulder width is the first parameter varied form 1.5 to 10 ft. (0.46 - 3.05 m) as shown in Figure 5.3a. The shoulder slab thickness required decreases from 7.9 to 7.0 in. (20-17.8 cm) as shoulder width increases from 1.5 to 10 ft (0.46-3.05 m). A change in the 28-day modulus of rupture from

650 to 900 psi (4500 to 6200 kPa) produces a change of about 1.4 in. (3.6 cm) in PCC shoulder slab thickness as shown in Figure 5.3b. A change in foundation conditions from no subbase over clay subgrade to 8 in. (20 cm) granular subbase to 6 in. (15 cm) of cement stabilized subbase reduces the required shoulder slab thickness by about 0.2 in. (0.50 cm), and 1.1 in. (2.8 cm), respectively, as shown in Figure 5.3c. The variation of PCC strength shown in Figure 5.3d is indicated by the coefficient of variation from excellent quality control (5 percent) to poor (20 percent) causes an increase in required PCC shoulder slab thickness of approximately 0.7 in. (1.8 cm).

The effect of increasing the number of trucks that park on the shoulder stretch from 1 truck to 25 trucks per day as shown in Figure 5.3 produces a change in required PCC shoulder slab thickness of 0.3 in. (0.8 cm).

Table 5.1. Determination of Axle Load Distribution for Use in Design of Project.

Axle Load Group (kips)	Design Axle Load Distribution (percent)
Single Axles	
0-3	5.75
3-7	10.33
7-8	7.76
8-12	20.54
12-16	4.37
16-18	1.77
18-20	1.02
20-22	0.54
22-24	0.34
24-26	0.14
26-30	0.04
30-32	0.01
32-34	0.01
Tandem Axles	
0-6	0.27
6-12	13.34
12-18	7.05
18-24	5.51
24-30	14.92
30-32	3.61
32-34	1.4
34-36	0.5
36-38	0.25
38-40	0.16
40-42	0.11
42-44	0.08
44-46	0.07
46-50	0.07
50-52	0.02
52-54	0.01
54-56	0.01
TOTAL	100.00

(1 kip = 4.444 kN)

Table 5.2. Listing of Computer Program Inputs for Example Design Problem for 9-in. Shoulder Slab.

```
                              PORTLAND CEMENT CONCRETE PLAIN JOINTED
                              PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
**********************************************************************************
 PROBLEM # 5
                    PCC SHOULDER DESIGN ON I-80 NEAR JOLIET,ILLINOIS

**********************************************************************************

                                    INPUT DATA
                                    **********

 DESIGN CRITERIA
****************

   SHOULDER DESIGN LIFE (YEARS)                                                 20.00

 SLAB PROPERTIES
****************

   SHOULDER THICKNESS - INS.                                                     9.00
   TRAFFIC LANE THICKNESS - INS.                                                 8.00
   SHOULDER WIDTH - FT.                                                         10.00
   MEAN PCC MODULUS OF RUPTURE (28-DAYS) - PSI                                 750.00
   COEFFICIENT OF VARIATION OF PCC MODULUS OF RUPTURE - %                       10.00
   LOAD TRANSFER EFF. BETWEEN SHOULDER AND TRAFFIC LANE - %                     42.00

 TRAFFIC
********

   AVERAGE DAILY TRAFFIC AT BEGINNING OF DESIGN PERIOD                         17100.
   AVERAGE DAILY TRAFFIC AT END OF DESIGN PERIOD                               39100.
   PERCENT TRUCKS OF ADT                                                        21.00
   PERCENT TRUCKS IN HEAVIEST TRAVELED OR DESIGN LANE                           85.15
   PERCENT DIRECTIONAL DISTRIBUTION                                             50.00
   MEAN AXLES PER TRUCK                                                          2.60
   LENGTH OF SURVEYED SHOULDER STRETCH - MI.                                    10.00
   AV. LENGTH OF TOTAL ENCROACHMENTS PER TRUCK IN THE SH. STRETCH - MI.          0.240
   PERCENT OF TRUCKS THAT PARK ON THE SHOULDER                                 0.01600
   NUMBER OF SINGLE AXLE LOAD INTERVALS                                            13
   NUMBER OF TANDEM AXLE LOAD INTERVALS                                            17
```

(1 in. = 2.54 cm)
(1 psi = 6.894 kPa)
(1 ft = .3048 in.)

Table 5.2. Continued.

```
S.A.L. DISTRIBUTION TABLE
           WEIGHT RANGE          PERCENT
            (POUNDS)

            0. -  3000.           5.75
        3001. -  7000.          10.33
        7001. -  8000.           7.76
        8001. - 12000.          20.54
       12001. - 16000.           4.37
       16001. - 18000.           1.77
       18001. - 20000.           1.02
       20001. - 22000.           0.54
       22001. - 24000.           0.34
       24001. - 26000.           0.14
       26001. - 30000.           0.04
       30001. - 32000.           0.01
       32001. - 34000.           0.01

T.A.L. DISTRIBUTION TABLE
           WEIGHT RANGE          PERCENT
            (POUNDS)

            0. -  6000.           0.27
        6001. - 12000.          13.34
       12001. - 18000.           7.05
       18001. - 24000.           5.51
       24001. - 30000.          14.92
       30001. - 32000.           3.61
       32001. - 34000.           1.40
       34001. - 36000.           0.50
       36001. - 38000.           0.25
       38001. - 40000.           0.16
       40001. - 42000.           0.11
       42001. - 44000.           0.08
       44001. - 46000.           0.07
       46001. - 50000.           0.07
       50001. - 52000.           0.02
       52001. - 54000.           0.01
       54001. - 56000.           0.01


FOUNDATION SUPPORT
******************

  DESIGN MODULUS OF FOUNDATION SUPPORT (K) - PCI                                  200.00

  ERODABILITY OF FOUNDATION AT BEGINNING OF DESIGN PERIOD (INS.)                    0.0
  ERODABILITY OF FOUNDATION AT END OF DESIGN PERIOD (INS.)                          8.00
```

(1 bf = 4.448 N)

(1 pci = .271 MN/m^3)

Table 5.3. Results From JCS-1 Computer Program for 9-in. Shoulder Slabs.

```
                      PORTLAND CEMENT CONCRETE PLAIN JOINTED
                      PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
********************************************************************************

PROBLEM # 5
                         PCC SHOULDER DESIGN ON I-80 NEAR JOLIET,ILLINOIS

********************************************************************************

RESULTS - ACCUMULATED FATIGUE DAMAGE OF P.C.C. SHOULDER
*******

         SUMMARY FOR DESIGN PERIOD

YEAR     PARKED TRAFFIC      ENCROACHED TRAFFIC

   1          0.332D-04            0.332D-07
   2          0.352D-04            0.450D-07
   3          0.372D-04            0.608D-07
   4          0.392D-04            0.820D-07
   5          0.412D-04            0.111D-06
   6          0.432D-04            0.149D-06
   7          0.452D-04            0.200D-06
   8          0.472D-04            0.269D-06
   9          0.492D-04            0.361D-06
  10          0.512D-04            0.484D-06
  11          0.532D-04            0.649D-06
  12          0.552D-04            0.869D-06
  13          0.572D-04            0.116D-05
  14          0.592D-04            0.156D-05
  15          0.612D-04            0.208D-05
  16          0.632D-04            0.279D-05
  17          0.652D-04            0.372D-05
  18          0.672D-04            0.498D-05
  19          0.692D-04            0.665D-05
  20          0.712D-04            0.888D-05




TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO PARKED TRAFFIC IS          0.104D-02

TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO ENCROACHED TRAFFIC IS      0.351D-04
```

Table 5.4. Summary of Fatigue Data for Example Problem Design.

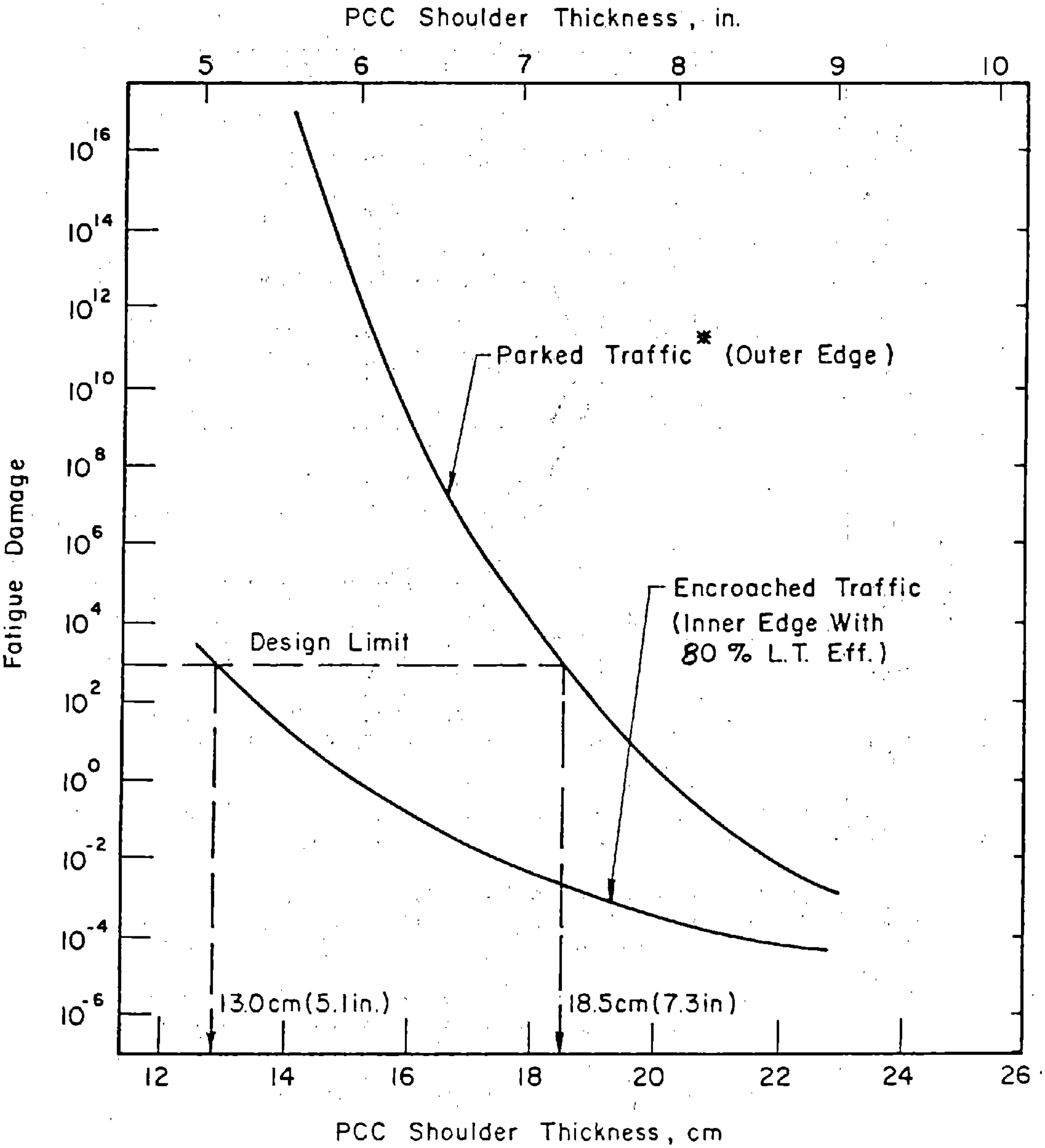
Slab Thickness in inches	Fatigue Damage	
	Due to Parked Traffic*	Due to Encroached Traffic
5	4.81×10^{24}	3.53×10^{3}
6	5.74×10^{11}	6.95×10^{-1}
7	3.34×10^{4}	6.52×10^{-3}
8	1.06×10^{0}	3.16×10^{-4}
9	1.04×10^{-3}	3.51×10^{-5}

* The volume of parked traffic used in this table is 25 trucks/day in the 2 mile shoulder stretch surveyed. (3.2 km)

Table 5.5. Summary of Structural Alternate Designs for PCC Shoulder Example Problem

Alternative	Design Parameter			Design Thickness (ins.)
	Slab Width (ft)	Subbase Type	PCC Strength (psi)	
1	10	8 in. Granular	750	7.3
2	10	6 in. Stabilized	750	6.4
3	10	8 in. Granular	900	6.6
4	10	6 in. Stabilized	900	5.8 (min. 6.0)
5	7	8 in. Granular	750	7.4
6	7	6 in. Stabilized	750	6.5
7	7	8 in. Granular	900	6.7
8	7	6 in. Stabilized	900	5.9 (min. 6.0)

(1 in. = 2.54 cm)
(1 psi = 6.894 kPa)
(1 ft = .3048 m)



*The parked traffic volume used in this figure is 25 trucks/day in the 2-mile shoulder stretch surveyed.

