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Robert Joseph Guinn
Iowa State University

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Assessment of highway pavement slab dowel bar research

by

Robert Joseph Guinn, Jr.

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Max L. Porter (Major Professor)
Fouad S. Fanous
Lester W. Schmerr, Jr.

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Graduate College
Iowa State University

This is to certify that the master's thesis of

Robert Joseph Guinn, Jr.

has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy

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ABSTRACT

The objective of this paper is to investigate the latest completed and on-going research from across the nation to determine technology gaps and duplications in recent dowel bar research. In order to obtain this collection of information about dowel bars, a search was conducted on a nationwide level. The technological gaps and duplications of the research were then determined. In addition, this report also provides a brief annotated bibliography of all sources used to determine the gaps in technology and knowledge for dowel bar and alternative dowel bar topics as applied to highway pavements.

CHAPTER 1 INTRODUCTION

A vast majority of the nation's highways and roads are made of jointed concrete pavement. Joints in this pavement allow for deformation and movement due to thermal and environmental conditions. Joints may either be longitudinal joints, parallel with traffic, or transverse joints, perpendicular to traffic. Transverse joints are placed at regular intervals creating discontinuities in the pavement, which form a series of slabs. Load transfer within a series of concrete slabs takes place across these joints. An effective load transfer device, therefore, must be present in order to transfer load between adjacent slabs.

For a typical concrete paved road, these joints are assumed to be approximately 1/8-inch gaps between two adjacent slabs. Dowel bars are located at these joints and used to transfer load from one slab to an adjacent slab. After a significant number of vehicles have passed over the joint an oblonging where the dowel bar contacts the concrete can occur. This oblonging creates a void space. This void space is formed due to a stress concentration where the dowel contacts the concrete at the joint face directly above and below the dowel. Over time, the repeated process of traffic traveling over the joint crushes the concrete surrounding the dowel bar and causes a void in the concrete. This void inhibits the dowels ability to effectively transfer load across the joint.

Possible corrosion of the dowel bar can potentially bind or lock the joint. When locking of the joint occurs no thermal expansion is allowed and new cracks parallel to the joint are formed directly behind the dowel bars in the concrete. As temperature decreases, contraction of the concrete will occur resulting in the new cracks becoming wider and a resulting load transfer failure. Once there is no longer load transferred across the joint all the load is then transferred to the subgrade and differential settlement of the adjacent slabs occurs. Differential settlement of the slabs creates a vertical discontinuity at the joints, making vehicle travel uncomfortable, and requires that the slab be repaired or replaced.

A majority of the dowel bars used today for load transfer are epoxy coated. This epoxy coating aids in the reduction of the exposure to corrosive agents. However, many times this coating is nicked or scraped before installation leaving the uncoated steel susceptible to deterioration.

As was mentioned previously, a void around a dowel bar is formed by stress concentrations crushing the concrete directly in contact with the dowel. When a wheel load is applied to the concrete slab the force is supported only by the top or bottom of the dowel bar, not the sides. Since the stress concentration region lays on the top or bottom of the dowel bar, the smaller the dowel the higher the stress concentration. The sides of the dowel bar do not aid in the distribution of the wheel load from the concrete. Therefore, the top and bottom of the dowel bar at the face of the joint is where the stress concentration is located and is directly related to the width and/or shape of the dowel bar. While round dowel bars handle these stress concentrations relatively well, other shapes and materials may provide a better distribution.

Iowa State University researchers have been actively performing continuous research in the area of dowel bars for pavement slabs since 1991. Interest in this work was generated by the utilization of alternative dowel bar shapes and materials. A significant amount of research was funded by the Iowa Department of Transportation (IDOT) in two fairly significant projects, resulting in several research reports, the most notable of which are Report HR343 “Non-Corrosive Tie Reinforcing and Dowel Bars For Highway Pavement Slabs” [1] and TR408 “Investigation of Glass Fiber Composite Dowel Bars For Highway

Pavement Slabs" [2]. These reports serve as examples of the work done by Iowa State University and others and will be referenced later in this document. The concepts of alternative materials and shapes were to provide dowel bars that are not subject to the severity of corrosion and stress experienced by the current steel circular dowel bars.

Additional work has been done at ISU on a compilation of preliminary needs for dowel bars for highway pavement slab joints. A number of other reports have also been prepared for the Iowa Department of Transportation, American Highway Technology (AHT), Highway Innovative Technology Evaluation Center (HITEC) and others concerning dowel bar performance. In combining past and present knowledge, gaps found within dowel bar research can be closed and a universal test may be developed in order to properly evaluate dowel bars. These reports and others will be summarized and referenced later in this report.

During the time that ISU has been conducting the IDOT-sponsored work, other states have also begun to conduct additional studies on both laboratory specimens and field applications of alternative dowel bars. The various studies, however, have not been coordinated amongst state or federal agencies. Therefore, over the recent years, apparent gaps in knowledge exist as to what is yet needed and as to what areas of research may have been duplicated. The purpose of this project report is to identify and summarize the identified gaps in the knowledge of dowel bars. In addition to the presentation of these gaps, this report will also provide a brief background of knowledge sources. In the pages to follow the identified gaps of knowledge will be discussed after the background summary, which in turn, will be provided after the next section stating the project objective and scope.

1.2 Objective

The objective of this “gap study” was to investigate the latest completed and on-going research from across the nation to determine technology gaps and duplications in recent dowel bar research. A gap in dowel bar knowledge is any piece of information that is not already known which may pertain to the effectiveness of the dowel bar as a load transfer device in highway pavement slabs.

1.3 Scope

The scope of this gap study included:

- a compilation of dowel bar research based on a nationwide search,
- a determination of the technology gaps and duplications in nationwide dowel bar research,
- contacting and questioning state and federal agencies that have been active in dowel bar work,
- preparing a summary of current and on-going research topics,
- the determination of the theoretical factors that need to be investigated in order to properly continue dowel bar research for bars of alternative shapes.

CHAPTER 2 LITERATURE REVIEW

In order to determine the technology gaps in dowel bar research, a collection of previous reports, studies and interviews were obtained so that each could be reviewed. From the review of this information the technology gaps and duplications in dowel bar knowledge were determined. This section provides a somewhat annotated reference listing of the many sources from previous dowel bar research and in several instances objectives and significant conclusions for particular projects that were reviewed.

Much of this information was located and/or obtained through:

- Database searches conducted by Mr. Theodore L. Neff of Peak Management Associates [3],
- Contacting individuals, via telephone and e-mail, currently involved in dowel bar interests, and
- By library and database searches conducted by the author, Dr. Max Porter and others (to be referenced later in this document).

This list is not to be considered to be comprehensive. Rather, its goal is to point out the holes or gaps pertaining to dowel bar research. It is intended to show the frequency with which the same research is being conducted and to point out research that needs to be done in order for dowel bar technology to advance.

Reports and papers on dowel bar topics written since 1990 only were included in this report. Most all of these reports/papers contain similar references before the year 1990. Therefore, the author has decided to only review the history of dowel bar reports occurring over the past 13 years. Among these reports, the entire history of dowel bar research is contained.

The following reports and papers are listed in chronological order, starting with the older reports and ending with the more recent reports. Listed in Section 2.2 are projects currently underway. Some of these projects either contain no report or a report was not completed at the time of this project, a project description, however, is still included.

2.1 Previous Dowel Bar Projects and Reports

Report: "The Design of Plain Doweled Jointed Concrete Pavement" (April 1989) [4]

As stated in this report:

> The main objectives of this report are to summarize the findings of past reports, to communicate the experiences of the various States and foreign countries, and to emphasize the need for dowels as a positive method of load transfer on most, if not all, medium and heavy truck traffic routes with plain jointed concrete pavements. Of the three basic types of concrete pavements—jointed plain concrete pavement (JPCP-doweled or undoweled), jointed reinforced concrete pavement (JRCP), and continuously reinforced concrete pavement (CRCP), this report will concentrate on the transverse joint design for JPCP. However, much of the information would apply to doweled joints in JRCP also. [4]

Report: "Concrete Pavement Joints" (1990) [5,6]

As stated in Reference [5]:

> This technical advisory provides guidance and recommendations relating to the design and construction of joints in conventional portland cement concrete (PCC) pavements. The various joint types found in PCC pavement are defined and then guidelines and recommendations on their use, design, and construction are presented. Information on transverse contraction joints (spacing, load transfer, joint reservoir design), construction joints (transverse and longitudinal), longitudinal contraction joints, and expansion joints is provided. [5]

Report: "Aggregate Interlock: A Pure-Shear Load Transfer Mechanism" (1990) [5,7]

As stated in Reference [5]:

> A finite element investigation was made of the behavior of jointed or cracked pavement systems equipped with a pure-shear load transfer mechanism, such as aggregate interlock. Dimensional analysis was used in the interpretation of the data, leading to a general definition of the relative joint stiffness of the pavement system in terms of its structural characteristics. Results obtained in this study were verified by comparisons with earlier published field, laboratory, and analytical information. The investigation demonstrated that deflection load transfer efficiency is related to stress load transfer efficiency and that this relationship is sensitive to the size of the applied load (or to the gear configuration). A simple back-calculation procedure is outlined to evaluate the in-situ joint stiffness of such pavements. Pure-shear load transfer devices are shown to be particularly desirable under a combined externally applied and thermal loading condition, since they offer no additional restraint to longitudinal curling. [5]

Report: "Control of Faulting Through Joint Load Transfer Design" (1990) [5,8]

As stated in Reference [5]:

> This paper describes and evaluates the development of mechanistic-empirical algorithms for more realistic estimates of anticipated faulting in concrete pavements. Earlier theoretical investigations are considered, interpreted through more recent finite element analysis results, and calibrated using an extensive database of field observations. A factor influencing faulting is the dowel-concrete bearing stress, for which an improved method of determination is presented. A procedure is outlined for assessing the need for dowels in both plain and jointed reinforced concrete pavements, and determining the bar diameter needed to prevent significant faulting. Application of the procedure is facilitated through use of the program PFAULT, which can be implemented on a personal computer. [5]

Report: "Evaluation of the Subbase Drag Formula by Considering Realistic Subbase Friction Values" (1990) [5,9]

As stated in Reference [5]:

> A modification of the reinforcement formula that considers the realistic frictional characteristics of subbase types is presented. The objective of this study is not to abandon the current formula but to arrive at a better formula, one that considers the field observations. Rational reinforcement design is important because the amount of reinforcement affects the restraint on the movement of a pavement section,

> or slab, and the long-term performance. The reinforcement formula was modified in accordance with the experimental results obtained concerning subbase frictional resistance. The new formula represents the actual components of frictional resistance at the interface: adhesion, bearing, and shear. The formula calculates the steel requirement for the middle of the slab; in other words, the calculated value is the maximum requirement, and the locations between the free end and the middle of the slab will require less reinforcement. Further experimental study is necessary to calibrate the new formula. [5]

Report: "Feasibility of Class C FRP Load Transfer Devices for Highway Jointed Concrete Pavements" (1990) [5,10]

As stated in Reference [5]:

> The objective of this paper is to analyze the feasibility of using corrosion free fiberglass reinforced plastic (FRP) devices in lieu of steel tie bars in the longitudinal joints of highway concrete pavements. The FRP devices are designed to provide the same shear transfer capability as the currently used steel tie bars. FRP devices consisting of bars, channel and I-beam shapes are considered. It is found that on terms of cross sectional area, the amount required for FRP devices is greater than that for steel bars. This is due to the fact that the modulus of elasticity of the FRP is lower than that of steel. In terms of cost of materials, it is found that FRP devices are more expensive than steel tie bars. However, prevention of deterioration due to corrosion may extend the service life of the joints and therefore that of the pavement. More research is needed to accurately define the increase of service life when corrosion is prevented. [5]

Report: "Design and Construction of Joints for Concrete Highways" (1991) [5,11]

As stated in Reference [5]:

> This publication addresses the design and construction of joint systems for concrete highway pavements (which typically range in thickness from 8 to 14 in.). The need for joints in concrete pavements is first discussed, including a description of the mechanisms of natural crack development due to thermal and shrinkage stresses. The various types of joints are described, and special emphasis is placed on the design of transverse joints, including recommendations for spacing, skewing, load transfer, and construction (dowel placement, sawing, sealing). The design and construction of other joint types (construction joints, expansion joints, longitudinal joints) are also described. [5]

Report: "Thermoset Composite Concrete Reinforcement Part 1 Final" (May 1992) [12]

This is Part 1 of a two-part report. Part 1 contains a comparison of unaged fiber composite and steel dowels and derivation of the appropriate theoretical model for analyzing the results.

Part 2 covers the theoretical and experimental models for accelerated aging of fiber composite reinforcing bars and dowels cast in a concrete environment.

As stated in this report:

The objectives of this study were:

- to determine shear behavior and strength of FC dowel bars without aging,
- to determine shear behavior and strength of FC dowel bars with aging,
- and to determine potential aging effects on bond of FC reinforcing bars.

The scope of this study included:

- selecting an appropriate theoretical model for analyzing the results,
- design and construction of experimental tests for objectives 1 and 2,
- testing the dowel-shear specimens both aged and unaged,
- analyzing the dowel shear testing results,
- design and construction of the test specimen details for examining the aging effects on bond behavior of FC reinforcing bars in concrete,
- conduct experiments and analyze results for FC reinforcing bars.

Conclusions made from this project report:

- Different theoretical models for the analysis of dowels were investigated and developed. Timoshenko's analysis was concluded to be the most appropriate method. A solution to the finite beam problem, as opposed to the conventional semi-infinite solution was considered. A comparison between the results obtained from the analysis using the developed theoretical model and the results obtained using the semi-infinite idealization was made.

- The experimental investigation yielded results establishing maximum strengths, behavioral characteristics and failure modes. The maximum strengths were based upon a reasonably expected elastic load (REEL). The average value of REEL observed for the FC dowel specimens was 13,849 lbs compared with a typical required maximum service load of 4500 lbs. The maximum bending moment in the FC dowel was observed to be 7000 lb-in resulting in a fiber stress value of 56,506 psi which is less than the ultimate coupon flexural stress of 100,000 psi. [12]

Report: "Feasibility of Fiberglass Pretensioned Piles in a Marine Environment" (August 1992) [13]

As stated in reference [13]:

> The primary aim of the study was to investigate the feasibility of using fiberglass pretensioned piles to replace steel in a marine environment. As a consequence experimental investigations were carried out to determine the short term, long term and impact response of specimens pretensioned using S-2 glass/epoxy composites. For comparability, identical steel specimens were also tested.
>
> The short term tests investigated transfer length, losses, static response of under-reinforced beams and the elastic and ultimate behavior of axially and eccentrically loaded columns. The long term tests examined fatigue and creep in concrete and in identically stressed fiberglass prestressed columns. In addition, a major investigation was carried out to determine the durability of pre-cracked and uncracked fiberglass pretensioned beams exposed to wet/dry cycles in 15% salt solution. The impact study investigated stresses in full sized fiberglass pretensioned piles under the application of a 3 kip drop hammer to drive it through medium to dense sands.
>
> The study indicated that the response of identical fiberglass and steel pretensioned specimens is, in general, comparable and may be predicted with reasonable accuracy using non-linear finite element analyses incorporating appropriate material properties. However, the long term durability study indicated that the fiberglass strands suffered degradation under wet/dry cycles. Pre-cracked specimens deteriorated between 3-9 months of exposure and the uncracked specimens between 12-18 months. Scanning electron micrographs showed degradation of the glass fibers in the alkaline concrete environment. Recommendations for overcoming this problem are addressed in the report. [13]

Report: "Thermoset Composite Concrete Reinforcement Part 2 Final" (October 1992) [14]

This is Part 2 of a two-part report. Part 1 contained a comparison of unaged fiber composite and steel dowels and derivation of the appropriate theoretical model for analyzing the results.

Part 2 covers the theoretical and experimental models for accelerated aging of fiber composite reinforcing bars and dowels cast in a concrete environment.

