Structural Dowel Bar Alternatives and Gaps of Knowledge

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ABSTRACT

Dowel bars are subject to large cycles of fatigue loading as the bars transmit loads from one portion to another of a concrete pavement, bridge, or other structural components. As the continued cycling occurs, the bearing of the contact from the bar on the concrete can cause an "oblonging" of the hole surrounding the bar for a typical circular bar. Thus, a need exists to reduce the bearing stresses between the dowel bar and the concrete.

The combination of the corrosion and bearing fatigue problems for dowel bars leads to the need to consider alternative shapes and materials for dowel bars. Research has been on-going at Iowa State University (ISU) on both the alternative shapes and the alternative materials for dowel bars. Several types of structural tests and analyses have been conducted at ISU. Recently, an extensive study was made of the gaps of knowledge that exists for design and research for all types of dowel bars and the associated parameters.

The structural laboratory work at ISU has focused on many different potential dowel bars of various shapes and materials, including elliptically-shaped fiber reinforced polymer (FRP) and steel dowels. The goal of the elliptically-shaped dowel bars was to reduce the maximum contact bearing stress between the bar and the concrete.

This paper will present some of the key results of earlier laboratory tests that have been conducted over a period of approximately 15 years, including a brief summary of the theory, as background. Key sections of the paper include knowledge gaps and needed research for FRP in concrete.

Key words: concrete pavement—corrosion—dowels—dowel bars—fiber reinforced polymer material

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INTRODUCTION

A vast majority of the nation's highways and roads are made of jointed concrete pavement. These joints 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 and forming 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 in. 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, the entire 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" (Porter et al. 1993) and #TR408 "Investigation of Glass Fiber Composite Dowel Bars For Highway Pavement Slabs" (Porter et al. 2001). These reports serve as examples of the work done by Iowa State University.

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.

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 among 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 paper is to summarize the identified gaps in the knowledge of dowel bars, which was part of an extensive investigation funded by the IDOT via report # HR-1080, "Assessment of Highway Pavement Slab Dowel Bar Research" (Porter and Guinn 2003). In the pages to follow the identified "gaps" of knowledge will be discussed. 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.

BACKGROUND

In order to determine the technology gaps in dowel bar research, a collection of previous reports, studies, and interviews were obtained so that each may be reviewed. From the review of this information, the technology gaps and duplications in dowel bar knowledge were determined. Details of this study are shown in the report by Porter and Guinn "Assessment of Highway Pavement Slab Dowel Bar Research" (2002). References (Porter et al. 1993; Porter et al. 2001) provide the results of full-scale tests and analysis. An example of the full-scale test is shown in Figure 1.

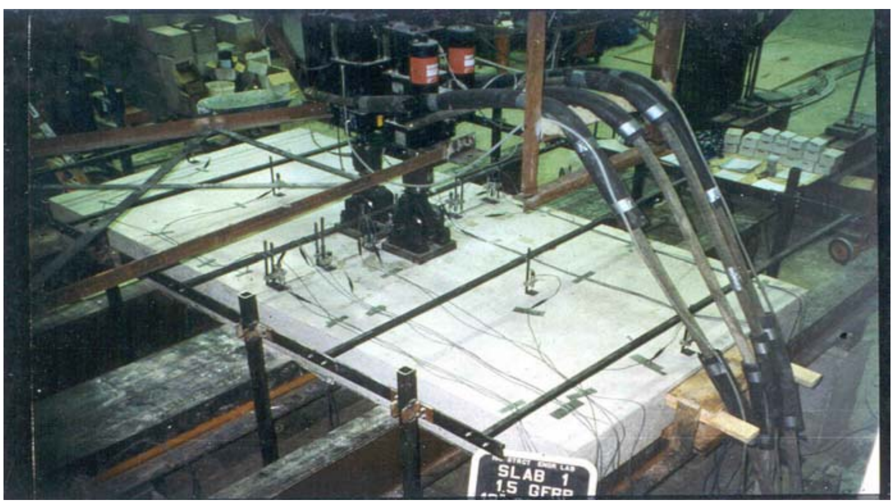

Figure 1. Full-scale test of pavement slab containing dowel bars

Some of the highlights from the IDOT Reports are as follows:

- The results indicated that the elliptical dowel bars behaved as predicted. When comparing the 1-1/2 in. 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 in. round epoxy coated steel dowel bars have a 44% increase in cross-sectional area over the smaller 1-1/4 in. 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 in. 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.
- The 1.5 in. diameter GFRP dowels spaced at 12 in. on center were inadequate in transferring load.
- The 1.5 in. diameter GFRP dowels spaced at 6 in. 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.
- The 1.75 in. FC dowels spaced at 8 in. performed at least as well as 1.5 in. steel dowels at 12 in. for 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 in. was similar to that of the 1.5 in. steel dowels spaced at 12 in. with any difference being attributed to dowel diameter.
- The load transfer efficiency of 1.75 in. FC dowels spaced at 8 in. for 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 in. for 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 in. FC dowels spaced at 12 in. for a full-scale pavement slab decreased from an initial value of approximately 44% to a final value of approximately 41% after 10 million cycles.

The structural laboratory work at ISU has focused on many different potential dowel bars of various shapes and materials. The different types of dowel bars investigated include the following:

- 1.5 in. diameter standard epoxy coated steel
- 1.5 in. diameter stainless steel
- 1.5 in. diameter FRP
- 1.875 in. diameter FRP
- 1.5 in. diameter aluminum
- 1.957 in. diameter aluminum
- 1.714 in. diameter copper
- 1.5 in. diameter copper
- 1.5 in. diameter stainless steel
- 1.5 in. diameter hollow-filled steel
- 1.75 in. diameter FRP
- aged FRP
- special-sized shaved FRP
- 1.5 in. diameter plain steel
- several sizes of elliptically-shaped steel
- several sizes of elliptically-shaped FRP

The goal of the elliptically-shaped dowel bars was to reduce the maximum contact bearing stress between the bar and the concrete. The FRP acronym is for fiber reinforced polymer material and these bars consisted of glass fibers and various types of polymers.

The types of structural laboratory tests conducted include the following:

- full-scale pavement sections subjected to fatigue loading
- Iosipescu elemental shear (static)
- AASHTO T-253 elemental shear (static and fatigue)
- pull-out
- alkalinity aging
- chemical properties

All of the above-mentioned tests were conducted in the Structural Engineering Laboratory at ISU. The elliptical shape has been used for steel and FRP dowels for laboratory testing.

ANALYSIS SUMMARY

On-going work at ISU is currently investigating the results of field applications and additional laboratory analysis. The laboratory analysis includes an investigation into the type of test element that can be used to determine property values needed in the analysis. Figure 2 shows the two test types under investigation to determine a needed parameter, k_o, for the analysis.