Figure 5.1. The Effect of PCC Shoulder Slab Thickness on the Accumulated Fatigue Damage at Both Shoulder Edges.

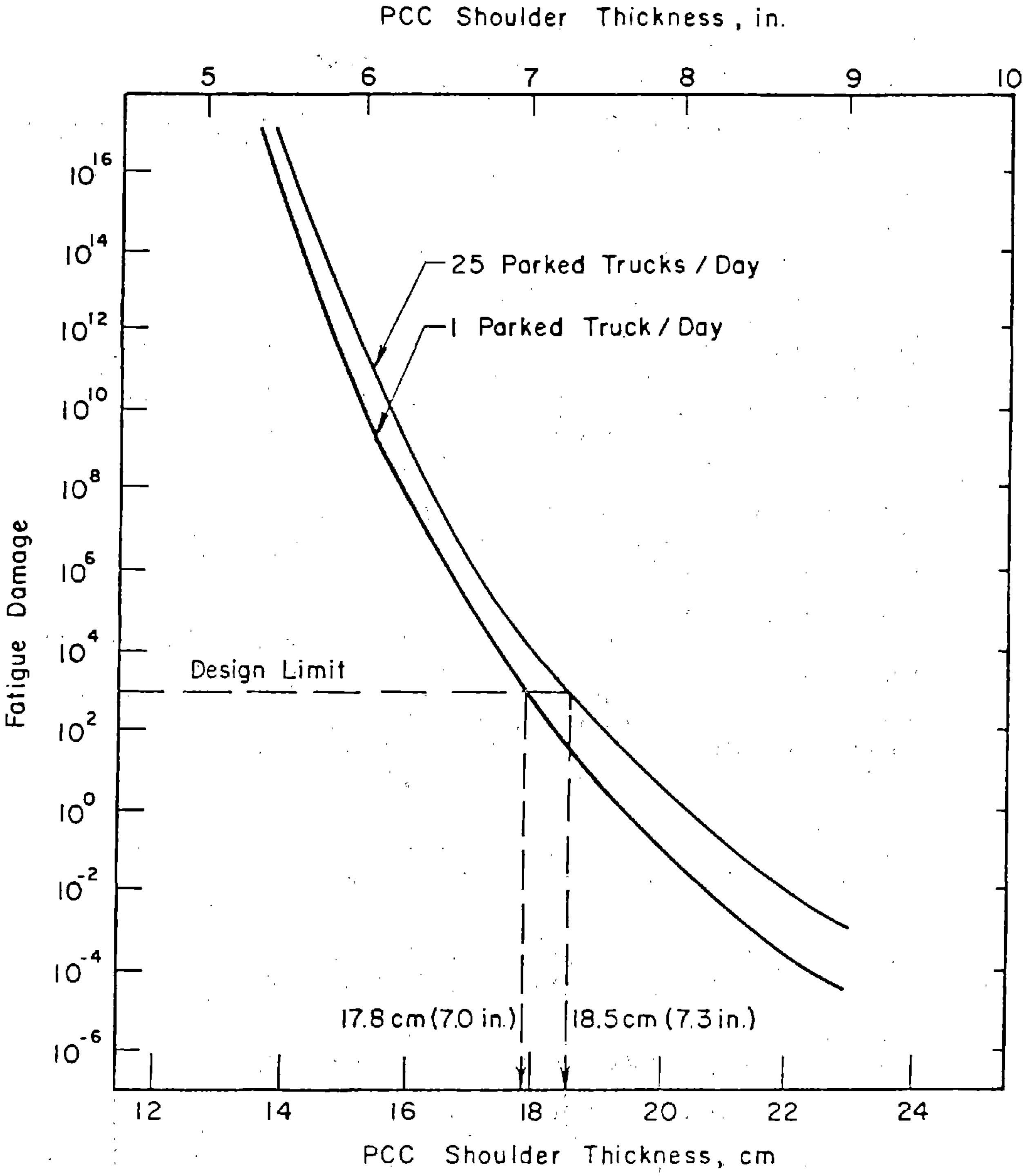
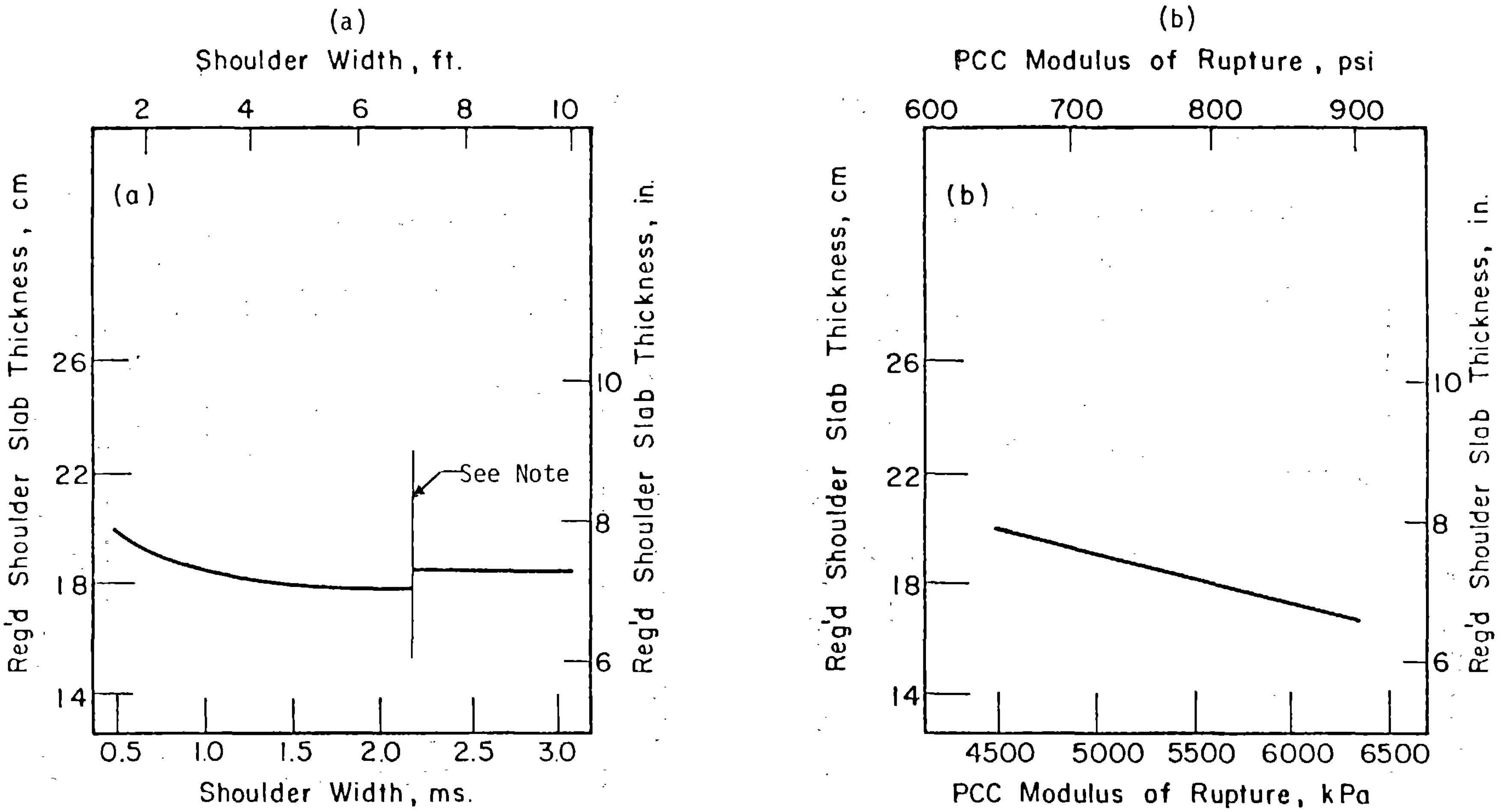


Figure 5.2. The Effect of Parked Truck Volume on the Accumulated Fatigue Damage at the Shoulder Outer Edge.



Note: The sudden increase in shoulder thickness is due to the assumption that both wheels of axle will be accomodated on the shoulder when its width is 7 ft. or more.

Figure 5.3. Sensitivity Analysis of Selected Design Parameters for Example Project.

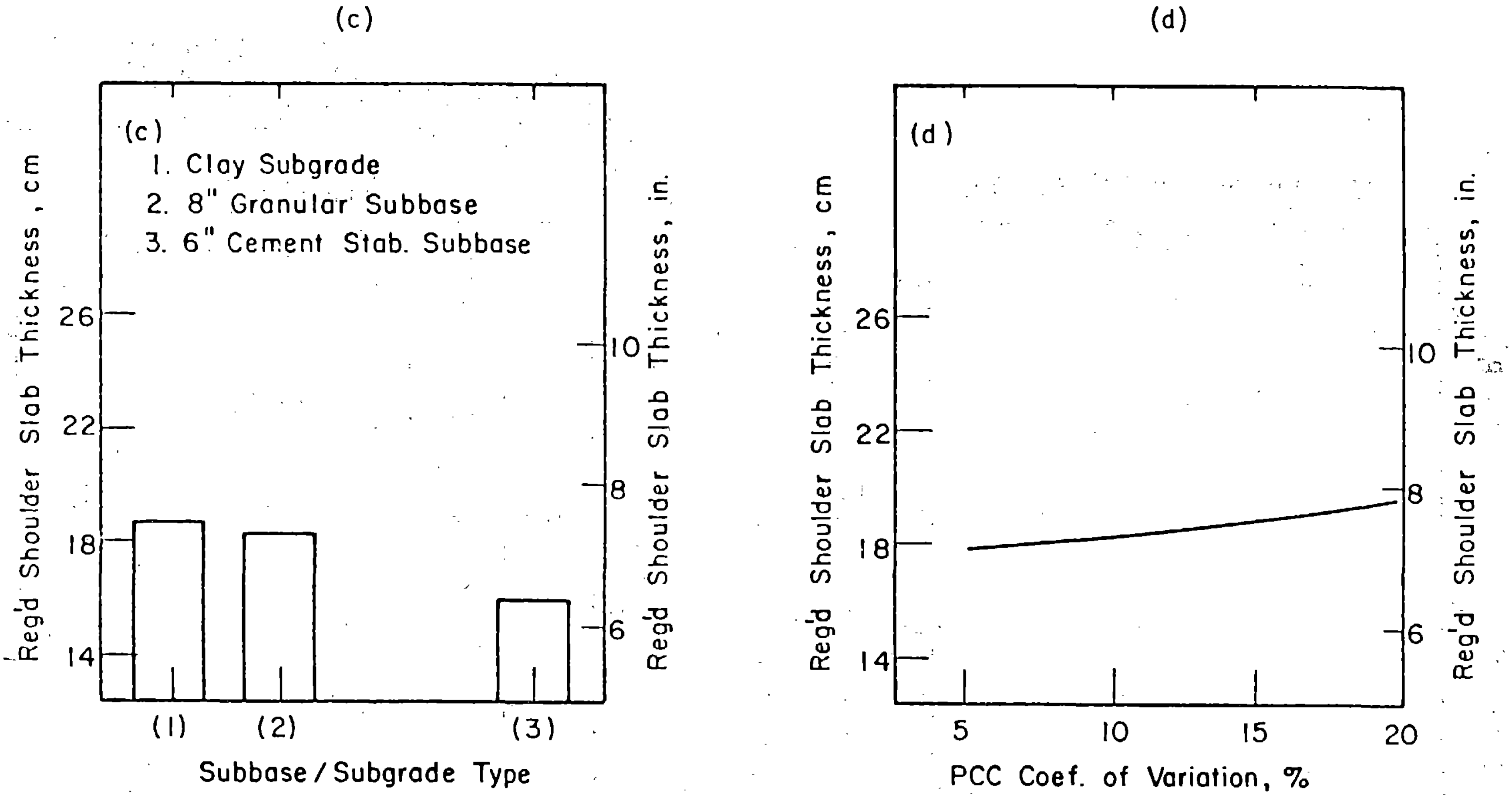


Figure 5.3. Continued.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

A comprehensive design procedure for plain jointed concrete shoulders has been developed. This report describes the PCC shoulder performance and current design practice, field and analytical studies upon which the procedure is based, and provides research documentation. Based upon these results a PCC shoulder design example was prepared that contains all necessary procedures needed for actual design. A computer porgram designated JCS-1 was developed that is used to obtain fatigue damage data for use in structural design. The program is written in FORTRAN and is easily adaptable to most computers. The design procedure developed in this research can be used for both new construction and rehabilitation purposes.