As stated in this report:

> The objectives of this study were:
>
> - to determine shear behavior and strength of FC dowel bars without aging,
> - to determine shear behavior and strength of FC dowel bars with aging,
> - to determine potential aging effects on bond of FC reinforcing bars.
>
> The scope of this study included:
>
> - selecting an appropriate theoretical model for analyzing the results,
> - design and construction of experimental tests for objectives 1 and 2,
> - testing the dowel-shear specimens both aged and unaged,
> - analyzing the dowel shear testing results,
> - design and construction of the test specimen details for examining the aging effects on bond behavior of FC reinforcing bars in concrete,
> - conduct experiments and analyze results for FC reinforcing bars.
>
> Conclusions made from this project report:
>
> > *Accelerated aging*
> >
> > A very good approximate model was developed for accelerated aging of FC materials that will approximate real weather aging. Two equations were developed for accelerated aging in central Iowa (Ames). The following

equation relates the temperature of the aging bath to the number of days aged per day.

$$\text{Age} * (\text{days/day}) = 0.200\ e^{0.052 * T}$$

The next equation, the acceleration factor (AF) equation adjusts the number of days aged per day to account for a mean annual temperature (MAT), that is different than the United Kingdom (UK) where the accelerated aging process was developed.

$$AF = 2.986\ E\text{-}19\ e^{13.783X}$$

The E-glass fibers encapsulated in a vinyl ester resin matrix have proven in this research to be very resistant to accelerated aging effects.

Pullout Specimens

A theoretical model was developed to approximate the mechanical bond degradation in the pullout specimens. Using the following equation, the tensile elongation could be approximated using a varying length L_b, that took into account the mechanical bond failure.

$$\delta = (P_t * L_b)/(E * A_{FC})$$

Dowel Specimens

Overall, the accelerated aging solutions of water, lime and salt apparently had little or no affect on the shear strength behavior of any of the dowel bars.

Approximate equations were developed for FC and steel dowels and accounted for both concrete splitting and concrete bearing type failure modes. These equations were developed for unaged dowel specimens and approximated the dowel specimens' failure very close. For a 1.25 in. diameter FC dowel cast in a 10 in. thick concrete specimen the equation is:

$$P_d = 1.68\ f'_c$$

For a 1.50 in, diameter steel dowel cast in a 10 in, thick concrete specimen the equation is:

$$P_d = 3.00\ f'_c$$

Verification was made on the testing procedure (clamping method) for the dowel specimens. The authors determined that it was a representative testing procedure based upon the Iosipescu shear test. The clamping method was modified to more closely represent the Iosipescu shear test. Upon doing

> so, the REEL loads, deflections, and failure modes were very consistent between the two testing procedures.
>
> The steel dowel bars in the dowel-shear specimens were strain gauged to check the theoretical moment distribution along the dowel bar as presented in Part 1 of this report. An experimental moment distribution was developed based upon the strain gauged dowel specimens. The theoretical moment distribution was approximately equal to the experimental moment distribution. An inflection point was not observed in the experimental moment distribution. Overall the author's feel that the theoretical model developed in Part 1 is representative of the steel dowel specimens and is also representative of the FC dowel specimens. [14]

Report: "Shear Response, Deformations, and Subgrade Stiffness of a Dowel Bar Embedded in Concrete" (November 1992) [15]

As stated in this report:

> This study has four different but closely allied objectives concerning the modelization and behavior of dowel action in a reinforcing bar in relation to the following topics:
>
> - the subgrade stiffness formulation of the concrete embedment,
> - the reliability of a few equations proposed in the literature for the evaluation of the dowel strength, including also a few cases which have particular relevance (high-strength concrete and inclined dowels),
> - the actual displacement field of a dowel bar embedded in the concrete,
> - the formulation of a plastic hinge in the dowel bar and a flake in the concrete underneath, and the evaluation of the length of the plasticized zone along the dowel bar.
>
> Conclusions:
>
> Tests from block-type specimens, reinforced with a single long dowel acting against the concrete core and with the shear plane coincident with specimen forefront, show that:
>
> - The behavior of a long dowel is mostly elastic (both in the bar and the embedment) for shear forces not exceeding 40 percent of the ultimate

capacity: such behavior is definitely confirmed by the actual, measured displacements and the ensuing curvature distributions.

- At collapse, more than 50% of the dowel section is plasticized over a bar length close to two diameters, with a peak at 1 diameter from the shear plane; as regards concrete, a flake gets detached underneath the dowel, at 75 percent of the ultimate load, with a depth close to 0.4 to 0.6 bar diameters from the shear plane.

- The load-displacement curves are mostly elasto-plastic in the case of the normal concrete, with natural rounded aggregate, but tend to be elasto-softening in the case of high-strength concrete, with basaltic, crushed aggregates.

- As a rule, the equations found in the literature for the evaluation of ultimate dowel capacity are reliable for normal concrete, both for dowels at right angles to the shear plane and for inclined dowels or slanted shear planes; to a lesser extent, the same equations are still valid for high-strength concrete. These equations are:

$$Vu = Vmax * \mathrm{sqrt}(30/f'c) \quad \text{for normal concrete}$$

$$Vu = Vmax * \mathrm{sqrt}(75/f'c) \quad \text{for high-strength concrete}$$

- Modeling the dowel as an “equivalent” elastic beam resting on a cohesionless soil can still provide a realistic description of the nonlinear response of the loaded section, on condition that the subgrade stiffness is formulated as a function of the “damage” accumulated in the concrete embedment and in the dowel bar: this damage may be represented by means of a suitable “damage index”.

- The proposed formulations for the subgrade stiffness of the concrete embedment cannot describe the entire distribution of the displacements along the interface (i.e., along dowel axis): with regard to this point, more refined formulations for the subgrade stiffness should be introduced, together with a better modelization of the bar (an elasto-platic constitutive law for the steel should be sufficient). [15]

Report: "Non-Corrosive Tie Reinforcing and Dowel Bars for Highway Pavement Slabs"

(November 1993) [1]

As stated in the project report:

> The objectives of this study were:
>
> - to develop a laboratory test method for the evaluation of highway pavement dowels which approximates actual field conditions,
> - to compare static, fatigue, and dynamic behavior of fiber composite (FC) dowels to those for steel dowels when used as load transfer devices in transverse joints of highway pavements,
> - to study the bond characteristics of the fiber composite tie rod.
>
> The scope of this study included:
>
> - an evaluation of previous testing performed on pavement dowels and an extensive review of literature dealing with pavement dowels and fiber composite materials,
> - placement of FC dowels and FC tie rods in an actual highway pavement during new construction,
> - development of a program for monitoring and evaluating the performance of FC dowels placed in an actual pavement,
> - monitoring and evaluation of the performance of FC dowels placed in an actual pavement,
> - computer modeling and analysis of an actual highway pavement joint system and a laboratory full-scale pavement joint system in order to design a laboratory testing setup,
> - design and construction of experimental test setups and specimens for static, fatigue, and dynamic testing of FC and steel dowels, and static bond tests on FC tie rods,
> - testing of elemental dowel specimens under static loading,
> - testing of full-scale slab specimens which use FC and steel dowels, and full-scale beams with FC tie rods, and

- analyzing results of tests on full-scale pavement slabs, elemental dowel specimens, and on FC tie rod beams.

Conclusions made from this project report:

Overall conclusions:

- The joints utilizing FC dowels studied in this report performed as well as joints utilizing standard steel dowels when both were subjected to conditions which simulated actual highway pavement use, including cyclic loading.
- The laboratory test methods for evaluation of highway pavement dowel bars, which were developed during this research (i.e. the elemental modified iosipescu and the full-scale slab), provided good behavioral results for highway pavement joint conditions.

- The full-scale pavement testing procedures applied in this research provided a good method for monitoring and evaluating the behavior of dowel bars when placed in a concrete pavement joint subjected to cyclic loading.

Conclusions specifically related to the full-scale slab testing:

- The 1.75-in. FC dowels spaced at eight inches performed at least as well as 1.5-in. steel dowels at 12 inches in transferring static loads across the joint in the full-scale pavement test specimens. The performance of the 1.75-in. FC dowels spaced at 12 inches was similar to that of the 1.5-in. steel dowels spaced at 12 inches with any difference being attributed to dowel diameter.

- The load transfer efficiency of 1.75-in. FC dowels spaced at eight inches in a full-scale pavement slab was nearly constant (approximately 44.5% load transfer) through two million applied load cycles with a maximum of 9,000 pounds.

- The load transfer efficiency of 1.5-in. steel dowels spaced at 12 inches in a full-scale pavement slab decreased (approximately from 43.5% to 41.0% load transfer) over the first two million cycles.

- The load transfer efficiency of 1.75-inch FC dowels spaced at 12 inches in a full-scale pavement slab decreased from an initial value of approximately 44% to a final value of approximately 41% after 10 million cycles.

- Load transfer by 1.5-in. steel dowels spaced at 12 inches in a full-scale pavement slab remained rather constant (approximately 41.0%) beyond two million cycles through ten million load cycles.

- The behavior of increasing relative displacements at a pavement joint, due to a 9,000-pound load, as the number of load cycles increased occurred for both the FC and steel dowels studied in this research.
- Relative displacements measured at pavement joints with 1.75-in. FC dowels spaced at eight inches were slightly smaller than at joints with 1.5-in. steel dowels spaced at 12 inches. Both were subjected to similar load and support conditions during the testing.

- Load transfer by individual FC and steel dowels in a full-scale pavement joint can be determined by relating the measured dowel strains to the strains measured during elemental testing of the same types of dowels.

- The use of steel beams as simulated subgrade in place of soil subgrade was effective for the study of pavement dowel performance under fatigue and static loading.

- The test procedure developed and applied in the full-scale pavement slab testing provided results which were valuable in performing an analysis of dowel behavior.

- Using hydraulic actuators to simulate truck traffic in laboratory testing of full-scale pavement joints was effective for the evaluation of dowel behavior at the joints.

Conclusions specifically related to the elemental specimen testing:

- Elemental specimen testing, by examining the performance of a single dowel in shear, was valuable in support of full-scale pavement testing.

- The behavior under static loading of FC dowels during elemental shear testing was similar to their behavior during full-scale slab specimen testing.

- Results from previous testing of steel dowels in elemental specimens [16] and results from full-scale testing in this study indicated that steel dowels behaved similarly during full-scale and elemental static testing.

- The modified Iosipescu shear test procedure for elemental dowel testing provided an adequate method for evaluating the shear properties of a pavement dowel/concrete system.

- Values of the modulus of dowel support, K_0, for dowels tested in elemental shear specimens with equal concrete strengths were directly related to the flexural rigidity of the dowels.

- Values of K_o for 1.75-in. FC dowels were determined to be 358,000 and 247,000 pci for elemental specimens with concrete compressive strengths, f’c, of 7,090 and 5,092 psi, respectively. These values compare to those determined in reference [16] $K_o = 650{,}000$ pci for 1.5-in. steel dowels in concrete with f’c = 7,090 psi.

- Steel shear reinforcing was not required in elemental specimens for the evaluation of the performance of highway pavement dowels under service level loads.

Conclusions specifically related to field testing of FC dowels in actual highway pavement joints:

- Evaluation using the Road Rater™ testing machine indicated that the performance of FC dowels in two test joints was equivalent to that of steel dowels in four adjacent joints. Average relative displacements were measured at the outside wheel track to be 0.035 and 0.03 mils for the joints with FC and steel dowels, respectively, and 0.05 mils at the inside wheel track for both types of joints.

- No difference in joint performance was observed during visual inspections of pavement joints with FC dowels and adjacent joints with steel dowels.

- The FC dowels placed in two test joints allowed the pavement to crack at the joint locations.

- During very cold weather, the FC dowels in the test joints functioned properly by allowing the pavement to contract and the joint opening to increase. [1]

Report: “Evaluation of Pavement Joint Performance” (January 1994) [17]

As stated in this report:

The objectives/scope of this study were:

- to examine the load transfer mechanism under traffic loading.

- to modify an existing finite element program to properly simulate the response of undercut contraction (YU) and contraction (Y) joints.

- to compare field data with results predicted by the finite element program.

- to recommend improvements in the design procedure of joints with emphasis on minimizing cost and construction time.

Conclusions made from this project report:

Based on the results of the field study and finite element analysis, the following conclusions can be drawn:

- The two dominating forces in the dowel bar are moment around the X-axis and the shear force. The moment about the Y-axis, axial force and torque do not make a significant contribution to the response of the dowel bar.
- Stiffness of the subgrade has a significant influence on the response of the dowel bar.
- The looseness of the dowel bar affects the response of the dowel. If the hole is larger than the dowel bar, the load transfer is not sufficient.
- Based on observations at the site and evaluation of the data, the 1 in. diameter fiberglass dowel is not recommended for rigid pavement.
- The larger diameter and stiffer bars transfer more load across the joint.
- The most efficient dowel for load transfer is the 1.5 in. diameter steel bar.
- The finite element model (ILLI-SLAB) is not capable of predicting true response of the joints.
- Stresses are small in concrete for bending and also dowel bearing.
- The presence of the undercut in a joint initially reduces the forces in the dowel bar; however, after a short period of time, the effectiveness of the undercut diminishes.
- Despite the type of joints (Y or YU), after several months the magnitude of forces in the dowel bars approaches the same range.
- In rigid pavement, shear forces, due to truck speeds from 45 to 65 mph, are similar, however, at speeds less than 30 mph shear forces increase.
- Measured dowel forces are smaller than values predicted by analytical and theoretical methods.

- The performance of a 1.5-inch diameter fiberglass dowel bar approached that of a 1.0 in. diameter steel dowel. [17]

Report: "Analysis Design, and Construction of Transverse Joint Load Transfer Systems For Rigid Pavements" (December 1994) [18]

As stated in the project report abstract:

> This report discusses…the evolutionary developments in mechanistic dowel behavior theory proposed by Bradbury, Grinter, Friberg, Lessels, Timoshenko, and Westergaard (in chronological order). New findings relating to dowel bar behavior obtained from finite element modeling are discussed. A sampling of pavement performance models which use empirical or empirical-mechanistic statistical regressions to estimate load transfer performance (expressed as transverse joint faulting) in terms of material, environmental and from a limited number of field performance and laboratory studies are summarized. Seventy years of design recommendations as inferred from theoretical developments, field performance observations and laboratory studies are reviewed. Recommended construction and transverse joint/load transfer restoration are presented. Joint related rigid pavement distresses are described. Finally, limited information concerning a proposed new load transfer system (X-FLEX™) under development at Kansas State University is presented. [18]

Report: "Design, Construction, and Maintenance of PCC Pavement Joints" (1995) [5,19]

As stated in Reference [5]:

> Portland cement concrete (PCC) pavements require joints to control the natural cracking associated with shrinkage caused by drying and with movements caused by changes in temperature and moisture conditions. This report records the state of the practice with respect to the design, construction, and maintenance of PCC pavement joints. An overview of concrete pavement jointing is presented, including a description of current practices used by highway agencies. This is followed by general joint design considerations, such as load transfer needs, joint spacing requirements, and joint reservoir and sealant design. A discussion on current joint construction practices and quality control considerations is also provided to illustrate critical construction requirements, and a summary of recommended joint repair and maintenance practices is presented. [19]

Report: "Coating Protection for Reinforcement: State of the Art Report" (1995) [5,20]

As stated in Reference [5]:

> This expert report provides a comprehensive survey of hot-dip galvanizing and epoxy-or-PVC-coating protection systems for steel reinforcement. It examines influences on materials and application in manufacturing, performance in concrete environments, and practical experience. It also offers guidance on the choice of protection systems. [20]

Report: "An Analysis of the Longitudinal Reinforcement in a Jointed Reinforced Concrete Pavement" (1995) [5,21]

As stated in Reference [5]:

> The longitudinal steel in many jointed reinforced concrete pavements (JRCP) designed using current procedures has failed prematurely, resulting in excessive crack widths, spalling, faulting, loss of subgrade support, and so on. A review of current procedures shows that only extensional tensile stresses are now considered in design. A new design procedure must be developed that will consider all sources of stress and thereby prevent premature failure. [21]

Report: "Aging Degradation of Fiber Composite Reinforcements for Structural Concrete" (September 1995) [22]

As stated in this project report:

> The objectives of this study were:
>
> - to overall, test long-term durability of commercially available FRP products for reinforcement of structural concrete.
> - to evaluate the structural behavior and tensile strength of unaged commercially available FRP rebars and prestressing tendons,
> - to evaluate the structural behavior and tensile strength of commercially available FRP rebars and prestressing tendons directly exposed to an accelerated aging solution
> - to determine the potential effect of corrosion or simulated aging on FRP rebars under constant load,

- and to investigate the potential effect of corrosion or simulated aging action on prestress losses in concrete beams reinforced with FRP prestressing tendons.

