USING FIBER-REINFORCED POLYMER LOAD TRANSFER DEVICES IN JOINTED CONCRETE PAVEMENTS

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ABSTRACT

Jointed concrete pavements require dowels to transfer the loads across transverse joints and to prevent faulting. The most commonly used dowels are made of epoxy-coated steel with a diameter ranging from 25 to 38 mm. Problems associated with dowels include corrosion of the dowel material and possible crushing of concrete surrounding the dowel causing looseness of the joint and faulting. The objective of this research is to evaluate corrosion-free alternatives to steel reinforcing elements. The use of Glass Fiber-Reinforced Polymers, GFRP, as load transfer devices is investigated and some material characteristics and design guidelines for GFRP dowels are introduced.

In the experimental program, two types of dowel construction are tested. The first type is a round GFRP dowel bar having a 38-mm diameter and the second is a concrete-filled GFRP pipe having a 60-mm outside diameter. Laboratory testing and a field implementation project were carried out. The field test section was constructed on a regional highway in the city of Winnipeg and involved three types of GFRP dowels in addition to epoxy-coated steel. Falling Weight Deflectometer (FWD) testing was conducted after one year of service and showed that GFRP dowels produced 30% higher deflections compared to steel, however the load transfer efficiencies for GFRP dowels remained excellent.

The use of GFRP dowels opens tremendous opportunities for optimizing dowel design and pavement performance. The increased diameter and reduced stiffness of the GFRP dowels results in lower bearing stresses between the concrete and dowel, which are major causes of dowel looseness and slab faulting.

INTRODUCTION

There are proven benefits to using dowels as load transfer devices in jointed concrete pavements. Recent research has shown that pavement joints supported with dowels have a longer service life than joints without dowels[1]. Dowels are predominantly made of epoxy-coated smooth steel bars with a diameter of 25 mm to 38 mm and in some instances, such as thick airfield pavements, pipe dowels were used with an outside diameter of 32 mm to 50 mm. Corrosion of these steel dowels can lead to joint deterioration, however, pavement joints often fail due to excessive bearing stresses between the dowel and surrounding concrete, namely looseness of dowel support which can diminish the load transfer across the joint and accelerate pavement damage. In recent years, fiber-reinforced polymers (FRP) emerged as a new material that is not prone to corrosion and that exhibits excellent strength and durability characteristics. Testing of FRP dowels in concrete pavements has been reported in the literature[3,4,10]. This paper reports on ongoing research at the University of Manitoba to investigate improving dowel design using FRP.

FRP composites consist of high-strength fibers embedded in a polymer resin matrix. The fibers resist uniaxial tensile stresses along their strands while the matrix provides bonding and structure to the composite. Glass fibers are the most economical class of FRP and can be easily produced in small manufacturing facilities. Two categories of FRP materials are used in this investigation. The first is Glass-FRP (GFRP) bars produced by a pultrusion process. These bars were tested in the laboratory and in a field trial section. The second is a GFRP pipe filled with concrete. The pipe walls consist of layers of fibers and resin. Tubular dowels are produced by either a pultrusion or a filament winding process. In total, seven types of dowels were tested; three types of GFRP bars and four types of tubular GFRP dowels in addition to control dowels made of epoxy-coated steel. A photograph in Figure 1 shows a sample of each type of dowel and their substantial variation in size.

Use of FRP allows for greater flexibility in the design and make-up of the dowels including ability to control the fiber volume fraction, type of polymer resin material, fiber orientation and surface smoothness. All dowels used in this investigation are available commercially and were not specifically designed for this application. It is anticipated that the knowledge gained in this investigation will culminate in product specifications and design guidelines for FRP dowels.

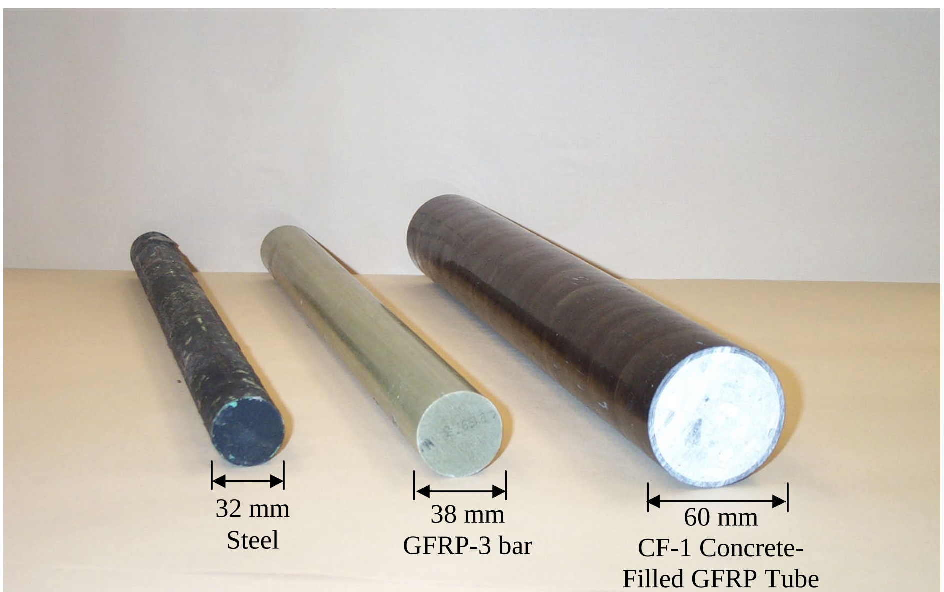


Figure 1: Samples of steel and GFRP dowels

MATERIALS

GFRP Dowel Bars

Three types of GFRP bars were tested in addition to epoxy-coated steel dowels as control specimens. The diameters of the steel and GFRP dowels bars were 31.75 mm (1.25”) and 38.1 mm (1.5”) respectively. The 32-mm diameter steel dowels were selected, as they are the standard size used by the city of Winnipeg. The dowels had a typical length of 457 mm (18”).