1. From a review of the literature about PCC shoulder performance and current design practice, it has been concluded that a) highway shoulders have been of concern to highway officials from the very beginning of highway construction. Their importance is multifold as they are used to provide structural support for encroaching traffic loads from the adjacent traffic lane, emergency parking, and regular traffic if the shoulder is used as a detour around a closed lane or as an additional lane during peak traffic hours; b) a need was found for construction of full-depth monolithic pavement throughout the entire width of the shoulder area, eliminating the "drop-off" or "raised shoulder" with maintaining a tight joint at the shoulder inner edge, construction of paved shoulders that will help improve the performance

of the adjacent mainline pavement, and eliminating shoulder structural distress due to traffic loadings; c) the use of Portland cement concrete shoulders is increasing because recent studies have shown that they perform better and may be more economical in the long-run than other types of paved shoulders; d) there is no rational structural design procedure for PCC shoulders available and the current design practice of PCC shoulders is based mainly upon trial and error, engineering judgement, and past performance of the few experimental PCC shoulders in service at the present time.

2. Field surveys of three experimental plain jointed concrete shoulders built in Illinois showed that PCC shoulders have performed satisfactorily over time periods of over 10 years under heavy traffic, and are expected to continue to perform as well in the future. Therefore, it is possible to construct a concrete shoulder that will last throughout its intended design life with only routine maintenance applied. Some sections, however, exhibited distress that has required maintenance. The following distress types commonly occurring in PCC shoulders must be considered in design and thereby prevented: a) lane/shoulder drop-off or heave and joint separation, b) transverse cracking, c) spalling, and d) blow-ups.

3. A comprehensive fatigue damage analysis procedure was developed that permits direct control of slab cracking. Stress due to traffic loadings are considered in the analysis through the use of the finite element method. A fatigue damage limiting design criteria was determined from field data.

4. Design recommendations were developed for joint spacing, the use of uniform shoulder thickness, determining the traffic that uses

the shoulder, and load transfer across the traffic lane/shoulder joint. These factors were found to have a major effect on the structural adequacy of PCC shoulder as well as its effect on improving the performance of the adjacent traffic lane.

5. An example design application is provided that describes the use of the procedure in detail. The economic justification of the selection of the final PCC shoulder design is an important factor and should be a criterion in giving the priority of one design over another.

6. Adequacy of the design procedure is assessed in terms of structural sufficiency and also through a sensitivity analysis. The results show that the procedure provides designs that are structurally compatible with those projects that have performed in a satisfactory manner over long periods of time and subject to heavy traffic.

7. The design procedure and results documented herein can be used for new construction of PCC shoulders and also for rehabilitation of existing concrete pavements. The effect of the following variables can also be analyzed: shoulder slab thickness, mainline slab thickness, concrete strength and variation, shoulder width, traffic that uses the shoulder, traffic overloads, foundation support (subbase and subgrade including degree of saturation), joint efficiency across the traffic lane/shoulder longitudinal joint, and others.

6.2 Recommendations

The structural PCC shoulder design procedure documented herein is ready for trial implementation. It has been partially verified and shown to give adequate shoulder structures. Many additional findings related to the design of PCC shoulders are believed to be significant and useful in minimizing the occurrence of distress and thus reducing maintenance costs.

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APPENDIX A

INPUT GUIDE - JCS-1 PROGRAM

Design of Plain Jointed Concrete Shoulders

IDENTIFICATION OF PROBLEM

Three Cards:

20A
20A
20A

1 80

Enter descriptive identification of design project; date of run, project number, designer, etc. (Any or all of the cards may be left blank).

DESIGN CRITERIA DATA

One Card:

F10.0	

1 10 80

DLIFE

DLIFE = PCC shoulder design life (years)

SLAB PROPERTIES

One Card:

F5.0	F5.0	F5.0	F5.0	F5.0	F5.0	

1 5 10 15 20 25 30 80

H1 H2 B FF FCV EFF

H1 = PCC shoulder thickness - inches

H2 = PCC traffic lane thickness - inches

B = shoulder width - feet

FF = Mean PCC modulus of rupture (28 days) - psi

FCV = Coefficient of variation of PCC modulus of rupture - percent

EFF = Load transfer efficiency between shoulder and traffic lane - percent

TRAFFIC DATA

One Card:

F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F5.0	F5.0	F10.0
ADTI	ADTF	T	LD	DD	A	LSS	LEPT	PEPT

1 10 20 30 40 50 60 65 70 80

ADTI = Average daily traffic at beginning of design period - two direction

ADTF = Average daily traffic at end of design period - two direction

T = Percent trucks in ADT

LD = Percent trucks in heaviest travelled or design lane

DD = Percent direction distribution

A = Mean axles per truck

LSS = Length of surveyed shoulder stretch - miles (use 10 miles)

LEPT = Average length of total encroachments per truck in the surveyed shoulder stretch - miles

PEPT = Percent of trucks that park on the surveyed shoulder stretch relative to the design lane truck traffic.

One Card:

I5	I5	
KK	KSAL	

1 5 10

KK = Number of axle load distribution groups (single plus tandem)(right justify), (maximum 40)

KSAL = Number of single axle load distribution groups (right justify)

As many cards as needed:

F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0
F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0

1 10 20 30 40 50 60 70 80

LOAD(I)

[LOAD (I), I = 1, KK]

LOAD(I) = The highest value of each axle load distribution group (first enter single axle loads [KSAL] and then tandem axle loads) - pounds

As many cards as needed:

F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0
F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0	F10.0
10	20	30	40	50	60	70	80

DIST(I)

[DIST (I), I = 1, KK]

DIST(I) = The percentage axle loads in each of the KK axle load groups input in the previous card (first enter single axle percentage and then tandem axle percentage).

FOUNDATION SUPPORT DATA

One Card:

F10.0	F10.0	
10	20	80
K	ERODEF	

K = Design modulus of foundation support - pci

ERODEF = The amount of erodability of foundation under the PCC shoulder at the end of design life - inches (max. 12 inches)

The following four cards may be added for each additional PCC shoulder-traffic lane configuration to be analyzed:

IDENTIFICATION OF PROBLEM

Three cards (same as first trial thickness):

20A4
20A4
20A4

1 80

SLAB PROPERTIES

One Card:

F5.0	F5.0	F5.0	F5.0	

1 5 10 15 20 80

H1 H2 B EFF

H1 = Shoulder thickness - inches

H2 = Traffic lane thickness - inches

B = Shoulder width - feet

EFF = Load transfer efficiency between shoulder and traffic lane - percent (Note: this is stress efficiency - use Figure 3.2 to determine stress efficiency from deflection efficiency).

FINAL CARD OF DATA DECK

/*

1 80

/* indicates end of data deck

APPENDIX B
SAMPLE INPUT/OUTPUT

IUB

FORTRAN Coding Form

Printed in U.S.A.

PROGRAM PCC Shoulder Design - Example Problem (JCS-1)
PROGRAMMER J.S. Sawan
DATE 1 May 1978
PUNCHING INSTRUCTIONS GRAPHIC PUNCH
PAGE 1 OF 2
CARD ELECTRO NUMBER*

STATEMENT NUMBER | CONT. | FORTRAN STATEMENT | IDENTIFICATION SEQUENCE

```
          (BLANK CARD)
               PCC  SHOULDER DESIGN ON I-80 NEAR JOLIET
          (BLANK CARD)
20.0
5.0  8.0  10.0 150.010.0 50.0
17100.0   37100.0   21.0      85.15     50.0      2.60      10.0 0.24 0.0160
   30   13
3000.0    7000.0    8000.0    12000.0   16000.0   18000.0   20000.0   22000.0
24000.0   26000.0   30000.0   32000.0   34000.0    6000.0   12000.0   18000.0
24000.0   30000.0   32000.0   34000.0   36000.0   38000.0   40000.0   42000.0
44000.0   46000.0   50000.0   52000.0   54000.0   56000.0
5.78      10.33     7.76      20.54     4.37      1.77      1.02      0.54
0.34      0.14      0.04      0.01      0.01      0.27      03.34     7.05
5.51      14.72     3.61      1.40      0.50      0.25      0.16      0.11
0.08      0.07      0.07      0.02      0.01      0.01
200.0     8.0
          (BLANK CARD)
          (BLANK CARD)
          (BLANK CARD)
6.0  8.0  10.0 50.0
          (BLANK CARD)
          (BLANK CARD)
          (BLANK CARD)
7.0  8.0  10.0 50.0
```

*A standard card form, IBM electro 888157, is available for punching statements from this form

IUB

FORTRAN Coding Form

Printed in U.S.A.

PROGRAM PCC Shoulder Design -Example Problem (JCS-1)

PROGRAMMER J. S. Sawan

DATE 1 May 1978

PUNCHING INSTRUCTIONS

GRAPHIC

PUNCH

PAGE 2 OF 2

CARD ELECTRO NUMBER*

STATEMENT NUMBER | CONT | FORTRAN STATEMENT | IDENTIFICATION SEQUENCE

```
          (BLANK CARD)
          (BLANK CARD)
          (BLANK CARD)
8.0  8.0  10.0 50.0
          (BLANK CARD)
               PCC SHOULDER DESIGN ON I-80 NEAR JOLIET,ILLINOIS
          (BLANK CARD)
9.0  8.0  10.0 50.0
/*
```