The scope of this study was:

- to obtain FRP reinforcement for prestressed and non-prestressed concrete applications which are available from domestic and/or international suppliers,
- to develop loading jigs to maintain FRP rebar specimens under constant load, a prestressing frame, aging tank, and an aging bath management system,
- to develop a gripping technique suitable for tensile testing of the FRP rebar specimens investigated in this study. Perform tensile testing of unaged FRP rebar and prestressing tendon specimens,
- to construct FRP prestressed beam specimens, using the prescribed prestress level specified by the sponsor,
- to study the effect of potential cracking of the resin by preloading FRP rebars prior to submerging the specimens in the aging solution.
- to develop an accelerated aging technique for the specimens submerged in a high alkalinity aqueous solution at an elevated temperature, expanding on the experimental technique developed by the Pilkington Bros. Ltd. [23-27] and also based on previous accelerated aging research at Iowa State University [14,16]
- to study the effect of the corrosion or simulated aging on the ultimate tensile strength and other properties of the FRP rebars and prestressing tendons
- to perform flexural testing on aged and unaged prestressed concrete beams. And to perform flexural testing on beams cast after the aging period with the aged and unaged FRP rebar reinforcement.

Conclusions made from this project report (GFRP rebars):

- The unaged GFRP rebars exhibited lower ultimate tensile strengths than expected. The test results were consistent with average results as low as 50-55 ksi (345-379 Mpa). This average was approximately 50% of the ultimate tensile strength specified by the manufacturers for these specimens. Based on the consistent results and the evaluation of the tensile failures the test results were found to be valid and not influenced by the grips.

- The tensile test results of unaged GFRP rebars obtained at ISU were verified by Dr. Dolan at the University of Wyoming (UW). Additional GFRP rebar specimens were gripped and tested by Dr. Dolan, using a gripping technique developed at UW, and compared to the specimens tested at ISU using the gripping technique developed at ISU. The fact that the tensile test results from UW were in the same range as the results obtained at ISU verified the test procedure used in this study. The tensile test results obtained at ISU were therefore concluded to be valid.

- The tensile test results of the unaged and aged GFRP rebars were also verified in flexural testing of concrete beams, containing either unaged or aged GFRP rebar reinforcement. These test results showed that the lower than expected ultimate tensile strengths obtained for the unaged and aged GFRP rebar specimens were not influenced by the test procedure or the gripping technique used in this study.

- Compared to the unaged specimen properties, the ultimate tensile strength was greatly reduced after 19 days of accelerated aging, which was equivalent to approximately 5.4 years of real time aging. The study, therefore, showed that the direct exposure to the highly alkaline solution could rapidly reduce the ultimate tensile strength of the GFRP rebars.

- Rebar specimens exposed to accelerated aging equivalent to approximately 50 years of real time aging exhibited reduced ultimate tensile strength and maximum strain capacity. The modulus of elasticity was not affected by the accelerated aging. The study showed that accelerated aging in a highly alkaline environment significantly reduces both the ultimate tensile strength and the maximum stain capacity of directly exposed GFRP rebar specimens. Furthermore, the comparison between the ultimate tensile strength after 19 and 81 days of accelerated aging showed that the strength losses were not a linear function of the number of days aged.

- Sustained loading at 40% of ultimate tensile strength of unaged GFRP rebars for almost three months did not affect the ultimate tensile strength or the modulus of elasticity of the rebars. However, the results from the final tensile testing indicated that the sustained loading reduced the maximum strain capacity slightly.

- The combination of sustained loading at 40% of ultimate tensile strength and of exposure to the aggressive environment from the aging solution significantly affected the ultimate tensile strength and the maximum strain capacity of the GFRP rebars. Several specimens failed after only a few days of exposure to the aging solution.

- Preloading specimens to 40% of the ultimate tensile strength for a few minutes followed by a release of stress prior to aging had no apparent effect on the GFRP rebars. After aging these specimens to an equivalent of approximately 50 years, the tensile test results were virtually identical to the results obtained for the aged specimens. Thus, the 40% stress preload and release did not appear to be causing instant cracking of the resin.

- The light microscope investigation verified the tensile test results. The images clearly showed that exposure to the aging solution had caused extensive corrosion of the protective resin seal on the outer surface of the GFRP rebar specimens. [22]

Report: "Three-Dimensional Modeling of Rigid Pavement" (September 1995) [28]

The objectives/scope of this study as stated in the report were:

> To develop a finite-element program to model the response of rigid pavement to both static loads and temperature changes. The program is fully three-dimensional and incorporates not only the common twenty-node brick element but also a thin interface element and a three-node beam element. The interface element is used in the pavement-soil interface and in the joints between slabs. The dowel bars in the joints are modeled by the beam element, which includes flexural and shear deformations. Stresses, strains, and displacements are computed for body forces, traffic loads, and temperature changes individually so that the program can be used to obtain either total stresses for design, or strain changes to compare with experimental data.
>
> The effects of varying the material properties in the pavement, base, subgrade, interface, and dowels are investigated to identify those parameters which most influence the solution. Results of various interface thickness and dowel diameters also are presented. A further study is conducted to determine the effect of average pavement temperature on the curling stresses and displacements.
>
> Conclusions made from this project report:

- The finite element program used in this study has proved to be capable of predicting accurately the displacements of a rigid pavement slab under a thermal gradient loading.

- Predicted stresses have differed from experimental data by a greater margin, but they have been in at least reasonable agreement. Better results probably could be obtained by extending the program to model nonlinear concrete behavior, pavement cracking, and steel reinforcement. [28]

Report: "Random Skewed Joints With and Without Dowels" (1996) [5,29]

As stated in Reference [5]:

> The objective of this study was to compare the performance of a nonreinforced concrete pavement with random spaced, skewed dowel bars versus one without dowel bars. The conclusions from this project are as follows:
>
> - The doweled pavement continues to perform better than the non-doweled pavement
> - The life of the doweled pavement is estimated to last approximately 2.5 times longer than the non-doweled pavement prior to any maintenance or rehabilitation
> - The epoxy coated dowel bars in the test section remained intact (i.e., no corrosion)
> - The use of dowel bars increases initial concrete pavement cost by approximately 7.8%
> - Over a 25-year service life, a non-doweled pavement would cost approximately 13.1% more than a doweled pavement
> - The use of dowel bars in concrete pavement currently saves the Wisconsin Department of Transportation approximately $6,000,000 per year, and
> - The employment of dowel bars is a cost effective method of extending the service lives of concrete pavements while enhancing the pavement performance and reducing user inconvenience. [5]

Report: "Summary of Glass Fiber Reinforced Plastic Dowel Bar Research at Iowa State University" (June 1996) [30]

As stated in this report:

> The content of this paper is constrained to research conducted on GFRP and steel pavement dowels at the ISU Structural Laboratory through the auspices of the Engineering Research Institute. Material included in this paper was adapted from research projects sponsored by the Highway Division of the Iowa Department of Transportation (DOT) and the Iowa Highway Research Board. Additional summaries and reference listings of research findings on related topics in construction oriented

fiber composites are also included. The information contained on some of the references is not available to the general public without prior approval.

In this paper each section is a self-contained unit including the full experiment setup, results, and conclusions for its specific objectives.

The scope of these sections includes:

- The investigation of the feasibility of substituting GFRP (thermoset) pavement dowels for steel pavement dowels. Examined is the load transfer capacity, flexural capacity, and material properties for unaged GFRP dowel bars. A theoretical model is developed which includes the effects of modulus of elasticity for the pavement dowels and concrete, dowel diameter, subgrade stiffness, and concrete compressive strength.

- An experimental investigation that is carried out to establish the modulus of dowel support which is an important parameter for the analysis of dowels. The experimental investigation includes measured deflections, observed behavioral characteristics, and failure mode observations. An extensive study is performed on various shear-testing procedures. A modified Iosipescu shear method is selected for the test procedure. Also, a special test frame is designed and fabricated for this procedure.

- The experimental values of modulus of support for shear and GFRP dowels are used for arriving at the critical stresses and deflections for the theoretical model developed. Different theoretical methods based on analyses suggested by Timoshenko, Friberg, Bradbury, and Westergaard are studied in the development of the theoretical model.

- Focus on the effects of accelerated aging on fiber composite reinforcing bars and dowel bars composed of E-glass fibers encapsulated in a vinyl ester resin matrix. These fiber composite specimens are cast in concrete and exposed to three different aging bath solutions (water, lime and salt) at an elevated temperature of 140°F for nine weeks. Control (unaged) specimens are compared with aged specimens, and the affects of aging are then observed. The aged fiber composite dowel bars in concrete specimens are tested in direct shear to find the effects of accelerated aging on the shear capacity.

- “Real-World” testing of GFRP dowel bars compared to steel dowel bars is investigated. GFRP dowel bars are placed at two transverse joints during construction of a new concrete highway pavement, as are steel dowel bars, in order to evaluate their performance under actual field conditions.

- Fatigue, static, and dynamic testing is performed on full-scale concrete pavement slabs which are supported by a simulated subgrade and which include a single transverse joint. The behavior of the full-scale specimens with both steel and GFRP dowels placed in the test joints are monitored during several million-load cycles which simulate truck traffic at a transverse joint.

- A discussion of related fiber composite research projects performed at the Iowa State University Structural Laboratory. Several projects dealt with structural testing of fiber composites as the primary tensile load carrying members in concrete. Other projects consisted of testing fiber composite sandwich wall connectors. [30]

Report: "Preliminary Assessment of the Potential Use of Alternative Materials for Concrete Highway Pavement Joints" (January 1997) [31]

As stated in this report:

> The objectives of this study were:
>
> - To identify background information on the use of load-transfer devices in highway pavement joints and to provide a preliminary assessment of the market for the use of alternative materials in that capacity.
>
> - To provide a concise compilation of information upon which the Highway Innovative Technology Evaluation Center (HITEC) personnel may judge whether or not the use of alternative materials for concrete highway pavement joints is worth a more thorough and rigorous evaluation.
>
> The scope of this study included:
>
> - A compilation of information provided by state organizations in the form of responses to the HITEC survey.
>
> - A brief overview of topics deemed vital by HITEC personnel to the evaluation of alternative material for concrete highway pavement joints. The contained information is the result of an extensive search of highway literature and expert knowledge.
>
> - Recent findings of research investigations and field applications (up to 1997) of alternative load-transfer devices are discussed to provide the most recent evaluations of performance of some of the currently available alternative products.

- Qualitative analysis of the information and should be treated as the first step in the complete evaluation of the use of alternative materials in concrete highway pavement joints. No attempt was made to perform a rigorous statistical analysis of the survey information, nor was an "in-depth" assessment of the dowel market undertaken.

Conclusions made from this project report:

Conclusions resulting from the 1997 HITEC Survey:

- The six states most interested in alternative material dowels are New York, Kansas, West Virginia, Ohio, Iowa, and North Dakota.

- Circular, epoxy-coated carbon steel bars predominate the existing use of load-transfer devices.

- The most common reported problems with load-transfer devices are placement/misalignment of the dowels during construction and "seizing" of the dowels due to corrosion during the service life of the pavement.

- Strength and corrosion resistance appear to be the most important performance characteristics of a joint system according to state organizations.

- A majority of the state organizations are either unsure of their financial commitment or would pay little or no more of a first-cost premium over their present systems for alternative materials.

- 40% of the responders indicated they had considered alternative materials, with the majority (79%) considering fiber composites.

- Although many field applications of alternative material dowel bars have been implemented (9 states), the long-term performance of the new materials is too soon to be evaluated.

- 86% of the state organizations would consider alternative materials given certain criteria are met, the most important being long-term demonstration project data.

- Interest in future HITEC activities related to the use of alternative materials appears to be quite high with 14 of the state organizations indicating interest in serving on a panel and 11 indicating interest in providing locations for field demonstrations.

Conclusions resulting from HITEC Major Topic Review

- Jointed rigid pavements represent most (≥ 90%) of the rigid pavements in the United States.

- The estimated total mileage of jointed rigid pavements in the current United States highway system is 115,404 miles.

- The estimated amount of doweled PCC paving in the United States is 40,850,000 square yards per year.

- The estimated quantity of required dowels for the United States is 18,500,000 dowels per year.

- The states of Alaska, Massachusetts, Montana, New Hampshire, New Mexico, and Vermont specify no significant amount of PCC pavement, and are therefore potentially poor markets for alternative material dowels.

- The states of Texas, Oregon, Maryland, and Illinois predominately specify continuous rigid pavement and may be poor potential markets for alternative material dowels.

- Initial costs and maintenance costs appear to be the most important bases upon which highway designers choose materials, however, life-cycle costs appear to be increasing in importance.

- For the last ten years, PCC paving has accounted for approximately 22% of the total pavement market in the United States.

- The potential market for alternative material dowels in rehabilitation projects appears to be quite small compared to new paving, accounting for only an estimated 925,000 dowels per year in the United States (estimated 5% of new pavement).

- Many metallic and non-metallic coatings of traditional carbon-steel dowels have been attempted and met with mixed results. Epoxy coating appears to be predominate.

- Of the alternatives to traditional steel, glass fiber-reinforced plastic appears to be the most popular, with the use of E-glass encapsulated in vinyl-ester and epoxy resins predominate.

- The three most common failures in transverse joints are joint seal damage, spalling, and faulting.

- Research investigations into the use of alternative materials for highway dowels have determined that FRP may be used when correct diameters and spacings are specified and stainless-steel may be reliable and cost effective, however, many questions involving the optimal design and corrosion resistance of these materials have yet to be answered. [31]

Report: "Field Instrumentation of Dowels, Final Report" (May 1997) [32]

As stated in the report:

> The objectives of this study were:
>
> - To compare the performance of the four different dowel bar types used in the project. These four types are: 1.5 in. diameter steel and fiberglass dowels and 1.5-inch high steel and fiberglass I-beams.
>
> - To measure the forces placed on dowels by environmental effects, namely temperature-induced curling of the concrete slab.
>
> Both objectives of this research are attempts at improving the problematic area of concrete roadway joints by experimenting with different dowel bar materials and shapes. In addition, this research will show, possibly for the first time, how the environment affects dowel bars.
>
> The scope of this study included:
>
> - The comparison of all four bars types of similar dimensions and mechanical properties. The dowel bars were compared not only to each other in response to dynamic loading but also will be monitored for loads induced by environmental effects in the field.
>
> - An analysis of environmental versus dynamic effects for each dowel type. The magnitudes of forces created in dowel bars by various environmental conditions, namely temperature-induced slab curling and moisture-related warping are analyzed in the field.
>
> Conclusions made from this project report:
>
> Based on the results of the Falling Weight Deflectometer (FWD) testing, the following conclusions can be made for dynamic performance of the four dowel types:
>
> - The dowel bars with higher stiffness and/or greater moment of inertia transferred higher loads across the joint.

- The magnitudes of the loads transferred by the steel dowels and steel I-beams were similar. The 1.5 in. diameter steel dowels carried slightly higher forces, except at the on-joint drop location.
- The fiberglass I-beams experienced the lowest moments of the four dowel types.
- The 1.5 in. diameter steel dowels performed the most effectively of the four dowel types.

Based on the results of the environmental testing, the following conclusions can be made of the four dowel types:

- A similar pattern of force magnitudes seen in the FWD testing was observed in the results of the environmental testing.
- The 1.5 in. diameter steel dowels underwent the highest changes in moment of the four dowel types. The 1.5 in. diameter fiberglass dowels experienced changes of moment slightly higher than the steel I-beams.
- The fiberglass I-beams experienced very small moment changes relative to the other dowel types.