The GFRP dowels were manufactured by a pultrusion process, in which all the fibers are oriented in the longitudinal direction only. Properties of all dowel types are provided in Table 1.

Concrete-Filled Composite Tube Dowels

Four types of GFRP tubes were tested in this investigation. The tubular sections were not specifically designed for shear applications and they differed in fiber orientation, number of layers (plies), fiber volume fraction, and wall thickness. The four types of GFRP tubes had a fiber volume fraction of 70% (fiber to resin composition of approximately 70 to 30 percent). The outside diameter and length of each composite dowel was approximately 60 mm (2.4"), and 457 mm (18"), respectively. The tubes were manufactured using a filament winding process in which the fibers are wrapped around the pipe mould, or using a pultrusion process in which all fibers are aligned parallel to the axis of the pipe. Filament winding requires the selection of a primary and a secondary wind angle for each fiber layer defined as the inclination of the fibers to the axis of the dowel bar and expressed as a tilt ratio (2:1 or 1:1) or in degrees. A diagram of the fiber orientations is shown in Figure 2.

Table 1: Dowel Properties

Dowel Type and Manufacturing Process	Primary/Secondary Fiber Wind Angle	Outside Diameter mm (in)	Inside Diameter mm (in)	Number of Fiber Layers	28-day Concrete Strength MPa (ksi)
Steel: epoxy coated	N/A	31.8 (1.25)	N/A	N/A	N/A
GFRP-1: pultruded bar	Longitudinal	38.1 (1.5)	N/A	N/A	N/A
GFRP-2: pultruded bar	Longitudinal	38.1 (1.5)	N/A	N/A	N/A
GFRP-3: pultruded bar	Longitudinal	38.1 (1.5)	N/A	N/A	N/A
CF-1: filament wound tubular section	2:1 / 1:2	62 (2.44)	56 (2.20)	7	40 (5.73)
CF-2: pultruded tubular section	Longitudinal	60 (2.36)	54 (2.13)	5	40 (5.73)
CF-3: filament wound tubular section	2:1 / 1:2	60 (2.36)	57 (2.24)	6	40 (5.73)
CF-4: filament wound tubular section	1:1 / 1:1	60 (2.36)	57 (2.24)	6	40 (5.73)

The tubes were cut into 2000-mm sections and filled with concrete having a 28-day compressive strength of 40 MPa (5800 psi), and a maximum aggregate size of 10 mm (3/8 in.). A 40 MPa concrete mix design was selected because a high slump was required. This high slump made higher concrete strengths more difficult to achieve. Several admixtures were used to enhance the concrete. An anti-shrink compound was added to prevent the separation of FRP and concrete after curing and to improve composite action and tensile strength. The concrete was cured under restrained expansion (RE) conditions by capping the tube ends. Maximum restrained expansion due to the anti-shrink compound was expected within 24 hours of mixing. Superplasticizers and water reducers were added to achieve a high slump (250 mm or more), which allowed the concrete to flow into the tube during casting and the tubes were vibrated to eliminate honeycombing. To increase durability and tensile strength, an air entrainment agent was added to the concrete. Air entrainment is known to improve concrete performance in cold climates.

Fourteen days after casting, each tube was saw-cut into four dowels of length 450 mm (18”) each using a masonry saw.