*A standard card form, IBM electro 888157, is available for punching statements from this form

```
                       PORTLAND CEMENT CONCRETE PLAIN JOINTED
                      PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
********************************************************************************

 PROBLEM # 1
                     PCC SHOULDER DESIGN ON I-80 NEAR JOLIET

********************************************************************************

                                      INPUT DATA
                                      **********

 DESIGN CRITERIA
****************

   SHOULDER DESIGN LIFE (YEARS)                                       20.00

 SLAB PROPERTIES
****************

   SHOULDER THICKNESS - INS.                                           5.00
   TRAFFIC LANE THICKNESS - INS.                                       8.00
   SHOULDER WIDTH - FT.                                               10.00
   MEAN PCC MODULUS OF RUPTURE (28-DAYS) - PSI                       750.00
   COEFFICIENT OF VARIATION OF PCC MODULUS OF RUPTURE - %             10.00
   LOAD TRANSFER EFF. BETWEEN SHOULDER AND TRAFFIC LANE - %           50.00

 TRAFFIC
********

   AVERAGE DAILY TRAFFIC AT BEGINNING OF DESIGN PERIOD               17100.
   AVERAGE DAILY TRAFFIC AT END OF DESIGN PERIOD                     39100.
   PERCENT TRUCKS OF ADT                                              21.00
   PERCENT TRUCKS IN HEAVIEST TRAVELED OR DESIGN LANE                 85.15
   PERCENT DIRECTIONAL DISTRIBUTION                                   50.00
   MEAN AXLES PER TRUCK                                                2.60
   LENGTH OF SURVEYED SHOULDER STRETCH - MI.                          10.00
   AV. LENGTH OF TOTAL ENCROACHMENTS PER TRUCK IN THE SH. STRETCH - MI.  0.240
   PERCENT OF TRUCKS THAT PARK ON THE SHOULDER                      0.01600
   NUMBER OF SINGLE AXLE LOAD INTERVALS                                  13
   NUMBER OF TANDEM AXLE LOAD INTERVALS                                  17
```

```
S.A.L. DISTRIBUTION TABLE
          WEIGHT RANGE            PERCENT
           (POUNDS)

           0.  -   3000.            5.75
        3001.  -   7000.           10.33
        7001.  -   8000.            7.76
        8001.  -  12000.           20.54
       12001.  -  16000.            4.37
       16001.  -  18000.            1.77
       18001.  -  20000.            1.02
       20001.  -  22000.            0.54
       22001.  -  24000.            0.34
       24001.  -  26000.            0.14
       26001.  -  30000.            0.04
       30001.  -  32000.            0.01
       32001.  -  34000.            0.01

T.A.L. DISTRIBUTION TABLE
          WEIGHT RANGE            PERCENT
           (POUNDS)

           0.  -   6000.            0.27
        6001.  -  12000.           13.34
       12001.  -  18000.            7.05
       18001.  -  24000.            5.51
       24001.  -  30000.           14.92
       30001.  -  32000.            3.61
       32001.  -  34000.            1.40
       34001.  -  36000.            0.50
       36001.  -  38000.            0.25
       38001.  -  40000.            0.16
       40001.  -  42000.            0.11
       42001.  -  44000.            0.08
       44001.  -  46000.            0.07
       46001.  -  50000.            0.07
       50001.  -  52000.            0.02
       52001.  -  54000.            0.01
       54001.  -  56000.            0.01


 FOUNDATION SUPPORT
********************

   DESIGN MODULUS OF FOUNDATION SUPPORT (K) - PCI                          200.00

   ERODABILITY OF FOUNDATION AT BEGINNING OF DESIGN PERIOD (INS.)            0.0
   ERODABILITY OF FOUNDATION AT END OF DESIGN PERIOD (INS.)                  8.00
```

```
                         PORTLAND CEMENT CONCRETE PLAIN JOINTED
                         PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
*****************************************************************************************
 PROBLEM # 1
                        PCC SHOULDER DESIGN ON I-80 NEAR JOLIET

*****************************************************************************************

 RESULTS - ACCUMULATED FATIGUE DAMAGE OF P.C.C. SHOULDER
********

          SUMMARY FOR DESIGN PERIOD

 YEAR      PARKED TRAFFIC        ENCROACHED TRAFFIC

   1            0.133D 24                0.148D 00
   2            0.141D 24                0.243D 00
   3            0.149D 24                0.398D 00
   4            0.157D 24                0.650D 00
   5            0.165D 24                0.106D 01
   6            0.173D 24                0.172D 01
   7            0.181D 24                0.279D 01
   8            0.189D 24                0.451D 01
   9            0.197D 24                0.729D 01
  10            0.205D 24                0.118D 02
  11            0.213D 24                0.189D 02
  12            0.221D 24                0.305D 02
  13            0.229D 24                0.490D 02
  14            0.237D 24                0.787D 02
  15            0.245D 24                0.126D 03
  16            0.253D 24                0.202D 03
  17            0.261D 24                0.324D 03
  18            0.270D 24                0.518D 03
  19            0.278D 24                0.828D 03
  20            0.286D 24                0.132D 04




 TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO PARKED TRAFFIC IS            0.418D 25

 TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO ENCROACHED TRAFFIC IS        0.353D 04
```

```
                       PORTLAND CEMENT CONCRETE PLAIN JOINTED
                       PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
**********************************************************************************************
 PROBLEM # 2


**********************************************************************************************
                                       INPUT DATA
                                       **********

 DESIGN CRITERIA
****************

   SHOULDER DESIGN LIFE (YEARS)                                                    20.00

 SLAB PROPERTIES
****************

   SHOULDER THICKNESS - INS.                                                        6.00
   TRAFFIC LANE THICKNESS - INS.                                                    8.00
   SHOULDER WIDTH - FT.                                                            10.00
   MEAN PCC MODULUS OF RUPTURE (28-DAYS) - PSI                                    750.00
   COEFFICIENT OF VARIATION OF PCC MODULUS OF RUPTURE - %                          10.00
   LOAD TRANSFER EFF. BETWEEN SHOULDER AND TRAFFIC LANE - %                        50.00

 TRAFFIC
********

   AVERAGE DAILY TRAFFIC AT BEGINNING OF DESIGN PERIOD                            17100.
   AVERAGE DAILY TRAFFIC AT END OF DESIGN PERIOD                                  39100.
   PERCENT TRUCKS OF ADT                                                           21.00
   PERCENT TRUCKS IN HEAVIEST TRAVELED OR DESIGN LANE                              85.15
   PERCENT DIRECTIONAL DISTRIBUTION                                                50.00
   MEAN AXLES PER TRUCK                                                             2.60
   LENGTH OF SURVEYED SHOULDER STRETCH - MI.                                       10.00
   AV. LENGTH OF TOTAL ENCROACHMENTS PER TRUCK IN THE SH. STRETCH - MI.            0.240
   PERCENT OF TRUCKS THAT PARK ON THE SHOULDER                                   0.01600
   NUMBER OF SINGLE AXLE LOAD INTERVALS                                               13
   NUMBER OF TANDEM AXLE LOAD INTERVALS                                               17
```

```
S.A.L. DISTRIBUTION TABLE
          WEIGHT RANGE            PERCENT
            (POUNDS)

            0. -   3000.           5.75
         3001. -   7000.          10.33
         7001. -   8000.           7.76
         8001. -  12000.          20.54
        12001. -  16000.           4.37
        16001. -  18000.           1.77
        18001. -  20000.           1.02
        20001. -  22000.           0.54
        22001. -  24000.           0.34
        24001. -  26000.           0.14
        26001. -  30000.           0.04
        30001. -  32000.           0.01
        32001. -  34000.           0.01

T.A.L. DISTRIBUTION TABLE
          WEIGHT RANGE            PERCENT
            (POUNDS)

            0. -   6000.           0.27
         6001. -  12000.          13.34
        12001. -  18000.           7.05
        18001. -  24000.           5.51
        24001. -  30000.          14.92
        30001. -  32000.           3.61
        32001. -  34000.           1.40
        34001. -  36000.           0.50
        36001. -  38000.           0.25
        38001. -  40000.           0.16
        40001. -  42000.           0.11
        42001. -  44000.           0.08
        44001. -  46000.           0.07
        46001. -  50000.           0.07
        50001. -  52000.           0.02
        52001. -  54000.           0.01
        54001. -  56000.           0.01


 FOUNDATION SUPPORT
********************

   DESIGN MODULUS OF FOUNDATION SUPPORT (K) - PCI                           200.00

   ERODABILITY OF FOUNDATION AT BEGINNING OF DESIGN PERIOD (INS.)           0.0
   ERODABILITY OF FOUNDATION AT END OF DESIGN PERIOD (INS.)                 8.00
```

```
                         PORTLAND CEMENT CONCRETE PLAIN JOINTED
                        PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
*****************************************************************************************
 PROBLEM # 2

*****************************************************************************************

 RESULTS - ACCUMULATED FATIGUE DAMAGE OF P.C.C. SHOULDER
********

           SUMMARY FOR DESIGN PERIOD

 YEAR      PARKED TRAFFIC         ENCROACHED TRAFFIC

   1            0.182D 11                  0.851D-04
   2            0.193D 11                  0.131D-03
   3            0.204D 11                  0.201D-03
   4            0.215D 11                  0.308D-03
   5            0.226D 11                  0.472D-03
   6            0.237D 11                  0.719D-03
   7            0.248D 11                  0.110D-02
   8            0.259D 11                  0.167D-02
   9            0.270D 11                  0.253D-02
  10            0.281D 11                  0.384D-02
  11            0.292D 11                  0.581D-02
  12            0.303D 11                  0.879D-02
  13            0.315D 11                  0.133D-01
  14            0.326D 11                  0.200D-01
  15            0.337D 11                  0.302D-01
  16            0.348D 11                  0.456D-01
  17            0.359D 11                  0.686D-01
  18            0.370D 11                  0.103D 00
  19            0.381D 11                  0.155D 00
  20            0.392D 11                  0.233D 00




 TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO PARKED TRAFFIC IS              0.574D 12

 TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO ENCROACHED TRAFFIC IS          0.695D 00
```

```
                             PORTLAND CEMENT CONCRETE PLAIN JOINTED
                            PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
********************************************************************************************
 PROBLEM # 3

********************************************************************************************
                                            INPUT DATA
                                            **********
 DESIGN CRITERIA
****************

   SHOULDER DESIGN LIFE (YEARS)                                                       20.00

 SLAB PROPERTIES
****************

   SHOULDER THICKNESS - INS.                                                           7.00
   TRAFFIC LANE THICKNESS - INS.                                                       8.00
   SHOULDER WIDTH - FT.                                                               10.00
   MEAN PCC MODULUS OF RUPTURE (28-DAYS) - PSI                                       750.00
   COEFFICIENT OF VARIATION OF PCC MODULUS OF RUPTURE - %                             10.00
   LOAD TRANSFER EFF. BETWEEN SHOULDER AND TRAFFIC LANE - %                           50.00

 TRAFFIC
********

   AVERAGE DAILY TRAFFIC AT BEGINNING OF DESIGN PERIOD                               17100.
   AVERAGE DAILY TRAFFIC AT END OF DESIGN PERIOD                                     39100.
   PERCENT TRUCKS OF ADT                                                              21.00
   PERCENT TRUCKS IN HEAVIEST TRAVELED OR DESIGN LANE                                 85.15
   PERCENT DIRECTIONAL DISTRIBUTION                                                   50.00
   MEAN AXLES PER TRUCK                                                                2.60
   LENGTH OF SURVEYED SHOULDER STRETCH - MI.                                          10.00
   AV. LENGTH OF TOTAL ENCROACHMENTS PER TRUCK IN THE SH. STRETCH - MI.               0.240
   PERCENT OF TRUCKS THAT PARK ON THE SHOULDER                                      0.01600
   NUMBER OF SINGLE AXLE LOAD INTERVALS                                                  13
   NUMBER OF TANDEM AXLE LOAD INTERVALS                                                  17
```

```
S.A.L. DISTRIBUTION TABLE
           WEIGHT RANGE          PERCENT
            (POUNDS)

          0. -   3000.           5.75
       3001. -   7000.          10.33
       7001. -   8000.           7.76
       8001. -  12000.          20.54
      12001. -  16000.           4.37
      16001. -  18000.           1.77
      18001. -  20000.           1.02
      20001. -  22000.           0.54
      22001. -  24000.           0.34
      24001. -  26000.           0.14
      26001. -  30000.           0.04
      30001. -  32000.           0.01
      32001. -  34000.           0.01

T.A.L. DISTRIBUTION TABLE
           WEIGHT RANGE          PERCENT
            (POUNDS)

          0. -   6000.           0.27
       6001. -  12000.          13.34
      12001. -  18000.           7.05
      18001. -  24000.           5.51
      24001. -  30000.          14.92
      30001. -  32000.           3.61
      32001. -  34000.           1.40
      34001. -  36000.           0.50
      36001. -  38000.           0.25
      38001. -  40000.           0.16
      40001. -  42000.           0.11
      42001. -  44000.           0.08
      44001. -  46000.           0.07
      46001. -  50000.           0.07
      50001. -  52000.           0.02
      52001. -  54000.           0.01
      54001. -  56000.           0.01


FOUNDATION SUPPORT
*******************

  DESIGN MODULUS OF FOUNDATION SUPPORT (K) - PCI                                 200.00

  ERODABILITY OF FOUNDATION AT BEGINNING OF DESIGN PERIOD (INS.)                   0.0
  ERODABILITY OF FOUNDATION AT END OF DESIGN PERIOD (INS.)                         8.00
```

```
                                  PORTLAND CEMENT CONCRETE PLAIN JOINTED
                                 PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
*******************************************************************************************
 PROBLEM # 3

*******************************************************************************************

 RESULTS - ACCUMULATED FATIGUE DAMAGE OF P.C.C. SHOULDER
********

           SUMMARY FOR DESIGN PERIOD

 YEAR      PARKED TRAFFIC        ENCROACHED TRAFFIC

    1           0.106D 04              0.184D-05
    2           0.112D 04              0.269D-05
    3           0.119D 04              0.392D-05
    4           0.125D 04              0.571D-05
    5           0.132D 04              0.830D-05
    6           0.138D 04              0.120D-04
    7           0.144D 04              0.175D-04
    8           0.151D 04              0.253D-04
    9           0.157D 04              0.365D-04
   10           0.164D 04              0.527D-04
   11           0.170D 04              0.760D-04
   12           0.176D 04              0.110D-03
   13           0.183D 04              0.158D-03
   14           0.189D 04              0.227D-03
   15           0.196D 04              0.326D-03
   16           0.202D 04              0.468D-03
   17           0.208D 04              0.672D-03
   18           0.215D 04              0.963D-03
   19           0.221D 04              0.138D-02
   20           0.228D 04              0.198D-02




 TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO PARKED TRAFFIC IS          0.334D 05

 TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO ENCROACHED TRAFFIC IS      0.652D-02
```

```
                           PORTLAND CEMENT CONCRETE PLAIN JOINTED
                          PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
*****************************************************************************************

 PROBLEM # 4

*****************************************************************************************
                                            INPUT DATA
                                            **********

 DESIGN CRITERIA
*****************

   SHOULDER DESIGN LIFE (YEARS)                                                      20.00

 SLAB PROPERTIES
*****************

   SHOULDER THICKNESS - INS.                                                          8.00
   TRAFFIC LANE THICKNESS - INS.                                                      8.00
   SHOULDER WIDTH - FT.                                                              10.00
   MEAN PCC MODULUS OF RUPTURE (28-DAYS) - PSI                                      750.00
   COEFFICIENT OF VARIATION OF PCC MODULUS OF RUPTURE - %                            10.00
   LOAD TRANSFER EFF. BETWEEN SHOULDER AND TRAFFIC LANE - %                          50.00

 TRAFFIC
*********

   AVERAGE DAILY TRAFFIC AT BEGINNING OF DESIGN PERIOD                              17100.
   AVERAGE DAILY TRAFFIC AT END OF DESIGN PERIOD                                    39100.
   PERCENT TRUCKS OF ADT                                                             21.00
   PERCENT TRUCKS IN HEAVIEST TRAVELED OR DESIGN LANE                                85.15
   PERCENT DIRECTIONAL DISTRIBUTION                                                  50.00
   MEAN AXLES PER TRUCK                                                               2.60
   LENGTH OF SURVEYED SHOULDER STRETCH - MI.                                         10.00
   AV. LENGTH OF TOTAL ENCROACHMENTS PER TRUCK IN THE SH. STRETCH - MI.               0.240
   PERCENT OF TRUCKS THAT PARK ON THE SHOULDER                                     0.01600
   NUMBER OF SINGLE AXLE LOAD INTERVALS                                                 13
   NUMBER OF TANDEM AXLE LOAD INTERVALS                                                 17
```

```
S.A.L. DISTRIBUTION TABLE
           WEIGHT RANGE          PERCENT
             (POUNDS)

             0. -   3000.          5.75
          3001. -   7000.         10.33
          7001. -   8000.          7.76
          8001. -  12000.         20.54
         12001. -  16000.          4.37
         16001. -  18000.          1.77
         18001. -  20000.          1.02
         20001. -  22000.          0.54
         22001. -  24000.          0.34
         24001. -  26000.          0.14
         26001. -  30000.          0.04
         30001. -  32000.          0.01
         32001. -  34000.          0.01

T.A.L. DISTRIBUTION TABLE
           WEIGHT RANGE          PERCENT
             (POUNDS)

             0. -   6000.          0.27
          6001. -  12000.         13.34
         12001. -  18000.          7.05
         18001. -  24000.          5.51
         24001. -  30000.         14.92
         30001. -  32000.          3.61
         32001. -  34000.          1.40
         34001. -  36000.          0.50
         36001. -  38000.          0.25
         38001. -  40000.          0.16
         40001. -  42000.          0.11
         42001. -  44000.          0.08
         44001. -  46000.          0.07
         46001. -  50000.          0.07
         50001. -  52000.          0.02
         52001. -  54000.          0.01
         54001. -  56000.          0.01


FOUNDATION SUPPORT
*******************

  DESIGN MODULUS OF FOUNDATION SUPPORT (K) - PCI                                 200.00

  ERODABILITY OF FOUNDATION AT BEGINNING OF DESIGN PERIOD (INS.)                   0.0
  ERODABILITY OF FOUNDATION AT END OF DESIGN PERIOD (INS.)                         0.00
```

```
                          PORTLAND CEMENT CONCRETE PLAIN JOINTED
                         PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
*****************************************************************************************
 PROBLEM # 4

*****************************************************************************************

RESULTS - ACCUMULATED FATIGUE DAMAGE OF P.C.C. SHOULDER
********
          SUMMARY FOR DESIGN PERIOD

 YEAR       PARKED TRAFFIC         ENCROACHED TRAFFIC

    1           0.336D-01                 0.173D-06
    2           0.356D-01                 0.242D-06
    3           0.376D-01                 0.339D-06
    4           0.397D-01                 0.474D-06
    5           0.417D-01                 0.662D-06
    6           0.437D-01                 0.922D-06
    7           0.458D-01                 0.128D-05
    8           0.478D-01                 0.178D-05
    9           0.498D-01                 0.247D-05
   10           0.518D-01                 0.343D-05
   11           0.539D-01                 0.476D-05
   12           0.559D-01                 0.659D-05
   13           0.579D-01                 0.912D-05
   14           0.600D-01                 0.126D-04
   15           0.620D-01                 0.174D-04
   16           0.640D-01                 0.241D-04
   17           0.660D-01                 0.332D-04
   18           0.681D-01                 0.458D-04
   19           0.701D-01                 0.632D-04
   20           0.721D-01                 0.872D-04




 TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO PARKED TRAFFIC IS            0.106D 01

 TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO ENCROACHED TRAFFIC IS        0.316D-03
```