Based on the results of both FWD and environmental testing, the following comparisons and conclusions can be made:

- The 1.5 in. diameter steel and fiberglass dowels and the steel I-beams experienced higher moments during environmental testing than during FWD testing, despite the dynamic FWD loading being very much heavier than that the pavement experiences from truck loading.
- The fiberglass I-beams experienced similar magnitudes of moment during both types of testing.
- In general, forces due to environmental causes are more significant than dynamic loads. In addition to transferring dynamic loads across joints, dowel bars serve as mechanisms to reduce curling of slabs due to temperature gradient. [32]

Report: "Load Transfer Design and Benefits for Portland Cement Concrete Pavements" (1997) [5,33]

As stated in Reference [5]:

> Throughout time, several methods have been developed to enhance performance at transverse and longitudinal joints. Some of the more common methods are increasing slab and base course thickness to improve aggregate interlock, protecting the base and subgrade against water intrusion, installing permeable bases, reducing joint spacing, and installing load transfer devices. Industry practice and research have determined that smooth, round, corrosion-resistant dowel bars are typically most effective in maintaining load transfer throughout the life of a pavement. This guide provides a summary of the benefits and design procedures that are applicable when dowel bars are used as a load transfer device. [5]

Report: "Mechanistic Design and Analysis Procedure for Doweled Joints in Concrete Pavements" (1997) [5,34]

As stated in Reference [5]:

> This paper provides a rational, mechanistic method for analysis, design, and evaluation of doweled joints in concrete pavements. The required inputs to the analytical model are the slab thickness, modulus of subgrade reaction, and the radius of the loaded area. All other model inputs can be set at default values or modified at the designer's discretion. Dowel bar diameters and spacings can then be interactively modified by the designer to yield a given level of load transfer capability at the joint. The same relationships can be used to evaluate the load transfer efficiency of in-service joints by entering FWD-measured joint deflections. The method can be used to back-calculate joint material and structural properties, as well as stress load transfer at the joint. The design and analysis procedures presented in this paper ignore the effects of curling and warping. Obviously, daily and seasonal temperature and moisture cycles have a significant influence on pavement response. Further investigation of the effects of environmentally induced responses is needed. [5]

Report: "Prevention of Joint Faulting Based on Field Performance Modeling" (1997) [5,35]

As stated in Reference [5]:

> This paper describes the development of faulting prediction models for doweled and undoweled joints, based on mechanistic concepts as well as analysis of field data. Site conditions (traffic, climate, and subgrade) and several design features

> (dowel diameter, subdrainage, joint spacing, base type, and slab welding) were found to enter significantly into the faulting prediction models. [5]

Report: "FRP Dowels for Concrete Pavements" (May 1999) [36]

As stated in this thesis:

> The objective of this research was to investigate the behavior of FRP dowels for transverse construction joints of a concrete highway pavement under the effect of typical traffic loading conditions. The behavior of glass fiber reinforced polymer (GFRP) dowels is compared to that of epoxy coated steel dowels. Two different types of GFRP dowels are used in this investigation; Glasform dowels produced by Glasform Inc. in San Jose, California and FiberDowels produced by RJD Industries in Laguna Hills, California.
>
> The scope of this study included:
>
> This research encompasses testing of GFRP and steel dowels using a scaled model of a concrete pavement slab section subjected to static and cyclic loads. The scaled model represents a portion of a full thickness, 254 mm (10 in.), concrete pavement slab with a limited length, 2440 mm (8 ft), and width, 610 mm (2 ft). A simulated half axle truckload was applied on one side of the joint until failure.
>
> The research program consisted of testing twelve slab specimens. The first nine were tested under monotonic load whereas the final three slabs were tested under cyclic loading conditions. Considered in this program are the level of subgrade support and the type of dowel material.
>
> Conclusions made from this project report:
>
> - This investigation of the behavior of GFRP dowels has shown that GFRP dowels can be used in place of the standard steel dowels. Not only do the GFRP dowels transfer sufficient load to an adjacent slab, but do so over the service life of a highway pavement.
>
> - Three materials were tested within this investigation. The top performing material was the Glasform dowel followed by the epoxy-coated steel dowel, and finally the FiberDowel product. All doweled joints performed above the 75 percent joint effectiveness acceptance level while the Glasform consistently performed above 90 percent.
>
> - The diameter of the GFRP dowels was 38 mm (1.5 in.) compared to 32 mm (1.25 in.) for the standard epoxy coated steel dowels. The larger diameter provided two advantages, higher shear stiffness of the dowel and lower

bearing stresses on the concrete. These features are the reason for the improved performance of the GFRP dowels despite their low shear strength.

- The use of deicing salts creates a harsh corrosive environment which deteriorates steel dowels. Epoxy coated dowels are relatively protected, however, dents, and cracks in the epoxy layer provide entry points for corrosion. GFRPs are a corrosion resistant material which will require no maintenance during the life span of the pavement. With continued support from the City of Winnipeg and the Department of Highways and Transportation, full utilization of corrosion resistant load transfer mechanisms could soon be standard practice in the pavement construction industry. [36]

Report: "SHRP Joint Study: A Seven Year Look" (1999) [5,37]

As stated in Reference [5]:

> In 1991 and 1992, test sites were constructed to evaluate the performance of joint seal materials and installation methods in new and old concrete. Five joint resealing sites were installed under the Strategic Highway Research Program (SHRP) project H-106 using 12 materials and 4 installation methods. Additionally, 6 new joint sealing sites were installed under the SHRP SPS-4 supplemental testing program using 20 materials and 5 installation methods. Yearly rigorous evaluation of the effectiveness of these seals have been conducted, providing 7 years of performance data regarding adhesion and cohesion failure, spall distress, and compression seal failures.
>
> This paper summarizes the final analysis results from these studies, providing material effectiveness rankings, life cycle cost evaluations, installation method rankings, and other performance results. [5]

Report: "Load-Deflection Behavior of Smooth Dowels" (November 1999) [38]

As stated in this paper:

> The focus of this study was to gain basic insight into the load-deformation response of a dowel embedded in concrete.... A test program was conducted to determine the load-deflection characteristics of a doweled joint interface representative of a pavement joint. A laboratory experimental technique was developed to directly measure deflections of the embedded dowel. Three concrete strengths, three dowel diameters, and two joint opening widths were tested.

The conclusions made from this study were:

- Concrete strength, dowel diameter, and joint opening width can have substantial impact on the ultimate strength and elastic dowel-concrete interaction of an interface containing a smooth dowel.

- In the elastic range, use of Timoshenko's analytical expression produced mixed success in back-predicting the measured displaced shape of embedded dowels from tests with different concrete strengths, dowel diameters, and joint widths. Large variations in the modulus of dowel support k were required to produce agreement of deflections at the joint face between theory and experimental data. Furthermore, larger values of k than might be expected were needed. In many cases, when agreement was realized near the face of the joint, displacements at other locations along the embedded length were still discrepant and vise-versa. Additional data is needed to relate a particular value of k to joint geometric, stiffness, and strength properties to accurately predict deflections near the joint face.

- For a given test, a single value of the modulus of dowel support could not be used to back-predict the experimentally observed dowel deformations. The modulus of dowel support had to be adjusted depending on the level of applied load (even in the joint's global linear range). Timoshenko's equation, which is based on linear elastic principles, does not account for the complex nonlinear behavior associated with dowel yielding and locally high bearing stresses around the dowel. [38]

Report: "Matching Load Transfer to Traffic Needs" (May 2000) [5,39]

As stated in Reference [5]:

> Current pavement design in Iowa calls for the inclusion of load transfer dowels in transverse joints in both state and local pavements. The dowels have been included to protect the pavement against faulting of the joints and other forms of distress resulting from erosion of the soils from beneath the joints. Faulting has been found to be present mostly at the outer edges of the driving lane. Iowa Highway Research Board Project TR-420 is directed at the evaluation of placing alternative numbers of dowels in the transverse joints of the pavement. A rural and an urban pavement were selected for the test sites on county highways near Creston, Iowa. The sites include subsections containing zero dowels in the transfer joint, three or four dowels in the outer wheel path only, and a full basket of dowels across the joint. This paper will discuss the results of the deflection testing in both wheel paths in both pavement directions on the rural and urban sections. Fault measurements, joint opening widths, and visual distress surveys have been conducted twice per year on

each of the projects. The construction projects are now one year old and the response to load in each case can now be evaluated. [5]

Report: "Long Term Pavement Performance Findings Pay Off For Pennsylvania"

(February, 2000) [5,40]

As stated in Reference [5]:

> The Pennsylvania Department of Transportation (PennDOT) decided to change its practice of using skewed joints after reviewing the results of a Long Term Pavement Performance (LTPP) program analysis project. The project analyzed LTPP pavement performance data to identify what worked and what didn't work to control the development of joint faulting. As of calendar year 1999, Pennsylvania policy specified perpendicular joints for any limited-access, four-lane concrete pavement highway projects. By changing its pavement joint design standard, PennDOT can reduce the occurrence of joint faulting and realize the following benefits: a smoother ride for motorists; reduced construction problems and related costs; reduced maintenance requirements; and fewer maintenance-related disruptions to traffic. [5]

Report: "Glass Fiber-Reinforced Polymer Dowels for Concrete Pavements" (March 2001)

[41]

As stated:

> This paper presents laboratory and field results on the performance of GFRP dowel bars used in transverse joints of concrete pavements. The study included static and cyclic laboratory testing in addition to field-testing using the falling weight deflectometer. Three types of GFRP were tested in addition to epoxy-coated steel. The paper provides information on load transfer in pavements and the feasibility of using GFRP in this application.
>
> Conclusions made from this paper:
>
> GFRP dowels are a viable, corrosion-free alternative to steel dowels. Test results at the laboratory level using two GFRP dowel types, as well as a field application using three types of GFRP, indicate similar performance of GFRP as dowels for concrete pavements in comparison to steel dowels. The study included static and cyclic loading tests using a full-scale model of concrete pavement slab/joint system. The laboratory testing showed that joint effectiveness or load transfer efficiencies are acceptable. The GFRP with relatively higher shear strength resulted in a better performance than GFRP with lower shear strength. Under dynamic (impact) field-testing, the three tested types of GFRP dowels exhibited higher joint

deflections (lower joint stiffness) than steel dowels. Once again the performance is consistent with the shear strength of these dowels. Presently there is no design provision for limiting deflections at joints. Although higher deflections are typically associated with loss of support and shorter pavement service life, this may not be the case for GFRP. In fact, the lower flexural stiffness modulus of GFRP compared to the stiffness modulus of steel and the larger dowel diameter are both advantageous in this type of application because of the reduced bearing stresses on the concrete surrounding the dowel. Bearing stresses are one of the major causes of joint failure. [41]

Report: TR-408. "Investigation of Glass Fiber Composite Dowel Bars for Highway Pavement Slab." (June 2001) [2]

This report consists of four phases. The objectives and scopes for each as stated in the report are as follows:

The objectives for Phase I-IV of this study were:

- to determine the material properties of all the GFRP dowel bars,
- to investigate the behavioral parameters of aged GFRP dowel bars under elemental static testing,
- to investigate the behavioral parameters of unaged GFRP dowel bars under elemental static testing,
- to investigate the behavior of aged GFRP dowel bars under elemental fatigue loading (0.5 to 1 million cycles),
- to investigate the behavior of unaged GFRP dowel bars under elemental fatigue loading (0.5 to 1 million cycles) in a full-scale test,
- to investigate the fatigue behavior of GFRP dowel bars under an accelerated partial design life number of cycles (3-5 million),
- to determine the bond characteristics of both aged and unaged GFRP dowel bars,
- to evaluate the condition of dowel bars placed in actual highway joints,

- to investigate the failure modes and adequacy of alternate dowel bar parameters,
- to develop a finite element model of a jointed concrete highway pavement, and
- to compile the results of the study into a final report and possible standards.

The scope of Phase I included the following tasks:

- The investigation of fatigue behavior of unaged GFRP and steel dowel bars in the modified American Association of State Highway & Transportation Officials (AASHTO) test set up,
- The investigation of the direct shear strength of unaged GFRP and steel dowel bars in the Iosipescu test set up,
- The investigation of failure modes of the dowel concrete system using altered cross-sectional parameters of unaged GFRP and steel dowel bars in the Iosipescu test set up,
- The investigation of bond strength of unaged GFRP and steel dowel bars in the elemental pullout format,
- The investigation of mechanical and material properties of GFRP through burnout, flexure and tensile testing and compare values with manufacturer specifications,
- The development of a finite element model of the dowel concrete pavement joint system based on the results obtained from Tasks 2 and 5 above, and
- The aging of specimens for Phase II.

The scope for Phase II of this study included:

- The investigation of fatigue behavior of aged GFRP and steel dowel bars in the modified AAHSTO test set up,
- The investigation of the direct shear strength of aged GFRP and steel dowel bars in the Iosipescu test set up,
- The investigation of bond strength of aged GFRP and steel dowel bars in the elemental pull-out format,

- A finite element model to verify the laboratory test arrangement for implementation in Phase III, and

- A theoretical model to investigate dowel bar spacing, diameter, and shape.

The scope for Phase III of this study included:

- The investigation of the fatigue behavior of GFRP and steel dowel bars in a full-scale test setup at a high number of cycles. Two test slabs were designed from the elemental testing and analysis conducted in Phases I and II, and

- The investigation of the behavior of dowel bars placed in Highway 30 by subjecting joints to service loading and measuring deflections.

The scope for Phase IV of this study included:

- The development of comprehensive design criteria for using GFRP dowel bars as load transfer devices in transverse highway pavement joints, the criteria was a product of the entire scope of GFRP research conducted at Iowa State University and relevant material from outside sources,

- The recommendation of a test standard to determine the shear properties of the dowel-concrete system for both GFRP and steel products; the recommendations are proposed for an ASTM or AASHTO standard, and

- Comprising a final report that summarizes and coordinates the results of all four phases of the project.

Conclusions made from this project report:

The following conclusions were made with regard to the results of this research and pertain to contraction joints within concrete pavements. (These conclusions may not apply for expansion joints.)

- The jointed plain concrete pavement (JPCP) model created for this study for full-scale slabs was successfully verified by comparing the results from the JPCP model for a pavement of assumed parameters to available theoretical and numerical solutions.

- The two dowel elements developed in this study accurately model the behavior of a dowel embedded in concrete.

- Actual field conditions are simulated by the laboratory test setup.

- All instrumentation, except for the strain gages attached to the dowel bars, was successful in collecting useful data for investigating the effectiveness of a GFRP dowel system in transferring load.

- The test procedure was effective in monitoring the fatigue performance of the GFRP dowels.

- The 1.5-inch diameter GFRP dowels spaced at 12 inches on center were inadequate in transferring load for the anticipated design life of the pavement.

- The 1.5-inch diameter GFRP dowels spaced at 6 inches on center were effective in transferring load over the anticipated design life of the pavement.

- The current design guideline for steel dowels cannot be applied to GFRP dowels. [2]

Report: "Performance of Dowel Bars and Rigid Pavement, Final Report" (June 2001) [42]

As stated in the report:

> The general purposes of this study were to evaluate dowel response under a variety of loading and environmental conditions in the field, and to compare the measured responses of different types of dowel bars. Specific objectives included the following:
>
> - Instrument standard steel and fiberglass dowel bars for the monitoring of strain induced by curing, changing environmental conditions and applied dynamic forces.
>
> - Install these dowel bars in an actual PCC pavement at the time of construction.
>
> - Record strain measurements periodically over time to determine forces induced in the dowel bars during curing and during changing environmental conditions.
>
> - Record strain measurements in the dowel bars as dynamic loads are applied with the Falling Weight Deflectometer (FWD).
>
> - Evaluate strain histories recorded for this in-service pavement.

Conclusions made from this project report:

Based upon data obtained from the instrumented dowel bars on U.S. 50 in Ohio during environmental cycling in the field, the following conclusions can be made for steel and fiberglass dowel bars:

- Steel dowel bars induced higher environmental bending moments across transverse PCC joints than fiberglass dowel bars.

- Both types of dowels induced a permanent bending moment in PCC pavement slabs during curing. The magnitude of this moment appears to be a function of bar stiffness.

- Curling and warping during the first few days after concrete placement can result in high bearing stresses being applied to concrete around the dowel bars. This stress may possibly exceed the allowable bearing stress of the concrete at that early age and results in some permanent loss of contact around the bars.

- Data shown in this report were obtained in the late fall and early winter months. High mid-summer temperature gradients in the pavement may result in even larger stresses being induced in the dowel bars and in the surrounding concrete, though concrete strength would also rise more rapidly during that time of the year.

Initial FWD testing took place on December 3, 1997, soon after construction was completed and when the weather was cold and wet. A second set of measurements was obtained on November 15, 1999. Based on the results of these tests, the following conclusions can be made regarding the dynamic response of steel and fiberglass dowel bars:

- On this project, the magnitude of bending moments and vertical shear forces transferred by steel dowels across transverse PCC joints was much higher than for fiberglass bars of the same size.

- The dynamic bending stresses induced in steel and fiberglass dowel bars by a 12,800 lbf FWD load were considerably less than environmental bending stresses induced by a 3°C (5.4°F) temperature gradient in these PCC slabs.

Based upon the combined results of dynamic and environmental testing, the following conclusions can be made:

- During these tests, steel and fiberglass dowels both experienced higher moments from environmental factors than from dynamic loading.

- The effects of environmental cycling and dynamic loading both must be included in the design and evaluation of PCC pavement joints.

- In addition to transferring dynamic loads across PCC pavement joints, dowel bars serve as a mechanism to reduce the curling and warping of slabs due to curing, and temperature and moisture gradients in the slabs.