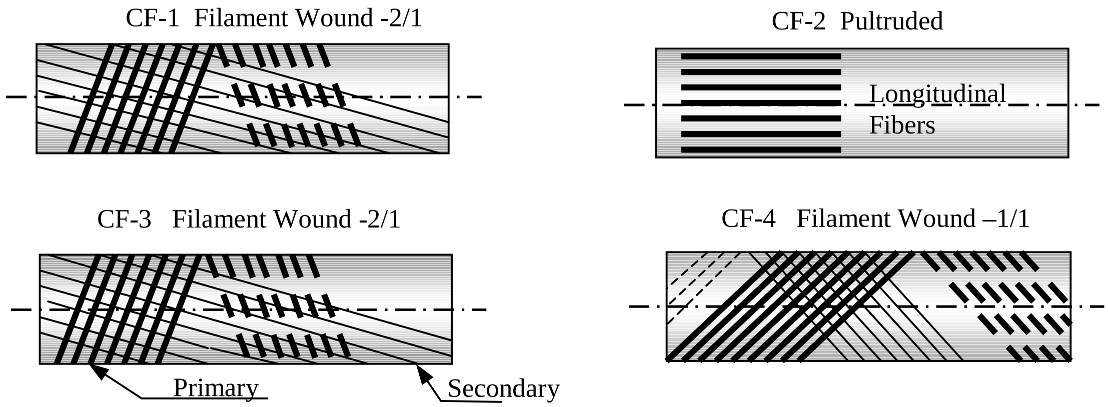


Figure 2: Fiber orientations of concrete-filled GFRP dowels

EXPERIMENTAL PROGRAM

Field Trial of GFRP Bars

The field application involved the use of GFRP-1, GFRP-2 and GFRP-3 dowels in the construction of a new 4-lane divided highway on Bishop Grandin Boulevard in Winnipeg, Manitoba. This highway section services approximately 27,000 veh/day with 10% truck traffic. Each type of dowel was used on a two-lane section of the road having 10 transverse joints. A total of 780 – 38.1 mm dowels were used for the 30 tested joints constructed with GFRP dowels. The pavement structure comprised a 230 mm (9”) thick slab with 16° skewed joints staggered at intervals of 4 to 6 meters. Underlying the concrete was a base layer of crushed limestone and a clay subgrade. During casting of the concrete, the GFRP dowels were supported in place by a standard steel basket assembly, which allowed for the dowel to be slid in from the end in the direction of paving, and be restrained on the other end by a pin. The joints at the dowel locations were saw-cut within a few hours after casting and allowed to crack under thermal contraction and shrinkage.

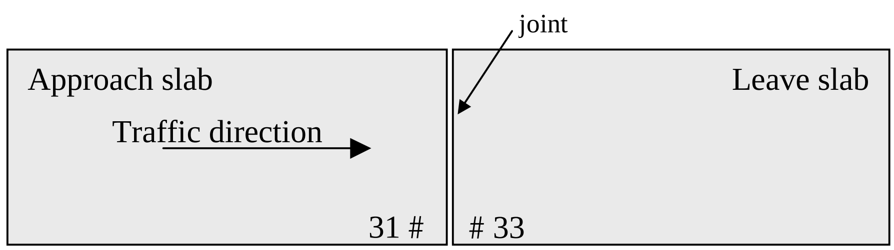
FWD testing was conducted on the trial section in May 1999, approximately eight months after the road was opened to traffic. The testing program included two repetitions from each of the two smaller drop heights (DH1 and DH2) and only one drop from the largest height (DH3). The tests were performed in the outer wheel path of the driving lane as close as possible to the joint, on both the approach and leave slabs using configurations identified by positions 31 and 33. The position on the corner of the approach slab in the outer wheel path at the joint is referred to as 31, while the position on the corner of the leave slab in the outer wheel path is referred to as 33. These configurations are illustrated in Figure 3(a). One-half of all tests were performed at the 31 position and the remaining tests were performed at the 33 position. Data pertaining to two GFRP-2 joints was lost due to a disk error during the data collection. In total, 380 FWD drops were successfully completed and reported.

The distributions of applied contact pressures from the three drop heights DH1, DH2, and DH3 are shown in Table 2. The radius of the loading plate is 150mm, and as such the peak applied dynamic load averaged 29.4 kN (6.4 kip) at DH1, 40.4 kN (8.9 kip) at DH2, and 58.6 kN (12.9 kip) at DH3. The peak applied dynamic loads were consistent and repeatable with a coefficient of variation of 0.49 to 1.77 percent. In this analysis, the coefficient of variation (COV) is the ratio of the standard deviation to the mean expressed as a percentage.

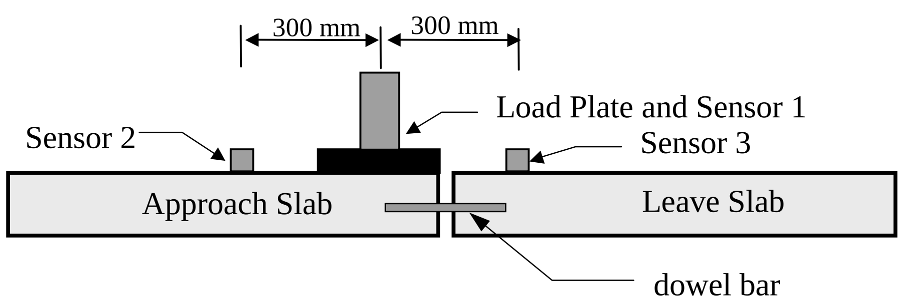
The load transfer efficiencies were computed for tested joints using the peak vertical deflections of sensors 1, 2, and 3 termed as u_1, u_2, u_3 respectively such that

$\%LTE = \frac{u_3}{u_1} \times 100$ for load applied on the approach slab (position 31, Figure 3b) and