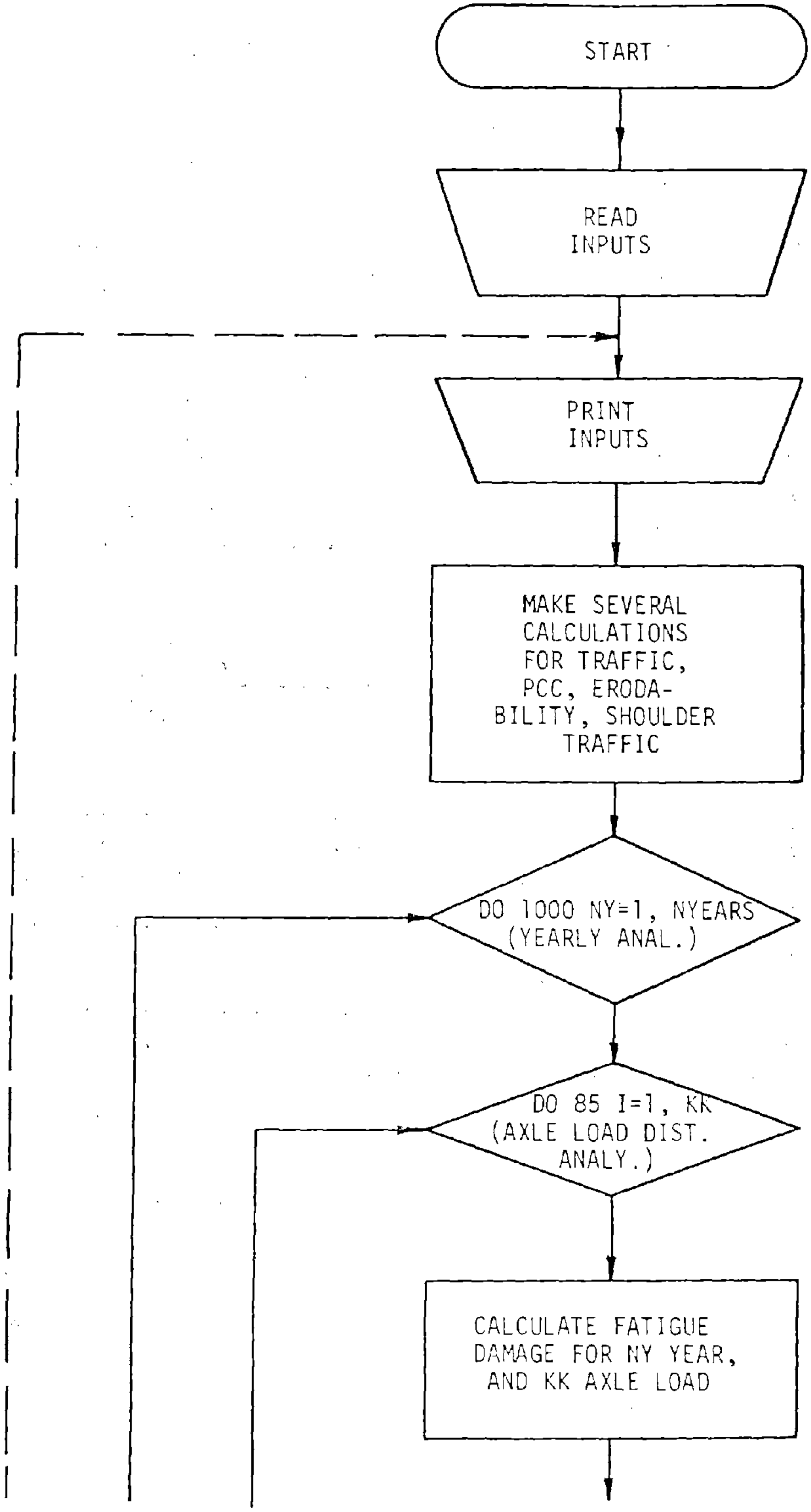
```
                        PORTLAND CEMENT CONCRETE PLAIN JOINTED
                       PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
********************************************************************************************
 PROBLEM # 5
                      PCC SHOULDER DESIGN ON I-80 NEAR JOLIET,ILLINOIS

********************************************************************************************
                                       INPUT DATA
                                       **********
 DESIGN CRITERIA
****************
   SHOULDER DESIGN LIFE (YEARS)                                                  20.00

 SLAB PROPERTIES
*****************
   SHOULDER THICKNESS - INS.                                                      9.00
   TRAFFIC LANE THICKNESS - INS.                                                  8.00
   SHOULDER WIDTH - FT.                                                          10.00
   MEAN PCC MODULUS OF RUPTURE (28-DAYS) - PSI                                  750.00
   COEFFICIENT OF VARIATION OF PCC MODULUS OF RUPTURE - %                        10.00
   LOAD TRANSFER EFF. BETWEEN SHOULDER AND TRAFFIC LANE - %                      50.00

 TRAFFIC
********
   AVERAGE DAILY TRAFFIC AT BEGINNING OF DESIGN PERIOD                          17100.
   AVERAGE DAILY TRAFFIC AT END OF DESIGN PERIOD                                39100.
   PERCENT TRUCKS OF ADT                                                         21.00
   PERCENT TRUCKS IN HEAVIEST TRAVELED OR DESIGN LANE                            85.15
   PERCENT DIRECTIONAL DISTRIBUTION                                              50.00
   MEAN AXLES PER TRUCK                                                           2.60
   LENGTH OF SURVEYED SHOULDER STRETCH - MI.                                     10.00
   AV. LENGTH OF TOTAL ENCROACHMENTS PER TRUCK IN THE SH. STRETCH - MI.          0.240
   PERCENT OF TRUCKS THAT PARK ON THE SHOULDER                                 0.01600
   NUMBER OF SINGLE AXLE LOAD INTERVALS                                             13
   NUMBER OF TANDEM AXLE LOAD INTERVALS                                             17
```

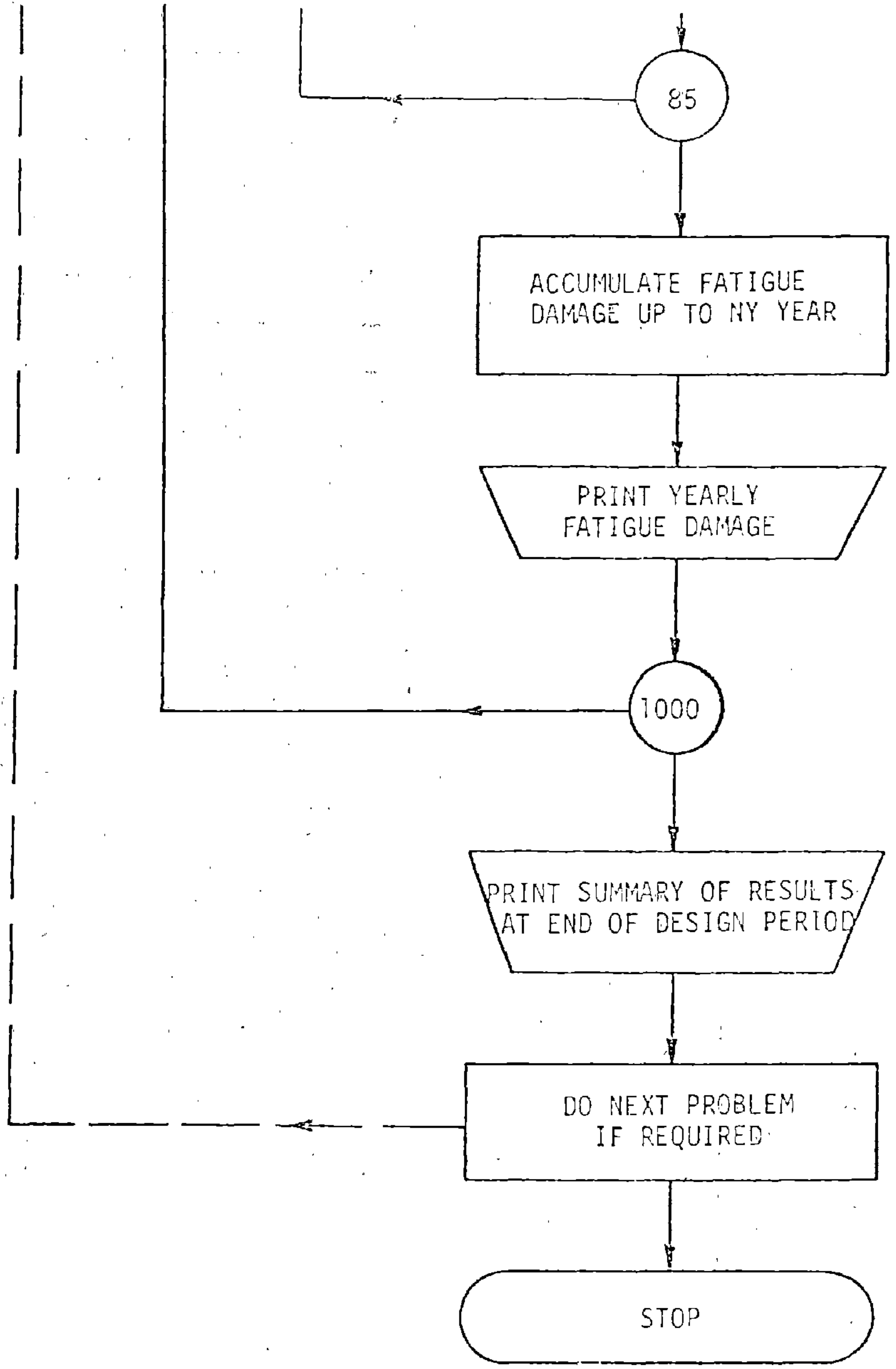
```
S.A.L. DISTRIBUTION TABLE
          WEIGHT RANGE           PERCENT
            (POUNDS)

            0. -  3000.           5.75
         3001. -  7000.          10.33
         7001. -  8000.           7.76
         8001. - 12000.          20.54
        12001. - 16000.           4.37
        16001. - 18000.           1.77
        18001. - 20000.           1.02
        20001. - 22000.           0.54
        22001. - 24000.           0.34
        24001. - 26000.           0.14
        26001. - 30000.           0.04
        30001. - 32000.           0.01
        32001. - 34000.           0.01

T.A.L. DISTRIBUTION TABLE
          WEIGHT RANGE           PERCENT
            (POUNDS)

            0. -  6000.           0.27
         6001. - 12000.          13.34
        12001. - 18000.           7.05
        18001. - 24000.           5.51
        24001. - 30000.          14.92
        30001. - 32000.           3.61
        32001. - 34000.           1.40
        34001. - 36000.           0.50
        36001. - 38000.           0.25
        38001. - 40000.           0.16
        40001. - 42000.           0.11
        42001. - 44000.           0.08
        44001. - 46000.           0.07
        46001. - 50000.           0.07
        50001. - 52000.           0.02
        52001. - 54000.           0.01
        54001. - 56000.           0.01


FOUNDATION SUPPORT
******************

   DESIGN MODULUS OF FOUNDATION SUPPORT (K) - PCI                              200.00

   ERODABILITY OF FOUNDATION AT BEGINNING OF DESIGN PERIOD (INS.)                0.0
   ERODABILITY OF FOUNDATION AT END OF DESIGN PERIOD (INS.)                      8.00
```

```
                         PORTLAND CEMENT CONCRETE PLAIN JOINTED
                        PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1)
********************************************************************************************
 PROBLEM # 5
                        PCC SHOULDER DESIGN ON I-80 NEAR JOLIET,ILLINOIS

********************************************************************************************

 RESULTS - ACCUMULATED FATIGUE DAMAGE OF P.C.C. SHOULDER
********

          SUMMARY FOR DESIGN PERIOD

 YEAR       PARKED TRAFFIC       ENCROACHED TRAFFIC

   1           0.332D-04             0.332D-07
   2           0.352D-04             0.450D-07
   3           0.372D-04             0.608D-07
   4           0.392D-04             0.820D-07
   5           0.412D-04             0.111D-06
   6           0.432D-04             0.149D-06
   7           0.452D-04             0.200D-06
   8           0.472D-04             0.269D-06
   9           0.492D-04             0.361D-06
  10           0.512D-04             0.484D-06
  11           0.532D-04             0.649D-06
  12           0.552D-04             0.869D-06
  13           0.572D-04             0.116D-05
  14           0.592D-04             0.156D-05
  15           0.612D-04             0.208D-05
  16           0.632D-04             0.279D-05
  17           0.652D-04             0.372D-05
  18           0.672D-04             0.498D-05
  19           0.692D-04             0.665D-05
  20           0.712D-04             0.888D-05




 TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO PARKED TRAFFIC IS          0.104D-02

 TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO ENCROACHED TRAFFIC IS      0.351D-04
```