Because of the high bearing stresses that can be generated in concrete surrounding dowel bars, this parameter should be considered in dowel bar design, especially during the first few days after placement of the concrete. [42]

Report: "Dowel Bar Optimization: Phases I and II" (July 2001) [43]

As stated in the report:

The objectives of Phases I and II were:

- to investigate the static behavior of steel elliptical and round epoxy coated dowel bars,

- to investigate the failure modes of steel elliptical and round epoxy coated dowel bars,

- to evaluate the benefits and drawbacks of elliptically shaped dowels bars for load transfer,

- to determine the effect of dowel bar spacing and projected load transfer efficiency, and

- to evaluate if variable spacing in combination with shape factor and bar size can optimize costs and constructability.

The main objective of this research was to determine which dowel bar and spacing should be used for the testing during Phase III, a full-scale accelerated laboratory test.

The scope of this study included:

- Construction of elemental specimens for static direct shear testing of steel elliptical and round epoxy coated dowel bars,

- Testing of elemental specimens under direct shear loading,

- Analyzing results from direct shear tests to determine the modulus of dowel support, K_o,
- Analyzing results using K_o to determine the concrete bearing stress at the face of the joint, σ_b,
- Compiling all available information on dowel bar spacing, and
- Analyzing the effect of dowel bar spacing on concrete pavements.

Conclusions made from this project report:

- The results of this research indicated that the elliptical dowel bars behaved as predicted. When comparing the 1-1/2”ϕ round epoxy coated steel dowel bars to the large elliptical steel dowel bars, the large elliptical steel dowel bars produce bearing stresses on the concrete that are greatly reduced while the increase in relative deflection is minimal.
- The large elliptical steel dowel bars have an increase in cross-sectional area of nearly 18% but provide a reduction in bearing stress of over 26%. In contrast, the 1-1/2”ϕ round epoxy coated steel dowel bars have a 44% increase in cross-sectional area over the smaller 1-1/4”ϕ round epoxy coated steel dowel bars yet only provide a 25% reduction in bearing stress.
- The round dowel bars did retain a slight advantage in the stiffness over elliptical dowel bars of a similar cross-sectional area due to their shape. However, this difference in stiffness is insignificant based on the small variance in the deflection of the slabs. The difference in magnitude of the deflections is so small that the dowel bars could be considered as having roughly the same deflection.
- This research has shown that the 1.5”ϕ round epoxy coated steel dowel bars have roughly same bearing stress as the medium elliptical dowel steel bars. This occurrence could be beneficial if the load transfer efficiency was determined.

- This research has shown that the 1.5”ϕ round epoxy coated steel dowel bars have roughly same bearing stress as the medium elliptical dowel steel bars. This occurrence could be beneficial if the load transfer efficiency was determined.

- Dowel bar spacing is a method to distribute load to the dowel bars. The smaller the spacing of the dowel bars the smaller the load on the dowel bars.

A decrease in pavement thickness will lower the number of bars available for load transfer and a smaller spacing may be required.

- Poor subgrade material will also decrease the number of dowel bars available for load transfer and therefore a smaller spacing may also be needed. [43]

Report: "Fatigue behavior of glass fiber reinforced polymer dowels" (May 2001) [44]

As stated in this research report:

The objectives were:

- to develop a computer model that accurately predicts a rigid pavement's response to vehicle loading,
- to verify the full-scale fatigue laboratory test setup used in previous research at Iowa State University [1]
- to investigate the static and fatigue behavior of GFRP dowels, and
- to recommend a preliminary design procedure for the incorporation of GFRP dowels in transverse joints of concrete highway pavements.

The scope of this research program was as follows:

- Construction of a finite element model for the analysis of jointed plain concrete pavement (JPCP);
- Construction of a finite element model for the verification of the laboratory test setup;
- Development of an element that can be used in both computer models that accurately models the behavior of a dowel bar embedded in concrete;
- Determination of an equivalent spacing for various diameters of GFRP dowel bars;
- Construction of two full-scale laboratory pavement specimens: one containing 1.5-inch diameter GFRP dowels spaced at 12 inches and the other containing the same diameter GFRP dowels spaced at an equivalent spacing, as determined from the theoretical portion of this research program;

- Subjection the two full-scale specimens to 5,000,000 cycles of cyclic loading;
- Analysis of the results from the fatigue test to determine the effectiveness of the doweled joints; and
- Development of a design methodology based on the results from this research, previous research, and the research of others for the implementation of GFRP dowels.

The following conclusions were made from the results in this research project.

- The jointed plain concrete pavement model crested for this study was successfully verified by comparing the results from the JPCP model for a pavement of assumed parameters to available theoretical and numerical solutions.
- The two dowel elements developed in this study accurately model the behavior of a dowel embedded in concrete.
- Actual field conditions are simulated by the laboratory setup.
- The steel supporting beams simulate a soil having a modulus of subgrade reaction equal to 145 pci.
- All instrumentation, except for the strain gages attached to the dowel bars, was successful in collecting useful data for investigating the effectiveness of a GFRP dowel system in transferring load.
- The test procedure followed during testing was effective in monitoring the fatigue performance of the GFRP dowels.
- The 1.5-inch diameter GFRP dowels spaced at 12 inches on center were inadequate in transferring load.
- The 1.5-inch diameter GFRP dowels spaced at 6 inches on center were effective in transferring load over the design life of the pavement.
- The current design guideline for steel dowels cannot be applied to GFRP dowels. [44]

Report: "Using the Minnesota Accelerated Loading Facility to Test Retrofit Dowel Load Transfer Systems" (2001) [45]

As stated in the report:

> The objective of this project was the development, construction, and demonstration of the Minnesota Accelerated Loading Facility (Minne-ALF) for rapidly accumulating simulated heavy traffic loads on pavement test slabs. The test stand demonstration included tests of a typical Minnesota Portland cement concrete (PCC) pavement design constructed on a composite foundation (natural base and soil over artificial foundation matting). Demonstration test variables included the use of various types and sizes of dowel bars (retrofit across transverse cracks and joints in the test slabs) and the use of different types of backfill material for the dowel slots that the Minnesota Department of Transportation (Mn/DOT) has either applied in the field or anticipates using in future construction or rehabilitation projects. Therefore, the intent of this testing was to determine the relative long-term performance potential of the given load transfer systems and to use this information to assist in deciding whether to use or continue using these systems in future field applications.
>
> Conclusions as stated in this report:
>
> - The Minne-ALF appears to be a useful tool for evaluating the relative performance potential of rigid pavement designs and design features.
>
> - The use of Speed Crete 2028 in lieu of MnDOT 3U18 concrete backfill improved load transfer system performance. This result is probably because of the higher early age strength and better consistency during placement of the proprietary material.
>
> - Reducing the dowel length from 38 cm to 33 cm appears unlikely to significantly reduce performance potential for properly sized and installed retrofit dowels.
>
> - The use of stainless steel-clad dowels did not appear to significantly reduce the performance potential of retrofit dowel installation when compared with that of epoxy-coated steel dowels. However, tests of the use of fiber-reinforced plastic and grout filled stainless steel tubes suggest that long-term performance potential may be reduced because of the higher flexibility of these systems.
>
> - At this time, it is very difficult to relate the number of load applications in the Minne-ALF to a number of load applications in the field. On one hand, every load applied by the Minne-ALF can be considered a critical load in terms of both placement and magnitude; this would suggest that even higher numbers

> of loads might be expected in actual field applications where loads are not highly channelized and critically placed. On the other hand, many factors are present in the field (e.g. pavement curling and warping, opening and closing of joints, changes in concrete strength and condition with time, seasonal variations in foundation stiffness) that have not yet been (or cannot be) adequately considered on laboratory-based accelerated testing programs. These factors often significantly reduce performance in the field. For these reasons, it is best to consider the Minne-ALF (and most other accelerated load testing facilities) to be capable of providing a good indication of only the relative performance potential of different designs and design features. [45]

2.2 Current Running Alternative Dowel Bar Projects

Project: "Field Evaluation of Alternative Load Transfer Device Locations in Low Traffic Volume Pavements" (Started in July 1998) [3]

Investigator: James Cable, Iowa State University, Ames, IA

As stated in this project statement:

> Objectives:
>
> The project seeks to evaluate the effect of reducing the number of dowels in a low-volume pavement transverse joint.
>
> Description:
>
> Two projects in Union County, Iowa have been used to conduct the study. One rural pavement on granular base has been outfitted with 20 joints each including no dowels, three dowels, and four dowels in the outer wheel path. A similar study on a county/city street employs ten joints of each pattern and a pavement overlay of an existing asphalt roadway. The joints will be monitored for opening width, faulting, visual distress, and deflection in both wheel paths for five years to evaluate performance. [3]

Project: "Identification of Critical Stress Concentration Around Dowel Bars" (Started in August 1998) [3]

Investigator: Samir Shoukry, West Virginia University, Morgantown WV

As stated in this project statement:

Objectives:

Use of nonlinear 3D-FEM to identify the distribution of critical stresses surrounding doweled transverse joints subjected to thermal and moving traffic loads. Alternative dowel and/or transverse joint design will be developed to eliminate the points of high stress concentration, which lead to joint failure thus improve load transfer efficiency and reduce maintenance cost.

Work Plan:

In recent years, West Virginia University (WVU) researchers have taken steps toward developing a mechanistic approach for studying different types of pavements. Explicit nonlinear three dimensional finite element modeling (3D-FEM) was used to simulate the dynamic response of different types of pavement structures to impact loads. The 3D-FEM results showed excellent correlation with the experimental results. Models were developed to investigate the response of rigid, flexible, and composite pavement response to a Falling Weight Deflectometer (FWD) load. The response of a thermally warped slab to FWD load was also modeled. Preliminary results obtained for the Y-stress distribution around the dowel bars indicate that techniques could be developed to prevent the concentration of stresses at the interfaces between the dowels and the supporting concrete. The improvement can be achieved through improving the load transfer between the dowels and the surrounding concrete. Thus, without significant increase in the construction cost, pavement joints could be designed to last longer, maintenance cost could be reduced, and the ride quality maintained for a longer time period. [3]

Project: "Influence of Special Design Variables Upon Rigid Pavement Performance Regarding Contraction Joints" (Started in 1990) [3]

Investigators: Minnesota Department of Transportation, St. Paul, MN

As stated in this project statement:

Objectives:

The objective of this research is to identify optimum contraction joint design parameters under in-situ Minnesota roadway conditions. Minnesota Department of Transportation design standards will be modified if they do not reflect the optimum parameters confirmed by this research project. A secondary objective of this research is to develop a method for nondestructive testing of deteriorated contraction joints that will sufficiently characterize their condition so appropriate repair actions can be recommended.

> Scope:
>
> Low Volume road cells with 1-inch dowels and no dowels, as well as ten-year mainline cells with 1.25-inch dowels and 1.5-inch dowels will be the focus of this project. Two outside lane contraction joints in each of the 4 cells will be instrumented. Radar will be used to verify the correct placement of dowels during construction. Ride levels and joint efficiency ratings using the falling weight deflectometer will be measured throughout the life of these sections. At the end of the life of these cells, a forensic evaluation will be performed on the instrumented joints to determine their condition.
>
> Contraction joints in the widened pavement area (5-year mainline) will be monitored visually during their life and at the time of the forensic evaluation for additional information.
>
> Background:
>
> The two basic designs used to accomplish vertical load transfer rely on either dowel bars or aggregate interlock. Under ideal conditions, contraction joints are designed to transfer all of the vertical loadings (traffic) and none of the longitudinal (temperature) loadings between rigid pavement slabs.
>
> Unfortunately Minnesota roadway conditions are far from ideal. As a result, the performance of contraction joints diminishes with time. Construction conditions, maintenance operations, weather, and real-world traffic all contribute to the deterioration and possible failure of these joints.
>
> The most pressing performance issue is how to establish and maintain good vertical load transfer so pumping and faulting at contraction joints are minimized. [3]

Project: "Seal Joints, Alternative Dowels" (Started in 1999) [3]

Investigator: Tom Winkelman, Illinois Department of Transportation, Springfield, IL

As stated in the project description:

> This research involves the field evaluation of four different experimental features in a PCC pavement joint. The concrete pavement will include polypropylene fibers for reinforcement, no-seal transverse pavement joints, uniform transverse tining, randomly spaced skewed tining, and some alternative materials for dowel bars. Three dowel types are used: Stainless steel, Stainless steel cement grout filled and fiber composite with cement grout filled. [3]

Project: "HITEC Test and Evaluation: Alternative Material Dowel Bars for Rigid Pavements – National Pooled Fund" (Started in 1999) [3]

Investigator: David Reynaud, HITEC, Washington, DC

As stated in the projection description:

> Objectives:
> The objectives of this evaluation are: a) to access the constructability, placement verification, environmental qualities and performance capabilities of fiber reinforced polymer dowels and stainless steel dowels to perform the load transfer and joint movement requirements in concrete pavement joints for the full service life of the pavement without detrimental corrosion or deterioration, and b) to consider the comparative performance and service-life costs of these alternatives materials and epoxy-coated mild steel for use on dowel bars.
>
> Description:
> The problem of deterioration of concrete pavement joints due to dowel bar corrosion has resulted in the search for alternate solutions. Fiber-reinforced polymer (FRP) and stainless steel represent corrosion resistant alternatives to conventional galvanized steel in this application. This is a non-proprietary evaluation program sponsored by the Composites Institute and the Specialty Steel Industry of North America.
>
> Work Plan:
> Project Commitments for a pooled-fund totaling $105,000 from State SP&R funds. Proposals are being accepted from potential consultants to conduct the evaluation in accordance with the HITEC plan. The evaluation will include laboratory testing, field-testing, and demonstration projects. The participating trade associations have provided both FRP composite and stainless steel dowel bars to the Wisconsin DOT for two demonstration projects. The Ohio DOT has removed several joints from experimental projects using FRP dowels installed in the 1980's to check for durability. [3]

Project: "Dowel Bar Retrofit of Rigid Pavements" (Started in 2000) [3]

Investigators: Pavement Research Center, University of California at Berkeley

As stated in this project statement:

> The objectives of this research are to:
>
> - Determine the effects of dowel size.

- Evaluate the performance of different dowel types, potentially including traditional epoxy coated steel, stainless steel and non-ferrous composite materials with respect to performance in the pavement, corrosion durability of the dowels, and chemical durability of the grout materials.

- Evaluate the load transfer restoration provided by the different techniques and determine whether dowel bar retrofit will provide faulting performance for the 10 to 15 years needed for it to be economically viable.

Description:

Since the early 1950s, Caltrans rigid pavement practices have relied on non-erodable bases and aggregate interlock at the transverse joints to control transverse joint faulting. At that time Caltrans stopped using dowels because of problems encountered with dowel alignment during construction, the relatively small benefit obtained from the small dowels used at the time and the level of traffic at the time.

Currently, Caltrans faulting typically occurs on rigid pavements within several years after construction or reconstruction. Faulting results in a rough ride and can increase noise. Caltrans is moving towards use of dowels in all new construction and reconstruction. Improved techniques for retrofitting existing concrete pavements have been developed over the past seven years by the Washington State DOT, among others. Dowel bar retrofitting consists of sawing grooves, insertion of dowels across the transverse joints and grouting, followed by grinding to remove the faulting and smooth the grout surface.

There results of dowel bar retrofit of rigid pavements will provide Caltrans and other research partners with the information needed to design and construct dowel bar retrofit projects to obtain maximum performance, and to determine where dowel bar retrofit is the most cost-effective strategy for rigid pavement rehabilitation. [3]

Project: "Demonstration and Field Evaluation of Alternative Portland Cement Concrete Pavement Reinforcement Materials" (Started in June 2003) [3]

Investigators: J.K. Cable, S.M. Schlorholtz, Iowa State University, Ames, IA.

As stated in this project statement:

Objective:

The objective of this work is the evaluation of two composite products and one stainless steel product in the reduction of deflections and corrosion in transverse and longitudinal pavement joints over a five-year period.