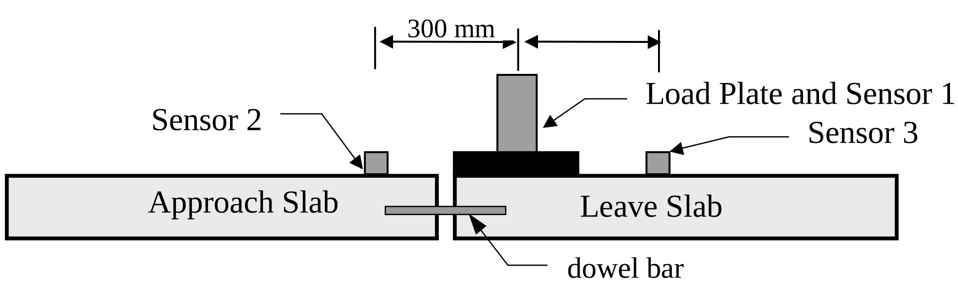
$\%LTE = \frac{u_2}{u_1} \times 100$ for load applied on the leave slab (position 33, Figure 3c)



a) Plan showing positions 31 and 33 on pavement surface



b) Position 31 load applied on approach slab

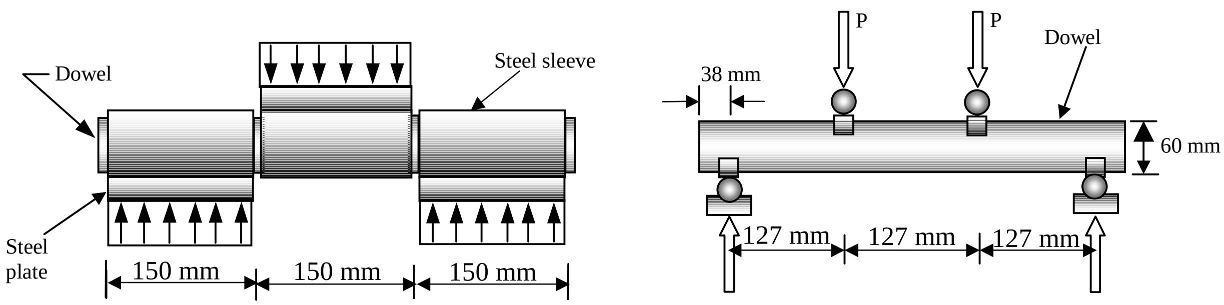


c) Position 33 load applied on leave slab

Figure 3: In-situ testing of load transfer using the FWD device

Concrete-Filled Composite Dowel Testing

The concrete-filled GFRP dowels were tested in double shear and four-point bending only. These tests were selected to determine the shear strength and flexural stiffness of the dowels. The tests would also allow the authors to investigate differences in performance due to variations in FRP configuration. The double shear test incorporated an apparatus consisting of three identical steel sleeve sections, 152 mm (6 in.) in length and 65 mm (2.5 in) in diameter, with welded-on steel loading plates. The middle steel section was simply forced down between the two adjacent sections by a hydraulic loading machine. A diagram of the double shear test set-up is given in Figure 4(a). The four-point bending test allowed for the determination of the flexural strength and stiffness of each dowel type. The apparatus comprised four free-rotating point loads placed at 127 mm (5 in.) spacing along the length of the dowel. The two support loads were positioned 38 mm (1.5 in.) from the ends of the dowel to avoid stress concentrations due to edge loading such as concrete spalling. The four-point bending set-up is shown in Figure 4(b).



a) Double shear test

b) Four point bending test

Figure 4: Double shear and four point bending test apparatus

Table 2: Sequence for testing load transfer (Total number of datasets = 380)

Type of Dowels	Drop Height	Tests Performed Per Joint	Joints with Complete Datasets	Peak Contact Pressure (kPa)	Std Dev. of Peak Contact Pressure (kPa)	Coefficient of Variation (Percent)
Epoxy Coated Steel	DH1	4	10	414.02	6.25	1.51
	DH2	4	10	577.42	10.20	1.77
	DH3	2	10	834.80	10.14	1.21
GFRP-1	DH1	4	10	410.25	5.85	1.43
	DH2	4	10	571.17	6.79	1.19
	DH3	2	10	828.45	10.27	1.24
GFRP-2	DH1	4	10	412.35	5.23	1.27
	DH2	4	10	570.67	4.35	0.76
	DH3	2	10	830.40	7.80	0.94
GFRP-3	DH1	4	8	410.78	3.41	0.83
	DH2	4	8	567.25	6.19	1.09
	DH3	2	8	824.25	4.04	0.49

TEST RESULTS

Field Test

Load transfer efficiencies (LTE) for approach and leave slabs are shown in Figure 5(a) and 5(b) respectively. Although all joints performed adequately, it is evident that the LTEs of GFRP-3 dowels are generally lower than the remaining types. The load transfer of GFRP-1 and GFRP-2 matched or slightly exceeded the LTE of steel dowels. Joint stiffness indicates the ratio of applied load to peak deflection measured under the loading plate. The deflections measured under the loading plate indicate that the steel dowels provide higher joint stiffness and, therefore, significantly lower deflections are experienced in comparison to all the GFRP dowels as shown in Figure 6(a) and 6(b). The values obtained for each group of joints were averaged so that the variability in base support can be minimized. The peak deflections under the center of the loading plate of the three types of GFRP joints are higher than those of steel-doweled joints by 10 to 30 percent as given in Table 3. However, it should be mentioned that there is no common standard for limiting the deflections other than those determined by load transfer efficiency ratios.