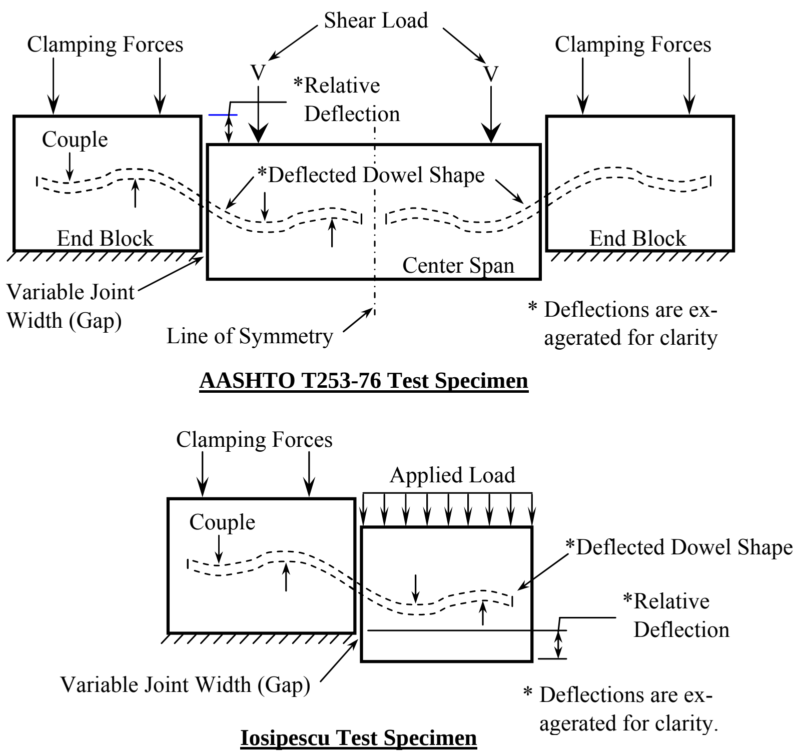

Figure 2. Testing schematics

The analysis has focused on determination of the deflection and the related bearing stress properties. The deflected shape and the key parameters are shown in Figure 3.

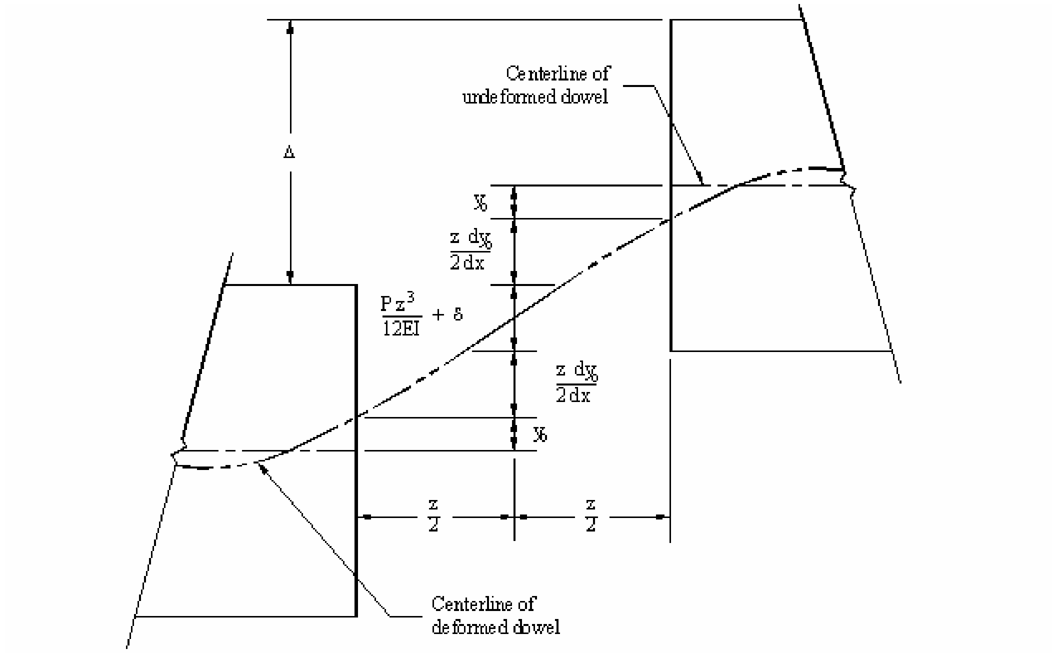

Figure 3. Deflection relationships across a joint width z

The deflection relationships shown in Figure 3 result in a predictive deflection shown by Equation 1.

$$\Delta_{relative} = 2\cdot\left(y_o\right) + 2\cdot\left(\frac{z}{2}\right)\cdot\left(\frac{dy_o}{dx}\right) + \frac{\lambda V\cdot z}{A_d\cdot G} + \frac{V\cdot z^3}{12\cdot E\cdot I_z} \tag{1}$$

y_o = dowel deflection relative to or within concrete at the face (in.)
z = gap width (in.)
V (or P in Figure 3) = shear transferred across the joint, including the center span weight in Figure 2 (lb.)
λ = form (or shear shape) factor
δ = shear deflection as shown in Figure 3 (in.)
A_d = dowel cross sectional area (in.^{2})
G = shear modulus (psi)
E = flexural modulus of elasticity (psi)
I_z = moment of inertia (in.^{4})