Description:

This project is being done in conjunction with a laboratory project to evaluate the potential fiber composite and stainless steel as a form of joint reinforcement for concrete pavements. The bars have been installed in a pavement near Des Moines, Iowa and will be evaluated twice each for year for five years. [3]

Project: "Field Evaluation of Elliptical Steel Dowel Performance" (Started in February 2002) [46]

Investigator: James Cable and Max Porter, Iowa State University, Ames, IA

As stated in this project statement:

Objectives of study:

Research will strive to answer the following questions:

- What is the relative performance over time of medium-sized and large-sized elliptical (as used in Phases I and II of the laboratory research) steel dowels as compared to that of the conventional steel dowels, in terms of deflection, visual distress, joint faulting, and joint openings?
- What is the impact of dowel spacing on the relative performance of the elliptical and round dowels in field conditions?
- What is the impact on performance of the various dowel shapes when placed in cut or fill sections of the roadway?
- What constructability problems, if any, are associated with the installation of dowel shapes other than round? [46]

CHAPTER 3 THEORETICAL INVESTIGATION/BACKGROUND

3.1 Dowel Bar Theory

3.1.1 Introduction

Transverse joints are placed at regular intervals creating discontinuities in the pavement, which form a series of slabs. Load transfer within a series of slabs takes place across these joints. Without a load transfer device, stresses and deflections located at the joint would be larger than those located on the interior portion of the slab. This increase in stress and deflection can produce pumping and faulting at the joint. Pumping is a condition where subgrade material is forced through the joints. Faulting is defined as the difference in elevation at the joint between two adjacent slabs. A dowel bar, however, effectively and efficiently transfers the load from slab to slab and into the subgrade, reducing the stresses and deflections at the joint, which in turn, prevents pumping and faulting actions. Therefore, an effective load transfer device must be present in order to successfully transfer load between adjacent slabs.

3.1.2 Analytical Model

According to Timoshenko [47] the differential equation for the deflection of a beam on an elastic foundation is as follows in Equation 3.1:

$$EI\frac{d^4y}{dx^4} = -ky \tag{3.1}$$

where k denotes the modulus of foundation and y represents the deflection. The modulus of foundation is defined as the reaction per unit length when the deflection is set equal to one.

The solution to Timoshenko's fourth order differential equation is found in Equation 3.2.

$$y = e^{\beta x}(A \cos \beta x + B \sin \beta x) + e^{-\beta x}(C \cos \beta x + D \sin \beta x) \qquad (3.2)$$

where,

$\beta = \sqrt[4]{k/4EI}$ = relative stiffness of the beam on the elastic foundation (inches^{-1})
k = modulus of foundation (psi)
E = modulus of elasticity of the dowel (psi)
I = moment of inertia of the dowel (inches^{4})

The constants A, B, C and D are determined by applying the appropriate boundary conditions to the problem. When a positive moment, M_o, and a point load, P, are applied to a semi-infinite beam on an elastic foundation, as seen in Figure 3.1, constants A and B are equal to zero and Equation 3.2 becomes equivalent to Equation 3.3 [47].

$$y = \frac{e^{-\beta x}}{2\beta^3 EI}[P \cos \beta x - \beta \, M_o \, (\cos \beta x - \sin \beta x)] \qquad (3.3)$$

The slope of the beam anywhere along its axis is then established by differentiating Equation (3.3) with respect to x.

$$\frac{dy}{dx} = \frac{e^{-\beta x}}{2\beta^2 EI}[(2\beta \, M_o - P) \cos \beta x - P \sin \beta x] \qquad (3.4)$$

By applying Timoshenko's solution for a semi-infinite beam on an elastic foundation to the dowel bar problem, Friberg [48] developed equations for the slope and deflection of a dowel bar at the face of the joint as shown in Figure 3.2 under the following assumptions:

1. The dowel bars are not bonded to the concrete,
2. The dowel bars fit tight within the concrete mass, without bonding
3. And an inflection point exists at the center of the joint.

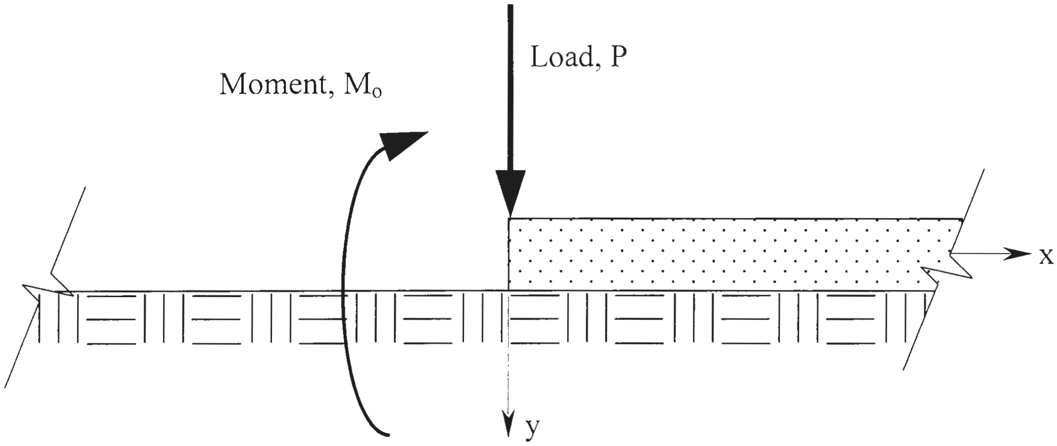


Figure 3.1 Semi-infinite beam on an elastic foundation

Assuming the inflection point does exist at the center of the joint width, z, the forces acting on the dowel bar are as shown in Figure 3.3. Substituting $M_o = -Pz/2$ and setting x equal to zero in Equations 3.3 and 3.4 yields the following two equations for the slope, dy_o/dx, and the deflection, y_o, at the face of the joint, respectively:

$$\frac{dy_o}{dx} = \frac{-P}{2\beta^2 EI}(1 + \beta z) \qquad (3.5)$$

$$y_o = \frac{P}{4\beta^3 EI}(2 + \beta z) \qquad (3.6)$$

where,

$\beta = \sqrt[4]{\frac{K_o b}{4EI}}$ = relative stiffness of the dowel bar encased in concrete (inches^{-1}) (3.7)
K_o = modulus of dowel support (pci)
b = dowel bar width, or diameter in the case of a circular bar (inches)
E = modulus of elasticity of the dowel bar (psi)
I = moment of inertia of the dowel bar (inches^4)
P_t = load transferred through the dowel bar (lbs)
z = joint width (inches)

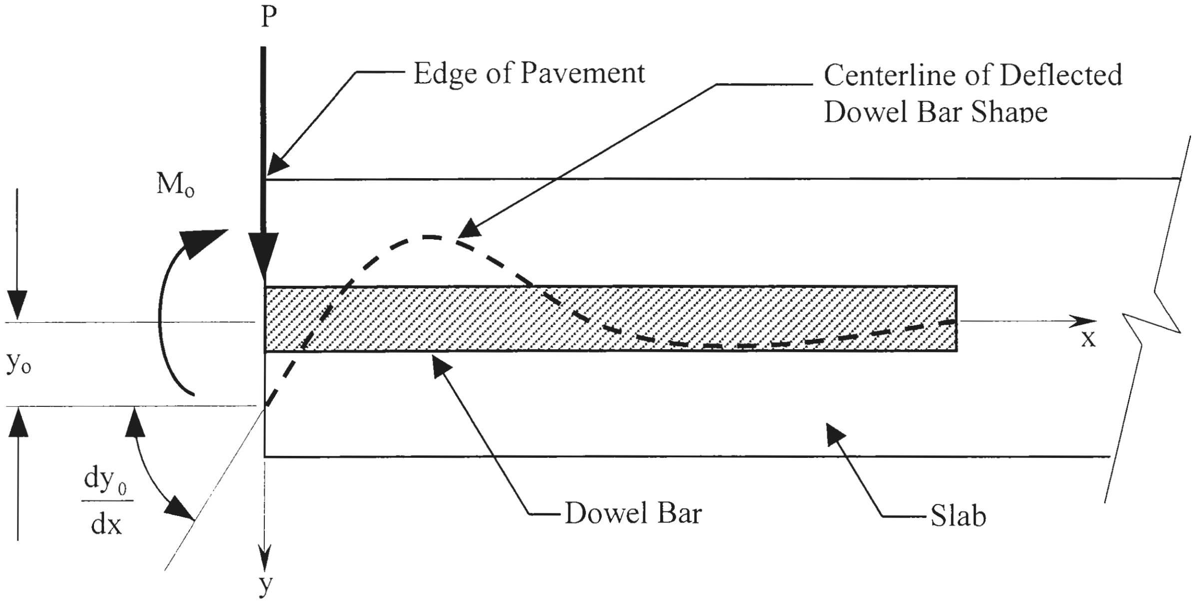
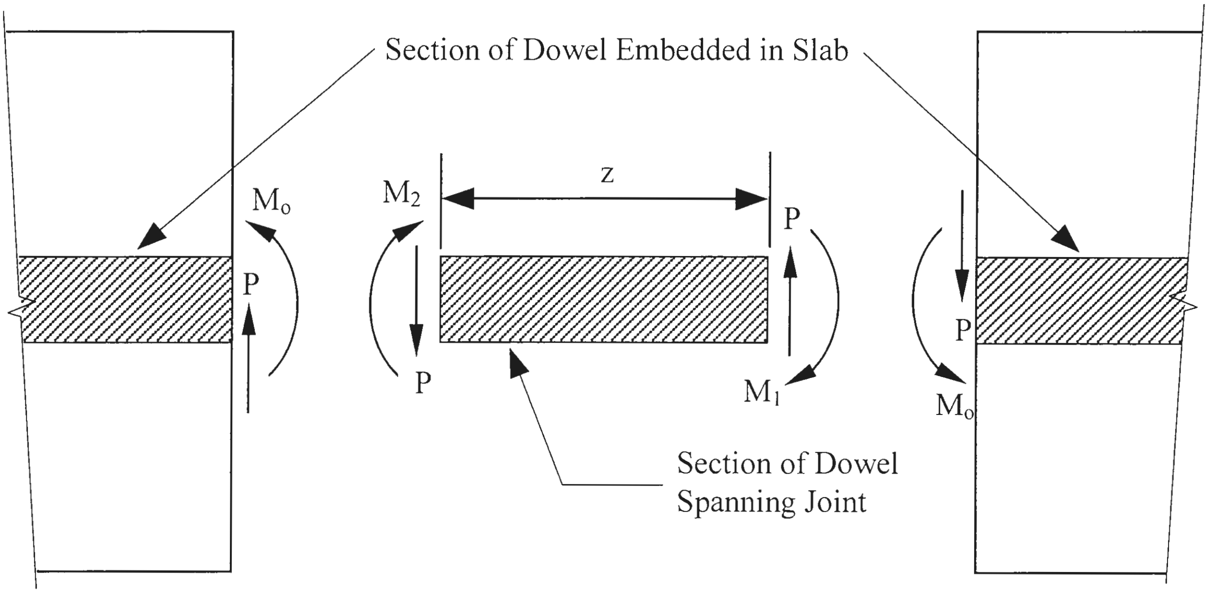


Figure 3.2 Slope and deflection of a dowel bar at the face of the joint



$$M_1 = M_2 = P\,z\,/\,2$$

$$M_o = -M_1 = -M_2 = -P\,z\,/2$$

Figure 3.3 Forces acting on a dowel bar assuming centered inflection point

3.1.3 Maximum Moment

Using Equation 3.4 as a starting point, the maximum moment of the dowel bar and its location can be determined. Equation 3.4 is stated again here for convenience.

$$\frac{dy}{dx} = \frac{e^{-\beta x}}{2\beta^2 E I}[(2\beta M_o - P)\cos\beta x - P\sin\beta x] \tag{3.4}$$

The moment, M, anywhere along the dowel bar may be obtained directly from Equation 3.4 as shown in Equation 3.8

$$M = -E I \frac{d^2 y}{dx^2} = -\frac{e^{-\beta x}}{\beta}[P\sin\beta x - \beta M_o(\sin\beta x + \cos\beta x)] \tag{3.8}$$

The shear, V, anywhere along the dowel bar may also be established as the derivative of Equation 3.8 as shown in Equation 3.9.

$$V = \frac{dM}{dx} = -e^{-\beta x}[(2\beta M_o - P)\sin\beta x + P\cos\beta x] \tag{3.9}$$

Setting the shear equation, Equation 3.9, equal to zero and solving for x yields the maximum moment location, x_m, Equation 3.10.

$$x_m = \frac{\tan^{-1}\left[\dfrac{1}{1 + \beta z}\right]}{\beta} \tag{3.10}$$

The maximum moment, M_{max}, is then determined by substituting Equation 3.10 into Equation 3.8.

$$M_{max} = -\frac{Pe^{-\beta x_m}}{2\beta}\sqrt{1 + (1 + \beta z)^2} \tag{3.11}$$

The positive x direction for the moment, load and direction are as shown in Figure 3.1.

3.1.4 Modulus of Dowel Support

Friberg used the modulus of dowel support, K_o, in his design equations as presented in Section 3.1.2. The modulus of dowel support is a variable defined as the reaction per unit area causing a deflection equal to one. The expression K_ob, where b is the width of he dowel bar, replaces the modulus of foundation, k, as used in Timoshenko's model. Both models by Friberg and Timoshenko are developed using a semi-infinite dowel bar length. Dowel bars, however, do have a finite length of eighteen inches, rendering the given equations from Section 3.1.2 inapplicable to dowel bars used in practice today. In spite of this, Albertson [49] has shown that Friberg's equation can be used with little to no error if the βL value is greater than 2, where the length, L, is taken to be the length of the dowel bar embedded in concrete, or approximately one-half the dowel bar length.

Currently no theoretical procedure for determining the modulus of dowel support exists, therefore, it must be determined experimentally. Results from numerous tests have indicated a wide range of values for the modulus of dowel support. Researchers have reported values anywhere from 132,800 pci to 5,000,000 pci [1,2,12,14,43,50]. Table 3.1 shows recommendations for design values of K_o for steel dowel bars. As can be seen from Equation 3.7, for each individual type of dowel bar, i.e. different size, shape and material, a different K_o exists.

Table 3.1 Recommended design values for the modulus of dowel bar support

Researcher	**Experimental Values used for K_o (pci)**	**Recommended Value for Design K_o (pci)**
Friberg [cited in 51]	200,000 to 5,000,000	1,000,000
Grinter [cited in 52]	300,000 to 1,500,000	300,000 to 1,500,000
Yoder and Witczak [cited in 53]	300,000 to 1,500,000	1,500,000

There is a vast difference in values used for the modulus of dowel bar support. However, researchers agree that the modulus of dowel bar support, K_o, decreases with increased concrete depth below the dowel bar, decreases with increased dowel bar diameter and increases with increased concrete strength [2,44,50,54]. In addition, the modulus of dowel support cannot be more than the modulus of elasticity of the concrete.