Table 3: Ratio of FRP to steel peak deflections under the loading plate on approach slabs

Drop Height	Deflection ratio by type of dowel					
	Loading on approach slab #31			Loading on leave slab #33		
	GFRP-1/ Steel	GFRP-2/ Steel	GFRP-3/ Steel	GFRP-1/ Steel	GFRP-2/ Steel	GFRP-3/ Steel
DH 1	1.285	1.077	1.232	1.351	1.105	1.287
DH 2	1.277	1.100	1.230	1.332	1.116	1.273
DH 3	1.279	1.099	1.232	1.319	1.114	1.275

Concrete-Filled GFRP Dowels

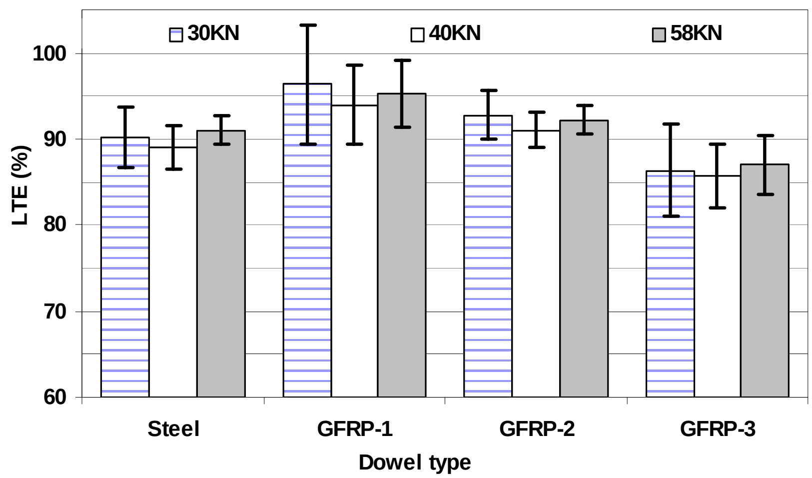
Performance differed significantly between the four dowel types. Strength and stiffness were found to improve greatly with increased glass fiber volume as was expected. As shown by the load-deflection graph in Figure 7, the filament wound (FW) dowels performed better in shear than the pultruded dowel. The CF-1 had the highest shear strength of all as it had the greatest total FRP volume. Longitudinal fibers as found in the pultruded dowel (CF-2) were found to contribute the least in shear. However, the pultruded dowel showed to have the highest flexural stiffness as seen in the load-deflection graph for four-point bending (Figure 8). This was achieved by the high tensile strength of the longitudinal fibers. The CF-2 dowel did not perform best in bending, however, due to the fact that it did not contain filament wound fibers that provide circumferential strength. This lack of ‘hoop’ strength caused the CF-2 dowel to fail as the fibers split apart longitudinally along the sides. The CF-1 dowel performed well in bending due to the combination of 2:1 hoop fibers and 1:2 fibers that are oriented relatively in the longitudinal direction. The strength properties of each composite dowel type obtained from the double shear and four-point bending tests are given in Table 4.

The bond between the concrete core and the outer FRP tube was monitored during the bending tests. It was observed that no breakage of the bond occurred in any of the four dowel types until ultimate failure was reached. This was an expected result of using an anti-shrink concrete mix.

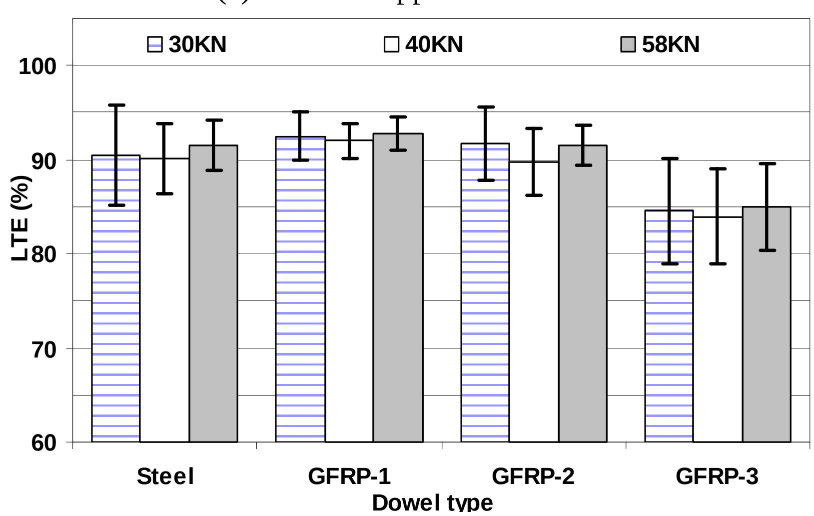
Table 4: Results of double shear and 4-point bending tests on dowels

Dowel Type	Dowel Diam. mm	No. of samples	Ultimate Shear Load (kN)		Shear Strength (MPa)		4-Pt bending Load (kN)		Max Moment Mr (N.m)	Elastic Modulus (MPa)
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.		
Steel	31.75	3	450.5	7.0	570.0	8.8	N/A	N/A	-	200,000
GFRP-1	38.10	3	122.0	4.3	107.0	3.8	N/A	N/A	-	41,300*
GFRP-2	38.10	3	171.5	3.7	150.0	3.2	N/A	N/A	-	
GFRP-3	38.10	3	115.5	3.5	101.3	3.1	N/A	N/A	-	
CF-1	62.00	4	85.1	1.1	28.2	0.4	27.4	2.2	3840	30,000
CF-2	60.00	4	53.0	3.5	18.7	1.2	11.3	1.0	1435	31,500
CF-3	60.00	4	55.1	4.0	19.5	1.4	11.9	0.6	1511	25,300
CF-4	60.00	4	66.6	5.4	23.6	1.9	9.4	0.3	1194	20,000