The AASHTO test shown in Figure 2 is being investigated to determine its ability to predict k_o. Previous work at ISU has utilized Friberg's semi-infinite beam theory (Friberg 1940), where

$$y_o = \frac{V}{4 \cdot \beta^3 \cdot EI_z} \cdot (2 + \beta \cdot z)$$

$$\beta = \sqrt[4]{\frac{k_o \cdot d}{4 \cdot EI_z}} \quad = \text{relative stiffness of the dowel bar encased in concrete (in.}^{-1}\text{)}$$

y_o = deflection at the face of the joint (in.)
k_o = modulus of dowel support or reaction (pci)
d = dowel width (in.)
V = shear load transferred through the dowel (lb.)
z = joint width (in.)

The relative deflection across the joint in the AASHTO test is given by Equation 2. This equation differs from Equation 1 by the flexural deflection (i.e., no inflection point at the center of the gap) and y_o terms. For large joint widths, these changes can be significant when solving for k_o. Slight differences in dowel slope at each face were determined theoretically for small joint widths. These differences are extremely small and were neglected in Equation 2.

$$\Delta_{relative} = (y1_o + y2_o) + 2 \cdot \left(\frac{z}{2}\right) \cdot \left(\frac{dy_o}{dx}\right) + \frac{\lambda V \cdot z}{A_d \cdot G} + \left(\frac{V \cdot z^3}{3 \cdot E \cdot I} - \frac{M_2 \cdot z^2}{2 \cdot E \cdot I}\right) \qquad (2)$$

All other terms are defined above with exception of

$y1_o$, $y2_o$ = dowel deflection relative to the concrete for the end block and center span, respectively (in.)
M_2 = moment in the dowel at the center-span face or load-side face (in.-lb.)

The bearing stress at the face of the joint is calculated using the following formula (assuming that the stress distribution across the dowel width is uniform):

$$\sigma_b = k_o \cdot y_o$$

Current ISU work is investigating these analysis equations for FRP, steel, and other materials of several shapes, including the new elliptical shape. The elliptical shape is receiving significant attention due to the better bearing stress distribution at the concrete-to-dowel-bar interface.

GAPS IN KNOWLEDGE

The "gaps" in knowledge that have been determined by the recently completed IDOT work (Porter and Guinn 2002) will be presented in this section of the paper. These gaps will utilize the information presented in the Background and Analysis Sections above. These gaps are the result of an extensive background investigation of work around the world. The compilation of the total work done versus what information is needed or questions that have been raised has led to the listing of the significant gaps of knowledge. These gaps have been grouped into seven major categories:

1. Bearing stress
2. Corrosion/aging/environment
3. Theory with respect to load transfer
4. Test procedures
5. Design procedures
6. Parameter changes
7. Other items

The earmarked items designated for each category are shown below.

Bearing stress

- 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
- Investigation of load transfer efficiency of different shaped dowels at different spacing
- 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

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

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_o, values for all shapes and sizes
- Investigation of form factors
- Investigation into the effects of oblonging of the hole for a large number of cycles
- The theory change for dowels used as expansion joints and larger joint widths

Test procedures

- Modulus of dowel support, K_o, 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

Design procedure

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

Parameter changes

- Modulus of dowel support, K_o, values for all shapes and sizes
- Investigation of load transfer efficiency of different shaped dowels at different spacings and sizes
- Investigation of form factors
- Fatigue for a large number of cycles correlated with field cyclic results

Other items

- Investigate criteria for large planes on runways and taxiways

FRP GAPS IN KNOWLEDGE

This past October a special workshop was conducted in San Francisco, CA, and sponsored by the National Science Foundation, American Concrete Institute, and ISIS of Canada. This NSF workshop concentrated on the use of FRP in conjunction with concrete structures, which includes topics affecting FRP dowel bars in concrete pavement slabs. In April 2005, a summary report was issued by Max Porter and Kent Harries, co-chairs for the workshop (Porter and Harries 2005). An Executive Summary is given below for reference, followed by items of interest to FRP dowel bar applications.