3.1.5 Relative Deflection Between Adjacent Pavement Slabs

The relative deflection across a pavement joint consists of four separate components. These components, as shown in Figure 3.4, consist of the deflection of the dowel at each joint face, the deflection due to the slope of the dowel bar, shear deflection, and flexural deflection. When considering all possible components for relative deflection the following expression in Equation 3.12 is found

$$\Delta = 2y_o + z\left(\frac{dy_0}{dx}\right) + \delta + \frac{P_t z^3}{12EI} \qquad (3.12)$$

where,

y_o = deflection at the face of the joint (inches)

$$\delta = \frac{\lambda P_t z}{AG} = \text{shear deflection(inches)} \qquad (3.13)$$

P_t = load transferred by dowel bar (lbs)

λ = form factor, equal to 10/9 for solid circular sections

A = cross-sectional area of the dowel bar (inches^2)

G = shear modulus (psi)

In construction, a small joint width around 1/8" is used. Using such a small joint width allows the deflection due to the slope of the dowel bar to be approximately equal to zero. This small joint width also means that the flexural deflection is approximately equal to zero since the joint width term is cubed. After removing both the slope and flexural deflections from Equation 3.12, Equation 3.14 remains.

$$\Delta = 2y_o + \delta \tag{3.14}$$

Solving Equation 3.14 for the deflection at the face of the joint, y_o, yields Equation 3.15.

$$y_o = \frac{\Delta - \delta}{2} \tag{3.15}$$

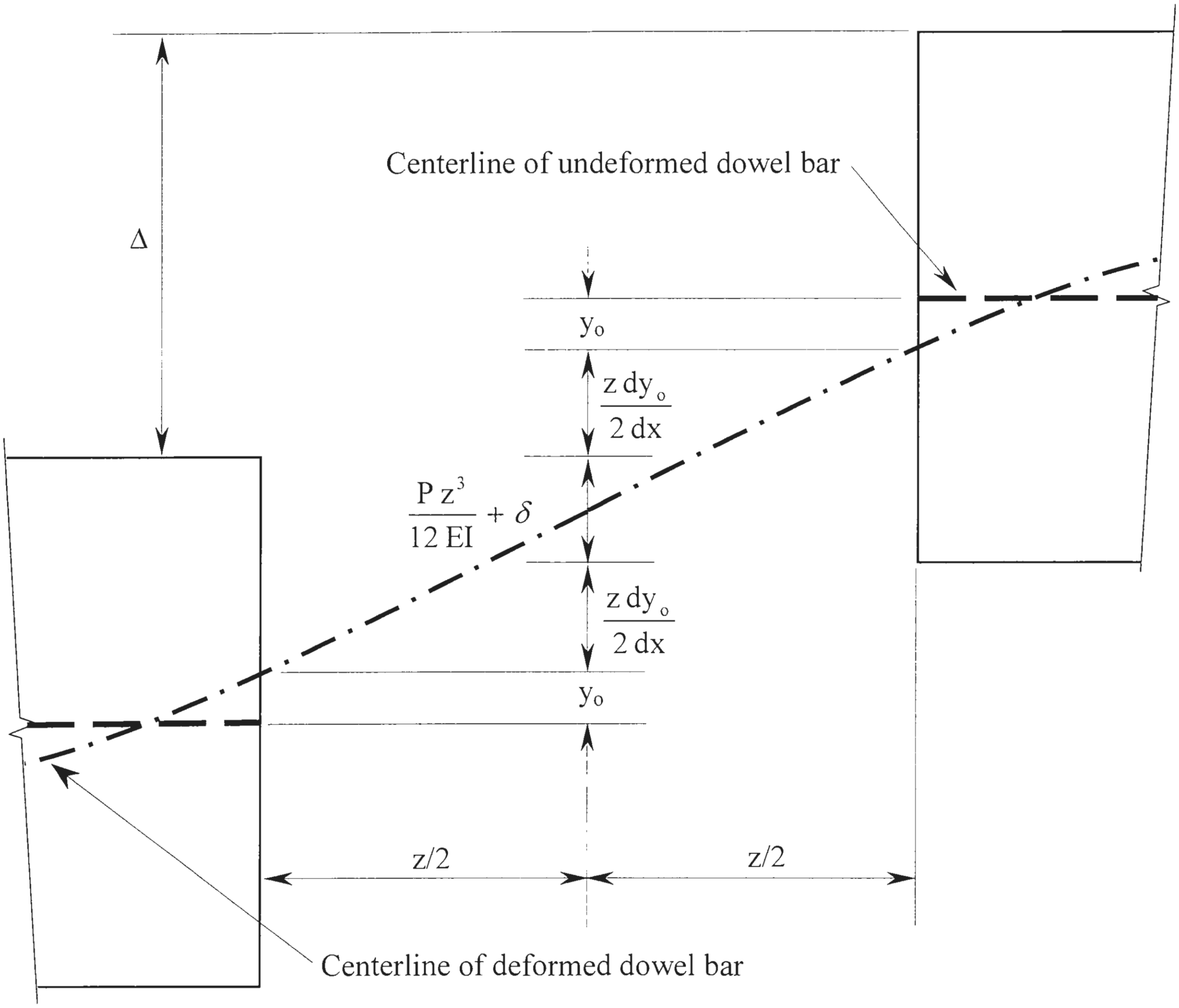


Figure 3.4 Deflection of a dowel across a pavement joint

3.2 Dowel Bar Load Distribution

3.2.1 Load Transfer Across a Joint

In an ideal situation, when a load is placed near a joint, the dowel bars would assume half the load and the remaining load would be transferred to the subgrade [55]. However, no joint will behave in this ideal manner due to the repeated loadings seen by a pavement joint. This repetitive loading will create a small void around the dowel and some load transfer efficiency of the dowel bar will be lost. According to Ioannides [55] this efficiency can be determined by calculating the transferred load efficiency (TLE) as in Equation 3.16.

$$\mathrm{TLE} = \frac{P_t}{P_w} \times 100\% \qquad (3.16)$$

where,

TLE = transferred load efficiency (%)
P_t = load transferred across the joint (lbs)
P_w = applied wheel load (lbs)

The maximum value for the transferred load efficiency is 50 percent [55]. Brown and Bartholomew [56] stated that for heavy truck traffic, a TLE ranging from 35 to 40 percent is considered acceptable.

Yoder [53] suggests a 5 to 10 percent decrease in load transfer across a joint due to the void under the dowel bar that appears after repetitive loadings. Therefore, after allowing a conservative 5 percent decrease in load transfer, the equation for load transferred across the joint, P_t, is shown in Equation 3.17.

$$P_t = 0.45P_w \qquad (3.17)$$

where,

P_t = load transferred across the joint (lbs)
P_w = applied wheel load (lbs)

When a wheel load is applied near a joint, not all dowel bars at the joint aid in transferring the load. The dowel bars closest to the applied wheel load transfer more of the load than the dowel bars furthest away from the applied load. Friberg [48] was the first to investigate the load distribution to the dowel bars across a joint. Based on an analysis by Westergaard [57], Friberg [48] proposed that dowel bars contained outside 1.8 l_r from the applied load were ineffective in transferring any additional load, where l_r is the radius of relative stiffness as shown in Equation 3.18.

$$l_r = \sqrt[4]{\frac{E_c h^3}{12(1-\mu^2)K}} \qquad (3.18)$$

where,

l_r = radius of relative stiffness (inches)
E_c = modulus of elasticity of the pavement concrete (psi)
h = pavement thickness (inches)
μ = Poisson's ratio for the concrete pavement
K = modulus of soil subgrade reaction (pci)

Friberg also believed that a linear distribution of load occurred inside the radius of relative stiffness as shown in Figure 3.5 [58]. Friberg's theoretical analysis was based on dowel bars having a diameter of 0.75 or 0.875 inches and with dowel bar spacing ranging from 12 to 20 inches [48]. Tabatabaie et al. [58] modeled a doweled joint using finite element methods and was able to show that an effective length of 1.0 l_r is more appropriate for today's construction practices where dowel bars of 1.5-inch diameter are used. Tabatabaie [58] was also able to show that a linear approximation does not exist. However, for design purposes, an approximation may be made by assuming that the dowel immediately under the applied load carries full capacity and the dowels on either side carry a load decreasing to zero at a distance l_r from this dowel. For dowel bar design, a calculation of the maximum shear load is useful and will be referred to as the load seen by the critical dowel bar, P_c, as seen in Figure 3.5.

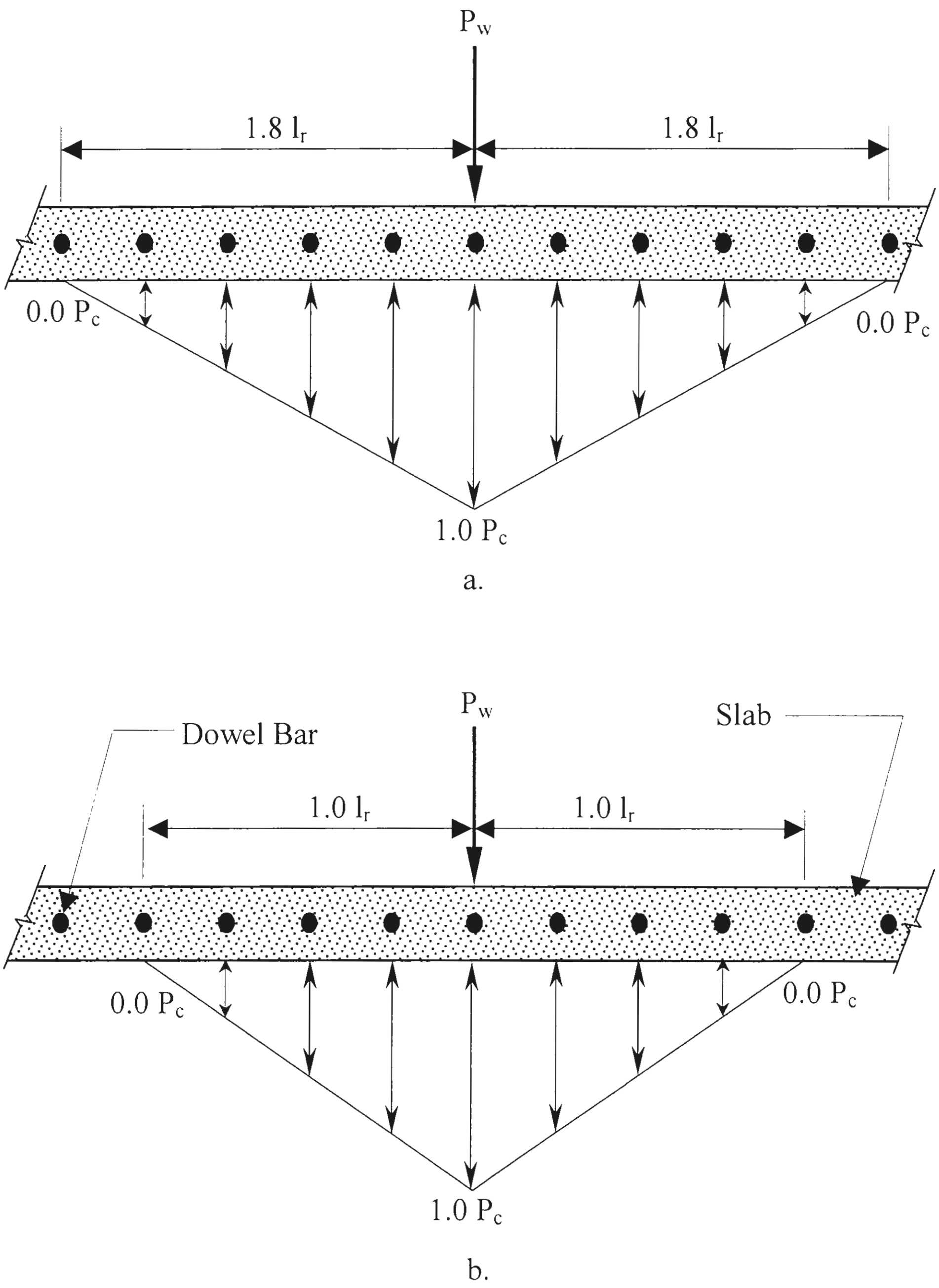


Figure 3.5 Illustration of dowel bar load distribution by a) Friberg and b) Tabatabaie

Using Tabatabaie's [58] linear approximation for the load distribution along a joint, the shear force in any other dowel can be determined. A value of 1.0 is assumed for the height of the triangle directly below the load as shown in Figure 3.5. Multiplying the height of the triangle below any dowel bar by the value of P_c will yield the shear force in that particular dowel bar. The shear force in the dowel directly under the load is determined by dividing the transferred load, P_t, by the number of effective dowels as shown by Equation 3.19.

$$P_c = \frac{P_t}{N_{eff}} \tag{3.19}$$

3.2.2 Joint Effectiveness

The joint effectiveness of a slab is used to measure how well dowel bars within a joint are performing. Joint efficiency of a loaded slab is determined by the joints ability to transmit part of the applied load from the loaded slab to the adjacent unloaded slab. Equation 3.16, repeated here for

$$TLE = \frac{P_t}{P_w} \times 100\% \tag{3.16}$$

convenience, gives one method used to calculate the transferred load efficiency of a joint as given by Ioannides and Korovesis [55]

where,

TLE = transferred load efficiency (%)
P_t = load transferred across the joint (lbs)
P_w = applied wheel load (lbs)

As stated in Section 3.2.1, the maximum permissible transferred load efficiency of a joint is 50 percent. This is due to the fact that if a joint were fully effective, it would transfer half the applied wheel load to the subgrade and the other half through the dowel bar to the adjacent slab. As an example, Brown and Bartholomew [56] state that a TLE of 35 to 40 percent is adequate for heavy truck traffic.

Another way to determine joint effectiveness is to measure deflection as done by the American Association of State Highway and Transportation Officials (AASHTO) and the American Concrete Pavement Association (ACPA). Equations 3.20 and 3.21 are given by the ACPA [59] and AASHTO [60], respectively, as a mode of rating joint effectiveness.

$$E = \frac{2\,d_U}{d_L + d_U} \times 100\% \tag{3.20}$$

$$LTE = \frac{d_U}{d_L} \times 100\% \tag{3.21}$$

where,

E = joint effectiveness (%)
d_U = deflection of the unloaded side of a joint (inches)
d_L = deflection of the loaded side of a joint (inches)
LTE = deflection load transfer efficiency (%)

As determined by the ACPA [59] a joint effectiveness of 75 percent or more is considered sufficient for medium to heavy truck traffic loadings. The LTE, however, must have a value between 70 and 100 percent to provide adequate load transfer [60]. For either Equation 3.20 or Equation 3.21 data deflection measurements should be taken at the location of the outside wheel path [44, 60].

3.2.3 Bearing Stress

The bearing stress on the concrete at the face of the joint is critical for proper function of the dowel bar in the concrete. If the bearing stress on the concrete becomes too large the concrete will begin to crack where it contacts the dowel bar. Repetitive high stress loadings of the dowel bar-concrete interface will create a void around the bar. This void creates an additional amount of deflection in the system before the dowel bar will begin to take on the load applied. This additional deflection creates a loss in the efficiency of the dowel bar to transfer load across the joint. This loss in efficiency must now be carried by the subgrade, which puts additional stress on the subgrade and creates the possibility for differential settlement of adjacent slabs.

If the dowel behaves as a beam on an elastic foundation, the bearing stress at the face of the joint, σ_b, is proportional (although not linear) to the deflection at the face of the joint. This relationship is expressed using Equation 3.22 [48].

$$\sigma_b = K_o\, y_o \tag{3.22}$$

If the deflection, y_o, as seen in equation 3.6, is substituted into Equation 3.22, Equation 3.23 remains.

$$\sigma_b = \frac{K_o P}{4\beta^3 E I}(2 + \beta z) \tag{3.23}$$

The bearing stress on the concrete needs to be kept low to make certain that no crushing of the concrete occurs. According to the American Concrete Institute's (ACI) Committee 325 the recommended allowable bearing stress on the concrete is equivalent to Equation 3.24 [54].

$$\sigma_a = \left(\frac{4 - b}{3}\right) f'_c \tag{3.24}$$

where,

σ_a = recommended allowable bearing stress (psi)
b = d dowel bar width, or diameter in the case of a circular bar (inches)
f'_c = compressive strength of concrete (psi)

The above Equation 3.24 was developed using circular dowel bar sizes ranging from 0.75 to 2 inches. This equation provides a factor of safety of approximately three [54].

CHAPTER 4 GAPS IN KNOWLEDGE

The following is a list of topical items listed as subjects for technological gaps in knowledge of highway dowel bars. These technology gaps are summarized as to the identification of the lack of knowledge (gap) along with a brief discussion of each topic. Topics are listed in no particular order.

4.1 Effects of Moisture on Fiber-reinforced Polymer Dowels

Research concerning the use of fiber-reinforced polymer (FRP) dowel bars in place of steel dowel bars is ongoing [1,2,10,13,16,22,27,30,31,36,41,44,50,56]. By using FRP, corrosion due to moisture will be less likely. Other effects, however, of moisture on FRP dowel bars need to be studied. Possible expansion of the FRP dowel bar due to moisture absorption may cause an increase in stress in the concrete resulting in possible cracks and/or oblonging of the hole.

4.2 Aging of FRP Dowels

An investigation into aging effects of FRP dowel bars needs to be performed. A determination of how long an FRP dowel bar is good to use and if or when they will deteriorate needs to be made. If an FRP dowel bar does deteriorate then an acceptable level of deterioration needs to be determined so that the dowel bar will still be able to function properly. If deterioration is present in FRP dowel bars a comparison should also be made with the steel bars to see which dowel performs better [2,12,13,14,22,25,26,27].

4.3 Effects of Road Chemicals on FRP Resin

If FRP dowel bars are structurally reasonable to use in jointed plain concrete pavement an investigation into the resin should be done. An exploration of how different resins resist different chemicals should take place. A determination of which fibers and resin are best able to withstand the effects of road salts, oils, acids, etc…also needs to be made. An investigation into which chemicals are detrimental to the resin and fibers of the FRP dowel bar needs to take place [12,13,14,20,36].

4.4 Development of an FRP Design Procedure

If FRP is used as a viable dowel bar material, a procedure for the design of these dowels to resist forces that develop when transferring load is needed. All current theory, calculations, and design procedures for dowel bars are based on using circular steel dowel bars. If FRP is to be used as an alternative to steel in the fight against corrosion, then the theory behind FRP dowels will have to be researched and a new design procedure will have to be created [30,31,44].