* Estimated from mechanical properties

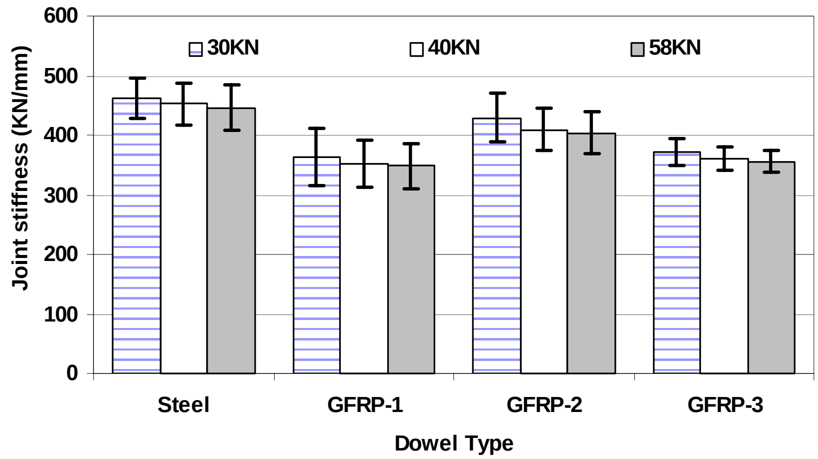


(a) tested on approach slabs

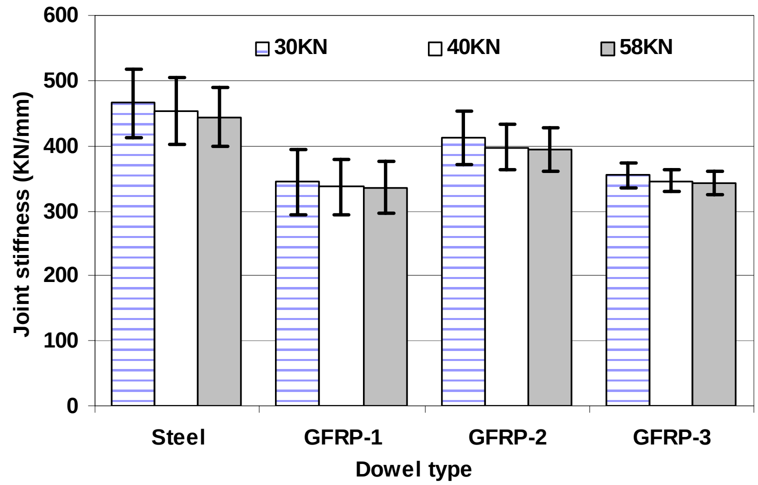


(b) tested on leave slabs

Figure 5: load transfer efficiency on test section by load level



(a) tested on approach slabs



(b) tested on leave slabs

Figure 6: Joint stiffness measured on test section by load level

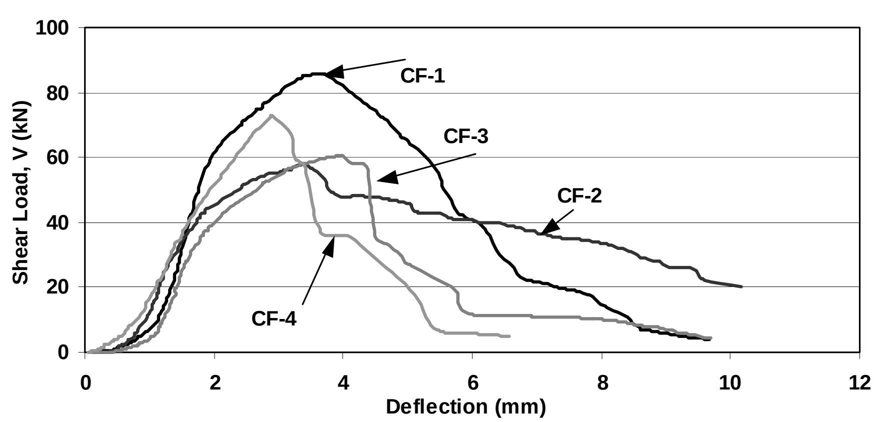


Figure 7: Load deflection graph for double shear loading

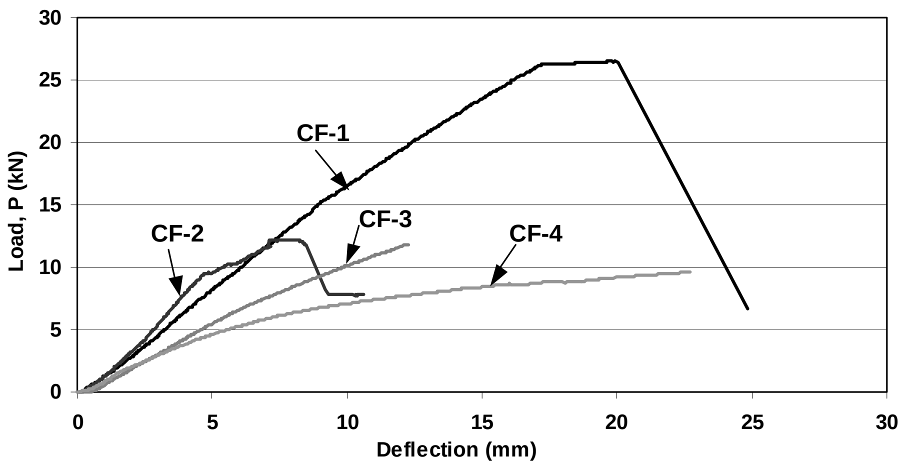


Figure 8: Load-deflection graph for 4-point bending

DISCUSSION

Field Testing of GFRP Bars

The laboratory and field testing presented in this paper demonstrated that 38-mm GFRP dowels can match the performance of 32-mm epoxy-coated steel dowels. Although the GFRP dowels have lower shear strength, the increase in dowel diameter from 32 mm to 38 mm results in lower bearing stresses between the dowel and concrete and hence an equivalent performance to the steel dowels. It is understood that 1.5" steel dowels are more commonly used today. This larger diameter would give more comparable bearing stresses at the joint face, however, due to the much higher flexural stiffness or the steel, the bearing stresses caused by bending of the dowel would still be greater than that of the GFRP dowels. Because the tests were performed after only eight months of service traffic and the load transfer ratios do not show appreciable difference at this time, it will be necessary to collect data over a longer term. A period of two to five years of service will be required to establish the environmental and traffic effects on the performance of GFRP dowels.

Design of Concrete-Filled Tubular Dowels

Tests conducted in this investigation allowed for the determination of the optimal structural recommendations of a composite dowel design. These include:

- Filament-wound fiberglass layers alternating in equal and opposite direction to provide shear and circumferential strength.
- Longitudinal glass fibers to provide flexural strength and stiffness.
- Even number of layers that alternate in direction to provide symmetric load resistance capabilities.
- Smooth outer surface provided by a synthetic veil with high resin content to reduce frictional resistance of dowel to slab movement (lower pull-out force).
- Large diameter dowel (greater than 2") to significantly reduce concrete pavement slab bearing stresses.

GFRP dowels have a much lower flexural stiffness than steel dowels. This can be beneficial for several reasons.

1. Bending moments in the dowel create bearing stresses in the surrounding slab. By reducing the flexural stiffness of the dowel, these bearing stresses will in turn be reduced over the embedded length of the dowel bar.
2. With reduced bearing stresses, the dowel embedment length can be reduced substantially. This will reduce the costs of materials.
3. Dowels with reduced flexural stiffness will reduce slab stresses due to misalignment.

Pavement Joint Design