Workshop Executive Summary

> The research community has made great progress identifying and quantifying the characteristics of fiber reinforced polymer (FRP) composite materials used in infrastructure applications. A growing number of demonstration projects and commercial applications contribute to the knowledge base in this area. The use of FRP materials in infrastructure is still in its infancy, however, and a number of issues remain to be adequately addressed. In some cases, the dearth of understanding and/or design guidance represents a significant limitation to the broader implementation of FRP materials in infrastructure applications. The objective of this Workshop is to identify and prioritize research areas and issues which industry, practitioners and academia identify as requiring further attention in order to improve our understanding of the behavior of FRP materials and FRP structural and repair systems.

The objectives of the Workshop were as follows:

- Develop a consensus of the current state-of-the-art in the application FRP composites for infrastructure applications through a review of previous and pending research projects and field applications.
- Identify critical research needs affecting the implementation of FRP composites in construction applications and develop a consensus on the priority of these needs.
- Identify emerging and novel applications for FRP composites in infrastructure and identify additional research needs associated with these.
- Develop a coordinated plan for a unified research approach to addressing research needs and matching research needs with appropriate funding agencies/opportunities.
- Identify improved mechanisms by which research results may be disseminated in a manner appropriate to the implementation of FRP composites in infrastructure.
- Provide a brief assessment of research facilities and capabilities in the United States pursuant to the identified research needs.

The Workshop was held October 22-23, 2004 at the San Francisco Hilton immediately preceding the 2004 ACI Fall Convention. Forty nine participants representing academe, industry, and government from the United States, Canada, Great Britain, and Belgium were in attendance.

Seven workshop sessions were held addressing relatively broad topic headings. Topic-specific research priorities were established and refined in a final plenary session from which the final priority of research needs was established. This report documents the activities of the Workshop."

Workshop Items of Interest for FRP Dowels (and FRP with Concrete)

The following excerpt is taken from the NSF report by Porter and Harries (2005). Most of this applies in some way to FRP dowel or tie rods used in pavement slabs.

Current Research Needs

In order to address the immediate needs of the use of FRP in concrete construction, the following research topics are ***highly recommended*** for investigation. These topics address needs based on widely accepted applications of FRP in civil infrastructure.

Durability and Performance-Related Topics

Identification of Appropriate Environments for Durability Testing

There remains considerable confusion and disagreement among researchers and practitioners as to exactly what environmental parameters need to be considered when using FRP materials. Additionally, it should be clear that intended use, regional climates and maintenance practices will significantly impact which parameters affect a particular application. Such a research study must include participation from all primary climatic regions of the US (NE, NW, SE, SW, Mountains, Alaska, coastal exposure).

Development of Standardized Durability/Environmental Exposure Test Methods

Coupled to the previous topic, a consensus on accelerated environmental conditioning techniques and subsequent durability test methods is required. Methods are required for both external FRP applications and internal FRP reinforcement applications

Durability Studies of Externally Bonded FRP Repair/Retrofit Measures

Identify time dependent effects and factors affecting them (including fatigue). Clearly the durability of the adhesive bond and/or substrate-FRP interface is of primary concern.