APPENDIX C

FLOW CHART OF COMPUTER PROGRAM




85
ACCUMULATE FATIGUE DAMAGE UP TO NY YEAR
PRINT YEARLY FATIGUE DAMAGE
1000
PRINT SUMMARY OF RESULTS AT END OF DESIGN PERIOD
DO NEXT PROBLEM IF REQUIRED
STOP

APPENDIX D

JCS-1 COMPUTER PROGRAM LISTING

```
FORTRAN IV G LEVEL  21            MAIN             DATE = 78107          13/50/44           PAGE 0001

      C***********************************************************************
      C***********************************************************************
      C*                                                                    *
      C*                                                                    *
      C*               PORTLAND CEMENT CONCRETE PLAIN JOINTED SHOULDERS     *
      C*                              DESIGN PROGRAM                        *
      C*                                 JCS-1                              *
      C*                                                                    *
      C*                                                                    *
      C***********************************************************************
      C***********************************************************************
      C*                                                                    *
      C*                           PROGRAM NARRATIVE                        *
      C*                                                                    *
      C*                                                                    *
      C*       THIS PROGRAM COMPUTES DATA FOR USE IN DESIGNING PLAIN JOINTED CONCRETE*
      C*    HIGHWAYS SHOULDERS. THE PROGRAM INPUTS DESIGN CONSTRAINTS, TRAFFIC,   *
      C*    MATERIALS,FOUNDATION SUPPORT, AMOUNT OF LOAD TRANSFER BETWEEN SHOULDER AND*
      C*    TRAFFIC LANE, AND GEOMETRIC DATA RELATED TO THE PROJECT UNDER DESIGN.  *
      C*    THE OUTPUT DATA CAN THEN BE USED TO SELECT APPROPRIATE STRUCTURAL AND  *
      C*    GEOMETRICAL CONFIGURATIONS OF THE SHOULDER-TRAFFIC LANE SYSTEM FOR DESIGN *
      C*    PURPOSES. THE PROGRAM OUTPUT IS AS FOLLOWS:                       *
      C*       TOTAL FATIGUE DAMAGE, DUE TO TRAFFIC LOADS, AS COMPUTED BY MINER'S   *
      C*    ACCUMULATIVE DAMAGE HYPOTHESIS OCCURING OVER THE LIFE OF THE PAVEMENT.  *
      C*    MODELS ARE DEVELOPED USING A FINITE ELEMENT SLAB PROGRAM USED TO COMPUTE  *
      C*    THE STRESSES.                                                   *
      C*       FATIGUE DAMAGE IS COMPUTED AT TWO SEPERATE LOCATIONS OF THE PCC     *
      C*    SHOULDERS,THE OUTERFREE EDGE OF THE SHOULDER DUE TO PARKED TRAFFIC AND  *
      C*    ,THE SHOULDER-TRAFFIC LANE LONGITUDINAL JOINT DUE TO ENCROACHED TRAFFIC  *
      C*    FROM THE MAIN LINE TO THE SHOULDER. FATIGUE DAMAGE IS COMPUTED     *
      C*    INCREMENTALLY EVERY YEAR AT THE TWO LOCATIONS AND THEN ACCUMULATED OVER  *
      C*    THE DESIGN LIFE.                                                *
      C*       THIS PROGRAM IS WRITTEN BY J. S. SAWAN AT THE UNIVERSITY OF ILLINOIS  *
      C*    AT URBANA-CHAMPAIGN, NOV. 1977.                                 *
      C*                                                                    *
      C***********************************************************************
      C
      C   THE FOLLOWING LIST OF VARIABLES INCLUDES ALL VARIABLES USED IN
      C   THE PROGRAM.  A '*' IN COLUMN 2 INDICATES THE VARIABLE IS AN INPUT.
      C
      C
      C*   A               AXLE FACTOR, MEAN NUMBER OF AXLES PER TRUCK
      C    ADT             AVERAGE DAILY TRAFFIC FOR A GIVEN YEAR , 2 DIRECTIONS
      C*   ADTI            AVERAGE DAILY TRAFFIC AT BEGINNING OF DESIGN PERIOD, 2 DIREC-
      C                    TIONS
      C*   ADTF            AVERAGE DAILY TRAFFIC AT END OF DESIGN PERIOD, 2 DIRECTIONS
      C    AXDAY           NUMBER OF TRUCK AXLES PER DAY IN DESIGN LANE
      C*   B               WIDTH OF THE SHOULDER IN FEET
      C    CON             =1 FOR SINGLE AXLE LOADS; =2 FOR TANDEM AXLE LOADS; USED WHEN
      C                    COMPUTING DAMAGE
      C    DAMGE1          FATIGUE DAMAGE COMPUTED USING MINER'S HYPOTHESIS,FOR ONE YEAR
      C                    ,USED FOR PARKED TRAFFIC.
      C    DAMGE2          FATIGUE DAMAGE COMPUTED USING MINER'S HYPOTHESIS,FOR ONE YEAR
      C                    ,USED FOR ENCROACHED TRAFFIC.
      C*   DD              DIRECTIONAL DISTRIBUTION, PERCENT OF VEHICLES TRAVELING IN
      C                    ONE DIRECTION ONLY
      C*   DIST(40)        LOAD DISTRIBUTION TABLE, PERCENT FOR EACH LOAD RANGE
      C    DISTP(40)       LOAD DISTRIBUTION TABLE, PROPORTION FOR EACH LOAD RANGE
```

```
C*    DLIFE           SHOULDER DESIGN LIFE (YEARS).
C     DYEAR1(50)      TOTAL DAMAGE FOR ONE YEAR, PARKED TRAFFIC ONLY
C     DYEAR2(50)      TOTAL DAMAGE FOR ONE YEAR, ENCROACHED TRAFFIC ONLY
C     DYEAR3          TOTAL DAMAGE OVER THE DESIGN PERIOD, PARKED TRAFFIC ONLY
C     DYEAR4          TOTAL DAMAGE OVER THE DESIGN PERIOD, ENCROACHED TRAFFIC ONLY
C*    EFF             LOAD TRANSFER EFFICIENCY BETWEEN SHOULDER AND TRAFFIC LANE
C                     , PERCENT.
C     ERODE           ERODABILITY OF FOUNDATION FOR A GIVEN YEAR
C     ERODEI          ERODABILITY OF FOUNDATION (IN.) AT BEGINNING OF DESIGN PERIOD
C*    ERODEF          ERODABILITY OF FOUNDATION (IN.) AT END OF DESIGN PERIOD
C     F28             MODULUS OF RUPTURE (FOR 28 DAYS) AFTER ADJUSTMENT FOR
C                     VARIABILITY
C     FCONF           STANDARD NORMAL DEVIATE AT CONFIDENCE LEVEL OF 85 PERCENT,
C                     USED FOR CONCRETE MODULUS OF RUPTURE
C*    FCV             COEFFICIENT OF VARIATION OF PCC MOD. OF RUPTURE
C*    FF              MEAN MOD. OF RUP. (FOR 28 DAYS) BEFORE ADJUSTMENT FOR
C                     VARIABILITY
C     FSD             STANDARD DEVIATION OF FF
C*    H1              PCC SHOULDER THICKNESS (IN.)
C*    H2              PCC TRAFFIC LANE THICKNESS (IN.)
C     I               USED ONLY IN ITERATIVE STATEMENTS
C     J               USED IN ITERATIVE STATEMENTS
C*    K               DESIGN MODULUS OF FOUNDATION SUPPORT (PCI)
C*    KK              NUMBER OF INTERVALS IN LOAD DISTRIBUTION TABLE
C*    KSAL            NUMBER OF SAL INTERVALS IN LOAD DISTRIBUTION TABLE
C     KSAL1           =KSAL+1; STARTING ELEMENT OF LOAD DIST FOR T.A.L.
C     KTAL            NUMBER OF TAL INTERVALS IN LOAD DISTRIBUTION TABLE
C*    LD              LANE DISTRIBUTION FOR COMPUTING AXDAY, PERCENT OF TRUCKS I
C                     ONE DIRECTION IN TRAFFIC LANE
C*    LEPT            AVERAGE LENGTH OF TOTAL ENCROACHMENTS PER TRUCK IN THE
C                     SURVEYED SHOULDER STRETCH - MILES
C*    LOAD(40)        VALUES OF LOADS IN LOAD DISTRIBUTION TABLE (POUNDS)
C     LOGN            LOG TO BASE 10 OF N
C     LRANGE(40)      LOWER END OF INTERVALS IN LOAD DISTRIBUTION TABLE
C*    LSS             LENGTH OF SURVEYED SHOULDER STRETCH - MILES
C     N               ALLOWABLE LOAD APPLICATIONS TO FAILURE OF PCC, OBTAINED FROM
C                     FATIGUE CURVE
C     NAAL            NUMBER OF APPLIED AXLE LOADINGS FOR ONE YEAR
C                     PASSING WITHIN 6 INCHES OF SLAB EDGE
C     NTPD            NUMBER OF TRUCKS PER DAY
C     NY              USED IN ITERATIVE STATEMENTS FOR YEARLY CALCULATIONS
C     NYEARS          NUMBER OF YEARS FOR WHICH PROGRAM IS TO BE EXECUTED
C*    PEPT            PERCENT OF TRUCKS THAT PARK ON THE SURVEYED SHOULDER STRETCH
C     PET             PROPORTION OF TRUCKS THAT ENCROACH ON THE SURVEYED SHOULDER
C                     FROM THE TRAFFIC LANE
C     PN              PROBLEM NUMBER
C     PPT             PROPORTION OF TRUCKS THAT PARK ON THE SURVEYED SHOULDER
C                     STRETCH
C     SLE             SLOPE OF ERODABILITY LINE
C     SLOPE           SLOPE OF ADT LINE
C     STRT            STRESS AT EITHER EDGE OF SHOULDER DUE TO TRAFFIC (PSI)
C     STRT,N          THE NTH COMPONENT OF THE STRESS EQUATION
C*    T               PERCENT OF TRUCKS IN ADT; USED FOR COMPUTING AXDAY
C*    TITLE(20,3)     STRING FOR STORING TITLE, 3 CARDS, 80 COLUMNS EACH
C     YI              Y-INTERCEPT OF ADT LINE
C     YIE             Y-INTERCEPT OF ERODABILITY LINE
C
C
C
```

```
               C***********************************************************************
 0001                IMPLICIT REAL*8 (A-H,O-Z)
 0002                REAL*8 DYEAR1(50),DYEAR2(50),LOAD(40),LRANGE(40),NTPD,K,LOGN,LD,
                    1NAAL,LSS,LEPT,N
 0003                INTEGER PN
 0004                DIMENSION TITLE(20,3),DIST(40),DISTP(40)
               C
               C***********************************************************************
               C
               C     READ TITLE
 0005                READ (5,500)   TITLE
               C
               C     WRITE PROBLEM NUMBER AND TITLE
 0006                PN=1
 0007                WRITE(6,600) PN,TITLE
               C
               C***********************************************************************
               C        PART I:
               C     READ IN ALL DATA AND DO ALL CALCULATIONS WHICH WILL NOT CHANGE
               C     FROM YEAR TO YEAR.
               C
               C     READ DESIGN LIFE
 0008                READ(5,530) DLIFE
               C
               C     IF DESIGN LIFE IS LESS THAN OR EQUAL TO ZERO,SET IT EQUAL TO ONE
 0009                IF(DLIFE.LE.0.) DLIFE=1.0
               C
               C     NUMBER OF YEARS FOR WHICH YOU WANT THE PROGRAM TO BE EXCUTED=
               C     DESIGN LIFE
 0010                NYEARS=DLIFE
               C
               C     WRITE OUT DESIGN LIFE
 0011                WRITE(6,630) DLIFE