Pavement joint design formulas most commonly used in practice today were first developed by Friberg[6] and were based on elastic theory by Timoshenko and Lessels[11]. These formulas, as listed below, incorporate properties of the pavement slab, the subgrade, the dowels, and the configuration of the pavement joint including dowel spacing and width of joint separation.

The design formulas are used to calculate the bearing stresses in the concrete slab along the dowel interface. These values are then compared with known or calculated allowable bearing stresses to determine if the design is acceptable. For the purpose of this investigation, the design formulas were used to calculate and compare bearing stresses for steel, GFRP bars, and concrete-filled GFRP tubular dowels.

In addition to bearing stresses, Friberg developed an expression for determining the maximum bending moment experienced by an embedded dowel under vehicle axle loads. These moments as well as calculated maximum shear loads transferred across the pavement joint by the dowels are compared. A relationship between the elastic properties of the dowel and the surrounding concrete[11] expressed as β, the relative stiffness between the dowel and concrete, is shown below.

$$\beta = \sqrt[4]{\frac{K d_b}{4 E_d I_d}} \qquad \text{Equation 1}$$

where, K = modulus of dowel support
d_b, E_d, I_d = diameter, elastic modulus and moment of inertia of dowel

The dowel deflection, y, within an elastic mass and under an external load is

$$y = \frac{e^{-\beta x}}{2\beta^3 E_d I_d}\left\{P_t \cos\beta x - \beta M_o\left(\cos\beta x - \sin\beta x\right)\right\} \qquad \text{Equation 2}$$

where, x = distance along the dowel measured from the joint face
P_t = load transferred by dowel
M_o = bending moment at the face of the surrounding mass

The maximum deflection occurs at the joint face and is given by y_o. Figure 9 shows the deflected shape of the dowel bar calculated by Equation 2.

$$y_o = \frac{P_t\left(2 + \beta z\right)}{4\beta^3 E_d I_d} \qquad \text{Equation 3}$$

where z = the width of the joint opening

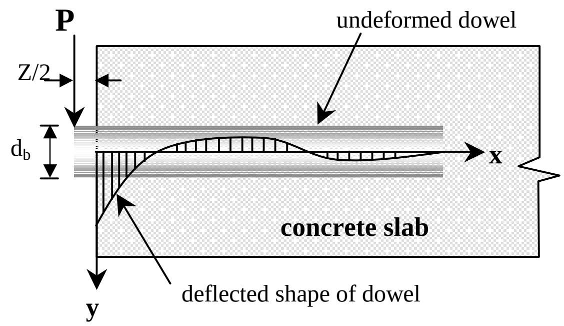


Figure 9: Deflected shape of dowel bar

The maximum bearing stress experienced at the dowel/concrete interface occurs at the joint face and is calculated by the following formula:

$$\sigma_b = K y_o \qquad \text{Equation 4}$$

The maximum load transferred by a dowel, P_t, across the pavement joint is determined by a concept known as 'dowel group action'[7]. Dowels that cross the joint with specified spacing act as a system to share the loads applied to the pavement. It is estimated that the load sharing contribution of each dowel decreases linearly with distance away from the dowel directly under or closest to the location of the wheel load[6,7,8]. The number of adjacent dowels that experience load is determined by the relative radius of stiffness of the slab-subgrade system defined by Westergaard[12] as:

$$\ell = \sqrt[4]{\frac{E_c h^3}{12\left(1-\nu^2\right)k}} \qquad \text{Equation 5}$$

where, h = thickness of concrete slab
E_c = modulus of elasticity of concrete slab
ν = Poisson's ratio of concrete
k = modulus of subgrade