Durability Studies of Internal FRP Reinforcement
Identify time dependent effects and factors affecting them (including fatigue). The critical issue here is the behavior of FRP *in situ*, thus studies must account for the concrete environment in which the FRP is embedded, the expected behavior (cracking) of that environment (which may differ from steel-reinforced members) and the environmental factors of importance (which also differ somewhat from those of importance for steel-reinforced members).
Service Life Prediction of Structures using FRP
Development of models to extrapolate short term test results to long term service life models. This topic also deals primarily with durability-related parameters and should involve models of degradation processes. Fatigue life of bonded FRP has been shown to of particular concern and predictive models of this behavior are required.
Fire Resistance/Protection of FRP
The behavior of FRP materials, whether imbedded in concrete or externally applied, subject to fire loading is largely unknown. Modeling techniques must be developed and verified for predicting fire performance of structures.
Seismic and Blast Resistance of FRP Systems
FRP is very often used for structural retrofit including efforts to mitigate the effects of earthquake or blast loads. Beyond pseudo-static testing, which does not capture strain rate effects, little is known of the performance of such retrofit systems under such extreme loads. Methods of assessing the appropriateness of existing and innovative FRP systems at mitigating the effects of extreme loading need to be developed.

New Materials and Systems
Innovative and Hybrid Materials
FRP materials are often not mechanically or hygrothermally suited to applications in concrete infrastructure. Research aimed at developing new and hybrid FRP materials having properties better matched to concrete is necessary. Such systems may be a simple as composite CFRP, GFRP and AFRP products or as innovative as polymer-free chemically prestressed systems.
Innovative Reinforcing Schemes
Taking proper advantage of the FRP materials should involve getting away from the paradigm of "replacing steel with FRP" and toward the development of innovative reinforcing schemes which should make both FRP reinforcement and concrete construction more cost-effective. One role that concrete plays in reinforced concrete systems is to protect the reinforcing system. If FRP systems can be made more robust and durable, this role for concrete becomes obsolete and should result in a savings.
Self-sensing FRP Structural Health Monitoring Systems
FRP materials are unique in terms of their properties and their fabrication which lends itself well to the development of integrated sensor systems. Such systems facilitate improved structural health monitoring and may be developed to allow the structure to interact with its occupants.

Overall, the items connected with durability received a high ranking in the gaps of knowledge. Interestingly enough to the author is that ISU started the durability research for FRP reinforcement approximately 17 years ago. A significant number of answers have been obtained, and today, FRP elliptical dowel bars have been used successfully in actual highway construction.

SUMMARY

The use of other sizes, shapes, and materials of dowel bars has been on-going at ISU. While success has been accomplished, additional information is needed. Many sizes of dowels have been included. The use of FRP dowels has merit in areas where possible corrosion exists. Elliptically-shaped FRP and steel dowel bars appear to provide benefit in the bearing contact with the concrete. Several key gaps in knowledge, as well as areas of FRP research, have been identified.

ACKNOWLEDGMENTS

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REFERENCES

Friberg, B.F. 1940. Design of Dowels in Transverse Joints of Concrete Pavements. *Transactions, American Society of Civil Engineers*. Vol. 105, No. 2081.

Porter, M.L., B. Barnes, B. Hughes, and K. Viswanath. 1993. *Non-Corrosive Tie Reinforcing and Dowel Bars for Highway Pavement Slabs, Final Report*. HR-343 Submitted to Highway Division of the Iowa Department of Transportation and Iowa Highway Research Board. Iowa State University, Engineering Research Institute, Ames, IA.

Porter, M.L., D. Davis, R. Guinn, Jr., A. Lundy, and J. Rohner. 2001. *Investigation of Glass Fiber Composite Dowel Bars for Highway Pavement Slabs, Final Report*. TR-408 Submitted to Highway Division of the Iowa Department of Transportation and Iowa Highway Research Board. Iowa State University, Engineering Research Institute, Ames, IA.

Porter, Max, and Kent Harries. 2005. “Workshop on Research in FRP Composites in Concrete Construction Final Report” submitted to National Science Foundation, Arlington VA 22230.

Porter, M. L., and Guinn, Robert. 2002. “Assessment of Highway Pavement Slab Dowel Bar Research”. Final Report No. HR-1080. Submitted to Iowa Highway Research Board, Center for Transportation Research and Education, Iowa State University.