4.5 Acceptable Corrosion of Steel Dowel Bars

Corrosion of steel dowels bars has been an on going battle. Steel bars have been epoxy coated in order to aid in the prevention of corroding. Many bars, however, are susceptible to corrosion even before they are placed in the concrete. Nicks during construction, manufacturing, moving, and placing all contribute to the wear of a dowel bar before it is placed. These dowel bars also see a good percentage of moisture during the concrete curing process. An investigation into how much corrosion of a steel dowel bar is acceptable needs to be determined. Exploring how much corrosion is acceptable before a steel dowel bar is considered useless, inadequate or causing joint lock up leading to its replacement would be extremely beneficial in the life and maintenance of a jointed plain concrete pavement [13,20,22].

4.6 Investigation of Wheel Load at Pavement Edge

Loads seen by dowel bars at or near the edge of a pavement will be different than those at the pavement centerline due to the smaller area over which to distribute the load. Changes in the bearing stresses and deflections of these dowel bars should be examined. Any affects on the dowel bars, slab and joints should also be noted. Investigation of the load at pavement edge should include but not be limited to the following variables: spacing, thickness of slab, and joint thickness [48,57,58].

4.7 Investigation of Uneven Dowel Bar Placement

The current practice when spacing dowel bars is to place them at an equal distance from one another at an on-center spacing. Lab and field-testing both need to be completed in order to determine if other dowel bar spacing configurations are of any benefit. Investigating the placement of three or four dowel bars in the wheel path and one in between is suggested as an example of one of the variable placements to be investigated [62].

4.8 Curvature of Slab Effects on Dowel when Load Placed in Middle of Slab

In order to determine the effects at the joint a concentrated wheel load is usually placed on either side of the slab joint. If a load, however, is placed in the center of the slab, between the joints, the joint and dowel bars will be affected differently. A consideration into how the dowel bar will react to this applied load needs to be taken into account. Slab and dowel bar stiffnesses, joint cracking, breaking and separation of the joint, and slab versus joint curvatures need to be investigated [3,45,62].

4.9 Bearing and Contact Surface Stresses for Shapes other than Circular

The bearing stress on the concrete at the face of the joint is critical for proper function of the dowel bar in the concrete. If the bearing stress on the concrete becomes too large the concrete will begin to break away where it contacts the dowel bar. Repetitive high-stress loadings of the dowel bar-concrete interface will create a void. This void creates an additional amount of deflection in the system before the dowel bar will begin to take on the applied load. This additional deflection creates a loss in the efficiency of the dowel bar to transfer load across the joint. This loss in efficiency must now be carried by the sub grade, which puts an additional stress on the sub grade and creates the possibility for differential settlement of adjacent slabs. The bearing stress is directly related to the bearing surface. To obtain the allowable bearing stress, calculations use the width of a dowel bar. This width is for circular shapes. Investigations of elliptical and other shaped dowel bar's actual and allowable bearing stresses need to be completed to find out the affects of the bearing stresses due to surface shape. The additional related stresses along the length of the bar due to bearing contact and deflection for alternative-shaped dowel bars are also needed [43].

4.10 Modulus of Dowel Support for Alternate Shapes and Sizes

The current procedure to determine how well a dowel bar will conduct shear transfer across a joint is to calculate its modulus of dowel support, K_o as discussed in Section 3. There is disagreement among researchers today on what values should be used as the modulus of dowel support, K_o. Values for round steel dowels have been reported to range from 200,000 pci to 5,000,000 pci. This large discrepancy in range could be due to the theory behind the calculations. These calculations are based the theory defined by Friberg [53]. Friberg's theory behind the derivation of K_o was developed using a semi-infinite dowel length for a circular bar only. All dowel bars in use today are of finite length, therefore making Friberg's equation in violation of its description. Furthermore, if a different dowel bar shape other than circular were to be examined, Friberg's theory would not apply. Therefore, a new analytical procedure is needed for comparing how well alternate-shaped dowel bars, such as elliptical and shaved, conduct shear transfer across a joint. Developing a procedure that correctly evaluates these alternate-shaped dowel bars is vital in the understanding of the behavior of these dowel bars. The modulus of dowel bar support, K_o, needs to be reevaluated as an acceptable means of evaluating dowel bars [2, 31, 38, 43].

4.11 Investigation of Load Transfer Efficiency of Alternate Shaped Dowels

In an ideal situation, when a load is placed near a joint, the dowel bars would assume half the load and the remaining load is transferred to subgrade. However, no joint will behave in this ideal manner due to the repeated loadings seen by a pavement joint. This repetitive loading will create a small void and some load transfer efficiency of the dowel bar will be lost. In addition, when a wheel load is applied near a joint, not all dowel bars at the joint aid in transferring the load. The dowel bars closest to the applied wheel load transfer more of the load than the dowel bars furthest away from the applied load. An investigation into the load transfer efficiency of dowel bars should be conducted. This investigation should include circular, elliptical, and other shaped dowels at different of different sizes using different spacing and pavement thicknesses [43, 62].

4.12 The Relationship Between Modulus of Foundation vs. Bearing Stress

The relationship between $K_o b$ (modulus of foundation) versus $K_o y_o$ (bearing stress), needs to be determined for different shapes. In calculating the modulus of dowel support the last step is to create a graph of the modulus of dowel support versus deflection, y_o, at the face of the joint. By imputing the geometric properties for the dowel bar and substituting multiple values of K_o into a theoretical equation the deflection at the face of the joint is determined. Using the modulus of dowel support and the deflection at the face of the joint, the concrete bearing stress can be calculated. The value of y_o is dependant on the shape of the dowel bar. The value b, width of the dowel bar, is also dependant on the shape of the dowel bar. These two values y_o and b need to be investigated for shapes other than circular [43].

4.13 Modifications of the AASHTO T253 Test Procedure

Modifications of the AASHTO T253 test procedure are needed to identify the true inflection point of the dowel bar. Many methods and qualifications for the current test procedure are outdated or inadequate for today's standards. The following are proposed modifications to the Load-Deflection Test Procedure portion of AASHTO T253:

- The specimens should be molded with a 1/8-inch gap in between sections, as in accordance with standard practice, as opposed to the test method's recommended 3/8-inch gap. Provisions are needed (as well as parameter studies) for the effects of various gap widths.
- Specimen dimensions should be changed according to pavement thickness.
- The ends of the specimen should be held down well enough in order to prevent rotation and instrumentation should be stipulated to monitor possible rotation.
- The bottom sides of the specimen need to be cast in plaster in order to be flush with the testing machine.
- An amount of allowable end rotation needs to be determined as to not void the test results.
- A new applied load rate and higher applied load need to be determined in order to construct better deflection versus load diagrams.
- A new maximum allowable deflection across the joint should be determined for design.
- The specimen should be loaded using point loads located at the ends of the interior section and not uniformly, pending inflection point investigation.

Updating this test will yield results more suitable to field application and allow different dowel bars to be compared. By modifying this test, a universal procedure may be used in order to determine and evaluate K_0 and the concrete bearing stress underneath any dowel bar [2, 43, 61, 62].

4.14 Standardized Testing Procedures and ASTM Tests for Dowel Bars

Current ASTM testing procedures are inadequate or out dated for use with today's dowel bar technology. Many of these tests specify changes in the dowel bar specimens, which in turn, changes the characteristics of the dowel bars and produces erroneous or unrealistic results. In order to develop and use fiber-reinforced dowel bars, testing needs to be developed and standardized. Some of the standard tests and their weaknesses, for example, used currently for dowel bar research:

ASTM D 3916: Standard Test Method for Tensile Properties of Pultruded Glass-Fiber-Reinforced Plastic Rod. This test is to be used on plastic rod of diameters ranging from 3.2 mm (1/8 inches) to 25.4 mm (1 inches). However, most dowel bars currently in use today are 1.5 inches in diameter [61].

ASTM D 4255/D 4255M: Standard Test Method for Testing In-plane Shear Properties of Composite Laminates. This test calls for a flat rectangular plate to be tested [60].

ASTM D 790: Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. This test calls for a bar of rectangular section to be used as a sample [61].

These tests, among others, use samples not conducive to the dowel bar shape and size. The development of standardized FRP dowel bar testing will need to take place in order to advance dowel bar technology [62].

4.15 Investigate the Effects of Oblonging for Large Number of Cycles

After a significant number of vehicles have passed over the joint an oblonging where the dowel bar contacts the concrete can occur. This oblonging creates a void space formed due to a stress concentration where the dowel contacts the concrete at the joint face directly above and below the dowel. Over time, the repeated process of traffic traveling over the joint crushes the concrete surrounding the dowel and causes a void in the concrete. This void inhibits the dowels ability to transfer load across the joint. An investigation into this oblonging for a large number of cycles using circular, elliptical and other shaped dowel bars needs to be done [48,50].

4.16 Need for a Universal Design Procedure

Full parameter studies are needed to formulate design and behavior for the interrelationships of: spacing, size, material, pavement thickness, loads, joint width, and shapes for any size or shaped dowel bar [2,3,43].

4.17 Investigate Criteria for Large Planes on Runways and Taxiways

Using dowel bars to transfer loads in runways and taxiways also needs to be researched. A determination of whether or not the same dowel bars used in highway jointed plain concrete pavement can be used in runways and taxiways needs to be made. The effect of impact loading on these dowel bars also needs to be investigated [62].

4.18 Investigate Theory Change for Dowels used as Expansion Joints

As the joint width increases, as may be the case for expansion joints in cold weather, the load transfer efficiency of the dowel bar may decrease. An investigation into the theory behind dowel bars used in expansion joints and larger joint widths needs to take place in order to determine whether or not the current dowel bar theory practiced is adequate [3,62].

4.19 Laboratory vs. Field Measurements

A distinction between whether laboratory and field measurements are true needs to be made. In order to determine the true characteristics of the dowel bars, a method for determining whether or not true measurements are being taken is needed. A relation between accelerated/repeated load tests vs. actuators in the lab needs to be determined and a way to obtain more consistent concise field measurements is also needed [32,62].

4.20 Fatigue for a Large Number of Cycles

An investigation into fatigue for a large number of cycles, (e.g. 10-60 million cycles for full-scale lab tests) correlated with field cyclic results needs to take place. This fatigue relation needs to be done with both steel and FRP with different shapes, sizes and spacing. This task will also aid in determining whether or not field and laboratory results are true measurements [2, 27, 44, 62].

4.21 Relative Deflection for Large Joint Widths

When calculating the relative deflection across a pavement joint four components are taken into account as discussed in Section 3.1.5. These components consist of the deflection of the dowel at each joint face, the deflection due to the slope of the dowel bar, the deflection due to flexure, and the deflection due to shear. If the joint width is around 1/8 of an inch or less, the deflection due to the slope of the dowel and flexural stresses may be ignored. However, if the joint width is larger than 1/8 of an inch than the deflection due to the slope of the dowel and the flexural stress should be considered in computing the relative deflection between adjacent pavement slabs. An investigation into the effects of an increase in joint width between adjacent slabs needs to take place [2].

CHAPTER 5 RECOMMENDATIONS AND CONCLUSIONS

5.1 Summary

As dowel bar technology advances, many of the past theories, equations and procedures should be questioned and challenged. Designing dowel bars in the future utilizing different sizes, shapes, spacings and materials will call for different equations and procedures. The summary of past dowel bar work listed in Chapter 2 provides an overview of where the nation is currently at in regards to dowel bar research. The gaps in knowledge must be accommodated for future design considerations.

The theoretical investigation/background in Chapter 3 gives an overview into the theory of the dowel bar design process. Many of these theories and equations are outdated when new dowel bar materials and shapes are introduced to the industry making it difficult to compare and contrast one dowel bar to another.

The more significant gaps in technology for dowel bar design and analysis are listed and described in Chapter 4. These significant gaps were concluded to be the following (in no certain order):

- Effects of moisture on FRP dowels
- Aging of FRP dowels
- Effects of road chemicals on FRP resin
- Development of FRP design procedure
- Acceptable corrosion of steel dowel bars
- Investigation of wheel load at pavement edge
- Investigation of uneven dowel bar placement

- Curvature of slab effects on dowel when load placed in middle of slab
- Bearing and contact surface stresses for shapes other than circular
- Modulus of dowel support, K_o, values for all shapes and sizes
- Investigation of Load Transfer Efficiency of different shaped dowels at different spacings
- The relationship between the modulus of foundation versus bearing stress for different dowel bar shapes
- Modifications to the AASHTO T253 test procedure
- Standardizing testing procedures and ASTM tests for dowel bars
- Investigation into the effects of oblonging of the hole for a large number of cycles
- Development of a universal design procedure
- Investigate criteria for large planes on runways and taxiways
- Investigate theory change for dowels used as expansion joints and larger joint widths
- A distinction between whether laboratory and field measurements are true needs to be made
- Fatigue for a large number of cycles correlated with field cyclic results
- Relative deflection for large joint widths

Researching these topics is vitally important in aiding the advancement of dowel bar technology.

5.2 Recommendations

The following Table 5.1 is a list of main categories under which each relative gap in knowledge is listed. The author believes these are the main categories under which each respective gap in knowledge can be easily classified. Some gaps are listed under more than one category due to their relevancy.

The categories listed in Table 5.1 may be researched in any order and many topics within each category cross over into other categories, therefore, the author recommends that universal testing procedures for both laboratory and field conditions first be determined so that a correct, consistent comparison between dowel bars can be made. While developing these procedures, the past dowel bar theory as proposed by Friberg and others needs revision to accommodate changes in shape, materials, spacings and sizes. Close attention should be paid to the accuracy of past theory, particularly the use of the modulus of dowel bar support, K_o. In order to achieve adequate comparative results, a standardized dowel bar testing procedure is vitally important.

Only after revised theories and testing procedures are obtained should dowel bar technology advance for highway pavements and other structures so as to keep the industry from spending money unnecessarily. An organizational method is needed to keep all interested parties informed and up to date on the advancement of the solutions to the technological gaps in dowel bar design changes, as new dowel bar sizes and shapes become available.

Table 5.1 Gaps in dowel bar research by major categories

Category 1 Bearing Stress

- Effect of corrosion of steel dowel bars on bearing stress
- Investigation of wheel load at pavement edge
- Investigation of uneven dowel bar placement
- Curvature of slab effects on dowel when load placed in middle of slab
- Bearing and contact surface stresses for shapes other than circular
- Investigation of Load Transfer Efficiency of different shaped dowels at different spacings
- The relationship between the modulus of foundation versus bearing stress for different dowel bar shapes
- Investigation into the effects of oblonging of the hole for a large number of cycles
- Fatigue for a large number of cycles correlated with field cyclic results

Category 2 Corrosion/Aging/Environment

- Effects of moisture on FRP dowels
- Aging of FRP dowels
- Effects of road chemicals on FRP resin
- Acceptable corrosion of steel dowel bars
- Fatigue for a large number of cycles correlated with field cyclic results

Category 3 Theory with respect to load transfer

- Investigation of wheel load at pavement edge
- Bearing and contact surface stresses for shapes other than circular
- Modulus of dowel support, K_0, values for all shapes and sizes
- Investigation into the effects of oblonging of the hole for a large number of cycles
- Investigate theory change for dowels used as expansion joints and larger joint widths

Category 4 Test Procedures

- Modulus of dowel support, K_0, values for all shapes and sizes
- Modifications to the AASHTO T253 test procedure
- Standardizing testing procedures and ASTM tests for dowel bars
- A distinction between whether laboratory and field measurements are true needs to be made
- Fatigue for a large number of cycles correlated with field cyclic results

Category 5 Design Procedure

- Development of FRP design procedure
- Development of a universal design procedure taking into account spacing and size of dowels
- Modulus of dowel support, K_0, values for all shapes and sizes

Category 6 Parameter Changes

- Modulus of dowel support, K_0, values for all shapes and sizes
- Investigation of Load Transfer Efficiency of different shaped dowels at different spacings and sizes
- Fatigue for a large number of cycles correlated with field cyclic results

Category 7 Other

- Investigate criteria for large planes on runways and taxiways

5.3 Conclusions

Much of the research done across the nation in regards to dowel bar technology has been duplicated from organization to organization. A nation wide effort needs to be made to discontinue replicate testing and advance technology. An agreement on how testing should be done and what theories and methods need to be in place in order to be effective, efficient, and consistent needs to be made. An organizational method is needed to keep all interested parties informed and up to date on the advancement of, and the solutions to, the technological gaps in dowel bar design changes as new dowel bar sizes and shapes become available.

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