               C
               C     READ AND WRITE SLAB PROPERTIES-SHOULDER SLAB THICKNESS,TRAFFIC LANE
               C     SLAB THICKNESS,SHOULDER SLAB WIDTH,MEAN MODULUS OF RUPTURE(28 DAYS) OF PCC
               C     BEFORE ADJUSTMENTS FOR VARIABILITY,COEFFICIENT OF VARIATION OF MODULUS OF
               C     RUPTURE,AND LOAD TRANSFER EFFICIENCY BETWEEN SHOULDER AND TRAFFIC LANE.
 0012                READ(5,501) H1,H2,B,FF,FCV,EFF
 0013                WRITE(6,601) H1,H2,B,FF,FCV,EFF
               C
               C     STANDARD NORMAL DEVIATE AT CONFIDENCE LEVEL OF 85% USED FOR CONCRETE
               C     MODULUS OF RUPTURE=1.03
 0014                FCONF=1.03
               C
               C     ADJUST MODULUS OF RUPTURE TO ACCOUNT FOR VARIABILITY OF PCC
 0015                FSD=FF*FCV/100.0
 0016                F28=FF-FSD*FCONF
               C
               C     READ AND WRITE TRAFFIC DATA-AVERAGE DAILY TRAFFIC (ADT) AT BEGINNING
               C     OF DESIGN PERIOD,ADT AT END OF DESIGN PERIOD, PERCENT OF TRUCKS IN ADT
               C     PERCENT OF TRUCKS IN DESIGN LANE,PERCENT DIRECTIONAL DISTRIBUTION,
               C     MEAN AXLES PER TRUCK,AVERAGE LENGTH OF TOTAL ENCROACHMENTS PER TRUCK,
               C     LENGTH OF SHOULDER STRETCH,PERCENT OF TRUCKS THAT PARK
               C     ON THE SHOULDER STRETCH.
 0017                READ(5,502) ADTI,ADTF,T,LD,DD,A,LSS,LEPT,PEPT
 0018                WRITE(6,602) ADTI,ADTF,T,LD,DD,A,LSS,LEPT,PEPT
               C
               C     CALCULATE SLOPE AND Y-INTERCEPT OF LINE:
```

```
                C      INITIAL ADT AND FINAL ADT WERE READ IN, TIME FOR ADTI=0, TIME FOR ADTF IS
                C      THE END OF THE DESIGN PERIOD,ASSUME ADT IS A STRAIGHT- LINE FUNCTION
                C      OF TIME.THE SLOPE AND Y-INTERCEPT OF THE ADT LINE IS FOUND SO THAT ADT
                C      FOR ANY GIVEN TIME CAN BE CALCULATED LATER.
 0019                  SLOPE=(ADTF-ADTI)/DLIFE
 0020                     YI=ADTI
                C
                C      COMPUTE PROPORTION OF AXLE-LOADS THAT ENCROACH FROM MAIN TRAFFIC LINE
                C      TO THE SHOULDER(PET):
 0021                  PET=LEPT/LSS
                C
                C      COMPUTE PROPORTION OF               AXLE-LOADS THAT PARK ON THE SHOULDER(PPT)
 0022                  PPT=PLPT/100.0
                C
                C      COMPUTE TOTAL PROPORTION OF AXLE-LOADS THAT ENCROACH AND PARK ON THE
                C      SHOULDER:
 0023                  PET=PET+PPT
                C
                C      READ NUMBER OF INTERVALS IN LOAD DISTRIBUTION TABLE, NUMBER OF SAL
                C      INTERVALS IN LOAD DISTRIBUTION TABLE.
 0024                  READ(5,503) KK,KSAL
                C
                C      COMPUTE NUMBER OF TAL INTERVALS IN LOAD DISTRIBUTION TABLE:
 0025                  KTAL=KK-KSAL
                C
                C      WRITE NUMBER OF SAL INTERVALS,NUMBER OF TAL INTERVALS
 0026                  WRITE(6,603) KSAL,KTAL
                C
                C      COMPUTE STARTING ELEMENT OF LOAD DISTRIBUTION FOR TAL
 0027                  KSAL1=KSAL+1
                C
                C      READ VALUES OF LOADS IN LOAD DISTRIBUTION TABLE AND PERCENT FOR EACH LOAD
 0028                  READ(5,504)  (LOAD(I),I=1,KK)
 0029                  READ(5,504)  (DIST(I),I=1,KK)
                C
                C      COMPUTE LOWER END OF INTERVALS IN LOAD DISTRIBUTION TABLE
 0030                  LRANGE(1)=0.0
 0031                     DO 16 I=2,KK
 0032               16 LRANGE(I)=LOAD(I-1)+1
 0033                  LRANGE(KSAL1)=0.0
                C
                C      WRITE OUT LOAD DISTRIBUTION TABLE FOR SAL AND TAL
 0034                  WRITE(6,604)  ((LRANGE(I),LOAD(I),DIST(I)),I=1,KSAL)
 0035                  WRITE(6,605)  ((LRANGE(I),LOAD(I),DIST(I)),I=KSAL1,KK)
                C
                C      CONVERT PERCENT FOR EACH LOAD INTO PROPORTION OF 1.0
 0036                     DO 11 I=1,KK
 0037               11 DISTP(I)=DIST(I)/100.0
                C
                C      READ FOUNDATION SUPPORT DATA:
 0038                  READ  (5,701) K,ERODEF
                C
                C      WRITE FOUNDATION MODULUS:
 0039                  WRITE(6,631) K
                C
                C      SET ERODABILITY AT BEGINNING OF DESIGN PERIOD AT ZERO,READ BOTH
                C      AT BEGINNING AND END OF DESIGN PERIOD
 0040                  ERODEI=0.00
 0041                  WRITE(6,702) ERODEI,ERODEF
```

```
                C
                C      CALCULATE THE SLOPE AND Y-INTERCEPT OF THE ERODABILITY LINE:
                C      INITIAL ERODABILITY WAS SET EQUAL TO ZERO,FINAL ERODABILITY WAS READ IN,
                C      TIME FOR ERODEI=0,TIME FOR ERODEF IS THE END OF THE DESIGN PERIOD.
                C      GIVES DATA TO PLOT ERODABILITY AS A STRAIGHT-LINE FUNCTION OF THE TIME.
                C      THE SLOPE AND Y-INTERCEPT OF THE ERODABILITY LINE WILL BE COMPUTED SO
                C      THAT ERODABILITY CAN BE CALCULATED FOR ANY PARTICULAR TIME.
 0042                  SLE=(ERODEF-ERODEI)/DLIFE
 0043                  YIE=ERODEI
                C
                C      INITIALIZE SUMS FOR TOTAL DAMAGE FOR DESIGN PERIOD:
 0044            3000  DYEAR3=0.0
 0045                  DYEAR4=0.0
                C
 0046                  EFF=EFF/100.0
 0047                  IF (EFF.LT.0.25) H2=8.0
                C*************************************************************************
                C         PART II:
                C
                C      ALL CALCULATIONS IN THIS PART OF THE PROGRAM WILL CHANGE FROM
                C      YEAR TO YEAR.
                C      DO THE ENTIRE PART(UP TO STATMENT 1000) FOR EACH YEAR.
 0048                     DO 1000 NY=1,NYEARS
                C
                C      INITIALIZE FATIGUE SUM FOR YEAR:
 0049                  DYEAR1(NY)=0.0
 0050                  DYEAR2(NY)=0.0
                C
                C      CALCULATE AVERAGE DAILY TRAFFIC FOR ONE YEAR:USE THE FORMULA
                C      Y=A*X+B WHERE Y=ADT,A=SLOPE,X=TIME,AND B=Y-INTERCEPT
 0051                  ADT=(SLOPE*NY)+YI
                C
                C      CALCULATE NUMBER OF TRUCKS PER DAY IN ONE DIRECTION AND IN DESIGN LANE
 0052                  NTPD=ADT*T/100.0*DD/100.0*LD/100.0
                C
                C      CALCULATE NUMBER OF TRUCK AXLES PER DAY IN DESIGN LANE
 0053                  AXDAY=NTPD*A
                C
                C      CALCULATE ERODABILITY FOR ONE YEAR:USE THE FORMULA Y=A*X+B WHERE
                C      Y=ERODABILITY,A=SLOPE,X=TIME,AND B=Y-INTERCEPT.
 0054                  ERODE=(SLE*NY)+YIE
                C
                C      SUM THE DAMAGE FOR ONE YEAR:
                C
 0055                     DO 85 I=1,KK
                C
                C      COMPUTE DAMAGE DUE TO PARKED TRAFFIC ONLY(DYEAR1)
 0056                  IF (I.GT.KSAL) GO TO 90
                C
                C      LOAD STRESS EQUATION FOR SAL
 0057                  STRT1=LOAD(I)/(18.0*H1**2)
 0058                  STRT2=116.36335+0.64672*H1
 0059                  STRT3=17.6412*H1**0.5
 0060                  STRT4=15.6341*K**0.25
 0061                  STRT5=-63.74884*DLOG10(K)
 0062                  STRT6=-2.4917*H1
 0063                  STRT7=-37.44179*DLOG10(D)*K**(-.25)
 0064                  STRT8 =6.50848*K**(-0.25)*H1
 0065                  STRT9=-115.5093*K**(-0.25)*H1**0.25
```

```
 0066                 STRT10=-0.00123*B*K
 0067                 STRT11=5.00214*B/H1
 0068                 STRT=(STRT2+STRT3+STRT4+STRT5+STRT6+STRT7+STRT8+STRT9+STRT10+
                     1STRT11)*STRT1
 0069                    CON=1.0
 0070                    GO TO 91
                C
                C     LOAD STRESS EQUATION FOR TAL:
 0071              90 STRT1=LOAD(I)/(36.0*H1**2)
 0072                 STRT2=-12.16860+12.36292*H1**0.5
 0073                 STRT3=-2.09608*H1
 0074                 STRT4=-31.73886*K**(-0.25)*DLOG10(B)
 0075                 STRT5=4.87504*K**(-0.25)*H1
 0076                 STRT6=-96.50225*K**(-0.25)*H1**0.25
 0077                 STRT7 =-0.00036*B*K
 0078                 STRT8 =0.03101091*H1**2
 0079                 STRT9 =6.75862*H1**0.75/K**0.25
 0080                 STRT10=-0.06193*B*DLOG10(H1**3/K)*DLOG10(H1**3/K)*DLOG10(H1**3/K)
 0081                 STRT11=4.11229*B/H1
 0082                 STRT12=140.71457*K**(-0.25)
 0083                 STRT=(STRT2+STRT3+STRT4+STRT5+STRT6+STRT7+STRT8+STRT9+STRT10+
                     1STRT11+STRT12)*STRT1
 0084                    CON=2.0
                C
                C     COMPUTE ALLOWABLE LOAD APPLICATIONS TO FATIGUE FAILURE OF PCC SLAB.
 0085              91 IF (B.GE.7.0) STRT=STRT*1.10
 0086                 LOGN=16.61-17.61*STRT/F28
 0087                 N=10.0**LOGN
                C
                C     COMPUTE NUMBER OF APPLIED AXLE LOADINGS DURING ONE YEAR
 0088                 NAAL=AXDAY*DISTP(I)*365.0*CON*PPT
                C
                C     COMPUTE DAMAGE
 0089                 DAMGE1=NAAL/N
                C
                C     SUM DAMAGE FOR ONE YEAR
 0090                 DYEAR1(NY)=DYEAR1(NY)+DAMGE1
                C
                C     COMPUTE DAMAGE DUE TO ENCROACHING TRAFFIC ONLY(DYEAR2)
 0091                 IF (I.GT.KSAL) GO TO 190
                C
                C     LOAD STRESS EQUATION FOR SAL:
 0092                 STRT1=LOAD(I)/(18.0*H1**2)
 0093                 STRT2=78.06105+0.64672*H1
 0094                 STRT3=17.6412*H1**0.5
 0095                 STRT4=10.51771*H2**0.5
 0096                 STRT5=15.6341*K**0.25
 0097                 STRT6=-63.74894*DLOG10(K)
 0098                 STRT7=144.41502*(EFF+1.)**(-2)
 0099                 STRT8=0.63417*H1*H2
 0100                 STRT9=-37.44179*DLOG10(B)*K**(-.25)
 0101                 STRT10=0.01356*K**(-0.25)*H1*H2
 0102                 STRT11=-40.8387*K**(-0.25)*H1**0.25*H2**0.5
 0103                 STRT12=-0.00274*ERODE*H1*H2
 0104                 STRT13=-0.00123*B*K
 0105                 STRT14=0.06268*ERODE*H1
 0106                 STRT15=-0.35561*H1*H2*EFF
 0107                 STRT16=0.0012*EFF*B*K
 0108                 STRT17=-135.56133*(EFF+1.)**(-1.5)
```

```
0109              STRT18=-0.12128*ERODE*EFF
0110              STRT19=-0.94563*H1*H2*(EFF+1.)**(-1)
0111              STRT20=5.00214*B/H1
0112              STRT21=+0.0425*(H2*EFF/H1)**5
0113              STRT=(STRT2+STRT3+STRT4+STRT5+STRT6+STRT7+STRT8+STRT9+STRT10+
                 1STRT11+STRT12+STRT13+STRT14+STRT15+STRT16+STRT17+STRT18+STRT19+
                 2STRT20+STRT21)*STRT1
0114                 CON=1.0
0115                 GO TO 191
            C
            C     LOAD STRESS EQUATION FOR TAL:
0116          190 STRT1=LOAD(I)/(36.0*H1**2)
0117              STRT2=-57.69734+12.36292*H1**0.5
0118              STRT3=37.03882*H2**0.25
0119              STRT4=140.71457*K**(-0.25)
0120              STRT5=-75.80695*(EFF+1.)**(-0.67)
0121              STRT6=59.34409*(EFF+1.)**(-2)
0122              STRT7=0.5065*H1*H2
0123              STRT8=-31.73886*K**(-0.25)*DLOG10(B)
0124              STRT9=0.60913*K**(-0.25)*H1*H2
0125              STRT10=-34.1187*K**(-0.25)*H1**0.25*H2**0.5
0126              STRT11=-0.0012*ERODE*H1*H2
0127              STRT12=-0.00096*B*K
0128              STRT13=-0.00001*ERODE*B*K
0129              STRT14=0.06195*ERODE*H1
0130              STRT15=0.03101091*H1**2
0131              STRT16=6.75862*H1**0.75/K**0.25
0132              STRT17=-0.29443*H1*H2*EFF
0133              STRT18=0.00102*EFF*B*K
0134              STRT19=-0.06193*B*DLOG10(H1**3/K)*DLOG10(H1**3/K)*DLOG10(H1**3/K)
0135              STRT20=-0.76851*H1*H2*(EFF+1.)**(-1)
0136              STRT21=-0.01283*H2*ERODE*EFF
0137              STRT22=4.11229*B/H1
0138              STRT23=+0.0300*(H2*EFF/H1)**5
0139              STRT=(STRT2+STRT3+STRT4+STRT5+STRT6+STRT7+STRT8+STRT9+STRT10+
                 1STRT11+STRT12+STRT13+STRT14+STRT15+STRT16+STRT17+STRT18+STRT19+
                 2STRT20+STRT21+STRT22+STRT23)*STRT1
0140                 CON=2.0
            C
            C     COMPUTE ALLOWABLE LOAD APPLICATIONS TO FATIGUE FAILURE OF PCC SHOULDER
0141          191 LOGN=16.61-17.61*STRT/F28
0142              N=10.0**LOGN
            C
            C     COMPUTE NUMBER OF APPLIED AXLE LOADINGS DURING ONE YEAR:
0143              NAAL=AXDAY*DISTP(I)*365.0*CON*PET
            C
            C     COMPUTE DAMAGE
0144              DAMGE2=NAAL/N
            C
            C     SUM DAMAGE FOR ONE YEAR:
            C
0145              DYEAR2(NY)=DYEAR2(NY)+DAMGE2
0146           85 CONTINUE
            C
            C     OBTAIN FATIGUE DAMAGE AT THE END OF THE DESIGN PERIOD:
0147              DYEAR3=DYEAR1(NY)+DYEAR3
0148              DYEAR4=DYEAR2(NY)+DYEAR4
            C
0149         1000 CONTINUE
```

```
                C
                C*****************************************************************************
                C
                C      PRINT SUMMARY OF FATIGUE DATA AT END OF DESIGN PERIOD:
 0150                  WRITE(6,600) PN,((TITLE(I,J),I=1,20),J=1,3)
 0151                  WRITE(6,6001)
 0152                  WRITE(6,610)  ((NY,DYEAR1(NY),DYEAR2(NY)),NY=1,NYEARS)
 0153                  WRITE(6,6002)  DYEAR3
 0154                  WRITE(6,6003)  DYEAR4
                C
                C         DO THE NEXT PROBLEM:
                C
                C*****************************************************************************
                C
                C      READ THE NEW TITLE AND INCREMENT THE PROBLEM NUMBER.IF THERE ISN'T A
                C      NEXT PROBLEM, GO TO STOP.
 0155                  READ (5,500,END=2000) TITLE
 0156                  PN=PN+1
                C
                C      WRITE PROBLEM NUMBER AND TITLE:
 0157                  WRITE(6,600) PN,TITLE
                C
                C      READ NEW SHOULDER-TRAFFIC LANE CONFIGURATION
 0158                  READ(5,707) H1,H2,D,EFF
                C
                C      WRITE DESIGN CRITERIA:
 0159                  WRITE(6,630) DLIFE
                C
                C      WRITE SLAB PROPERTIES,TRAFFIC DATA,FOUNDATION SUPPORT:
 0160                  WRITE(6,601) H1,H2,B,FF,FCV,EFF
 0161                  WRITE(6,602) ADTI,ADTF,T,LD,DE,A,LSS,LEPT,PEPT
 0162                  WRITE(6,603) KSAL,KTAL
 0163                  WRITE(6,604)  ((LRANGE(I),LOAD(I),DIST(I)),I=1,KSAL)
 0164                  WRITE(6,605)  ((LRANGE(I),LOAD(I),DIST(I)),I=KSAL1,KK)
 0165                  WRITE(6,631)  K
 0166                  WRITE(6,702)  ERODEI,ERODEF
                C
                C      GO TO 3000 TO REPEAT THE DAMAGE CALCULATIONS FOR DESIGN PERIOD FOR
                C      NEW SHOULDER SLAB
 0167                     GO TO 3000
                C
 0168            2000  STOP
                C
                C*****************************************************************************
                C
                C      INPUT FORMATS
                C
 0169              500 FORMAT(20A4)
 0170              530 FORMAT(1F10.0)
 0171              501 FORMAT(6F5.0)
 0172              502 FORMAT(6F10.0,2F5.0,F10.0)
 0173              503 FORMAT(2I5)
 0174              504 FORMAT(8F10.0)
 0175              701 FORMAT(2F10.0)
 0176              707 FORMAT(4F5.0)
                C
                C*****************************************************************************
                C
                C      PRINT FORMATS FOR INPUT VALUES
```

```
                   C
 0177                600 FORMAT(1H1,T25,39H PORTLAND CEMENT CONCRETE PLAIN JOINTED,/T25,41H
                        1PAVEMENT SHOULDERS DESIGN PROGRAM (JCS-1),/,100(1H*)/1H0,      10H
                        2PROBLEM #,I2,5X,20A4/18X,20A4/18X,20A4//100(1H*))
 0178                630 FORMAT(1H0,T40,11H INPUT DATA/T41,10(1H*)/1H0,16H DESIGN CRITERIA/
                        117(1H*)//3X,29H SHOULDER DESIGN LIFE (YEARS),T70,F10.2)
 0179                601 FORMAT(/,1H0,16H SLAB PROPERTIES/,17(1H*)//,3X,        26H SHOULDER
                        1THICKNESS - INS.,T70,F10.2/3X,30H TRAFFIC LANE THICKNESS - INS.,
                        2T70,F10.2/3X,21H SHOULDER WIDTH - FT.,T70,F10.2/3X, 44H MEAN PCC M
                        3ODULUS OF RUPTURE (28-DAYS) - PSI,T70,F10.2/3X,55H COEFFICIENT OF
                        4VARIATION OF PCC MODULUS OF RUPTURE - %,T70,F10.2/3X,57H LOAD TRAN
                        5SFER EFF. BETWEEN SHOULDER AND TRAFFIC LANE - %,T70,F10.2)
 0180                602 FORMAT(/,1H0,8H TRAFFIC/,9(1H*),//,3X,  52H AVERAGE DAILY TRAFFIC
                        1AT BEGINNING OF DESIGN PERIOD,T70,F10.0/3X,      46H AVERAGE DAILY
                        2TRAFFIC AT END OF DESIGN PERIOD,T70,F10.0/3X,  22H PERCENT TRUCKS
                        3OF ADT,T70,F10.2,/3X,  51H PERCENT TRUCKS IN HEAVIEST TRAVELED OR
                        4DESIGN LANE,T70,F10.2,/3X,33H PERCENT DIRECTIONAL DISTRIBUTION,T70
                        5,F10.2,/3X,21H MEAN AXLES PER TRUCK,T70,F10.2,/3X,42H LENGTH OF SU
                        6RVEYED SHOULDER STRETCH - MI.,T70,F10.2,/3X,69H AV. LENGTH OF TOTA
                        7L ENCROACHMENTS PER TRUCK IN THE SH. STRETCH - MI.,T75, F5.3,/3X,
                        844H PERCENT OF TRUCKS THAT PARK ON THE SHOULDER,T70,F10.5)
 0181                603 FORMAT(3X,37H NUMBER OF SINGLE AXLE LOAD INTERVALS,T70,I10,/3X,37H
                        1 NUMBER OF TANDEM AXLE LOAD INTERVALS,T70,I1),/)
 0182                604 FORMAT(27H1 S.A.L. DISTRIBUTION TABLE,/12X,13H WEIGHT RANGE,6X,8H
                        1PERCENT,/,14X,9H (POUNDS),/20(/,F17.0,2H -,F7.0,F10.2))
 0183                605 FORMAT(/1X,26H T.A.L. DISTRIBUTION TABLE,/12X,13H WEIGHT RANGE,6X,
                        18H PERCENT,/,14X,9H (POUNDS),/20(/,F17.0,2H -,F7.0,F10.2))
 0184                631 FORMAT(///1H,19H FOUNDATION SUPPORT,/,20(1H*),//3X,      47H DESIGN
                        1MODULUS OF FOUNDATION SUPPORT (K) - PCI,T70,F10.2,//)
 0185                702 FORMAT(3X,    63H ERODABILITY OF FOUNDATION AT BEGINNING OF DESIGN
                        1PERIOD (INS.),T75,F5.2/3X,57H ERODABILITY OF FOUNDATION AT END OF
                        2DESIGN PERIOD (INS.),T70,F10.2//)
                   C
                   C***********************************************************************
                   C
                   C      OUTPUT FORMATS FOR RESULTS
                   C
 0186               6001 FORMAT(/1H0,56H RESULTS - ACCUMULATED FATIGUE DAMAGE OF P.C.C. SHO
                        1ULDER,/,9(1H*),//,11X,26H SUMMARY FOR DESIGN PERIOD,/)
 0187                610 FORMAT(/1H0,5H YEAR,5X,15H PARKED TRAFFIC,5X,19H ENCROACHED TRAFFI
                        1C,/,40(/,1H0,I5,7X,E13.3,11X,E13.3))
 0188               6002 FORMAT(/,/,1H0,64H TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO P
                        2ARKED TRAFFIC IS,T70,E14.3)
 0189               6003 FORMAT(/,1H0,68H TOTAL FATIGUE DAMAGE FOR DESIGN PERIOD DUE TO ENC
                        1ROACHED TRAFFIC IS,T70,E14.3)
                   C
                   C***********************************************************************
                   C
 0190                     END
```