The maximum bending moment experienced by the embedded dowel under load was expressed as[4]

$$M_{\max} = \frac{-P_t e^{-\beta x_m}}{2\beta}\sqrt{1+(1+\beta z)^2} \qquad \text{Equation 6}$$

Where x_m is the distance from the face of the joint to the location of M_{max} and is determined by the following equation:

$$\mathrm{Tan}(\beta x_m) = \frac{1}{1+\beta z} \qquad \text{Equation 7}$$

There are three criteria examined in this investigation regarding the design of a concrete-filled GFRP composite dowel and its suitability for load transfer in concrete pavements. These criteria are (1) bearing stresses produced at the dowel-concrete interface due to vehicle axle loads, (2) shear loads transferred by the dowel across the pavement joint, and (3) bending moments induced by both axle loads and curling due to thermal gradients in the concrete pavement slab. Bearing stresses, shear loads, and bending moments due to axle loads are calculated using theoretical design formulas. As for slab curling caused by thermal gradients, recent work has shown that bending moments in the dowel can reach as high as 500 N-m[9].

Table 5 shows the bearing stresses produced by each type of dowel due to axle loads as well as maximum shear loads and bending moments, P_t and M_{max} respectively. The purpose of Table 5 is to show that when comparing steel to GFRP bars and concrete-filled tubular GFRP dowels, it is clear that regardless of pavement slab thickness, subgrade modulus, dowel modulus, and width of joint separation, the concrete-filled dowels produce bearing stresses that are 50% of the magnitude calculated for the steel and GFRP bar dowels. The reduction in bearing stress at the dowel-slab interface can significantly increase the life of a concrete pavement.

Table 5: Comparison of Bearing Stresses at Concrete Slab-Dowel Interface

Dowel Type	Slab Thickness mm (in)	Dowel-Slab Interface Bearing Stresses (MPa)							
		Weak Subgrade, k				Stiff Subgrade, k			
		Low dowel support		High dowel support		Low dowel support		High dowel support	
		Joint opening				Joint opening			
		5 mm	10 mm	5 mm	10mm	5 mm	10 mm	5 mm	10 mm
		Pt = 8.2 kN M_{max} = -199 N-m				Pt = 10.0 kN M_{max} = -243 N-m			
Steel	203 (8")	8.54	8.86	13.01	13.74	10.42	10.82	15.88	16.77
GFRP-2		9.31	9.76	14.26	15.27	11.36	11.92	17.40	18.65
CF-I		4.25	4.41	6.47	6.82	5.19	5.38	7.90	8.33
CF-4		5.00	5.21	7.64	8.11	6.11	6.37	9.33	9.90
		Pt = 7.2 kN M_{max} = -173 N-m				Pt = 8.7 kN M_{max} = -210 N-m			
Steel	254 (10")	7.44	7.72	11.33	11.97	9.02	9.37	13.75	14.52
GFRP-2		8.11	8.50	12.42	13.30	9.84	10.32	15.06	16.14
CF-I		3.70	3.84	5.64	5.94	4.49	4.66	6.84	7.21
CF-4		4.36	4.54	6.65	7.06	5.29	5.51	8.07	8.57
		Pt = 6.4 kN M_{max} = -155 N-m				Pt = 7.9 kN M_{max} = -191 N-m			
Steel	305 (12")	6.67	6.92	10.16	10.73	8.19	8.51	12.49	13.19
GFRP-2		7.27	7.63	11.13	11.93	8.93	9.37	13.68	14.66
CF-I		3.32	3.44	5.05	5.33	4.08	4.23	6.21	6.55
CF-4		3.91	4.07	5.97	6.33	4.80	5.00	7.33	7.78

Note: properties of slab-subgrade system used for calculations

Modulus of subgrade reaction, k		Joint gap, z	
Weak (low k)	10 MN/m^3	Small gap	5 mm
Stiff (high k)	27 MN/m^3	Large gap	10 mm
Low modulus of dowel support		Maximum wheel load, Q	40 kN
Low K	80 GN/m^3	Dowel spacing	300 mm
High K	400 GN/m^3		
Slab concrete strength, f'_c	30 MPa	Elastic Moduli of dowels, E_d are given in Table 4	

From Table 4, it is evident that concrete-filled GFRP dowels have much lower strength than that of steel in both shear and bending. However, when comparing shear load and bending moment values to the theoretically determined shear loads, P_t, and bending moments, M_{max}, shown in Table 5, it is clear that the concrete-filled GFRP dowels have adequate capability of withstanding loads produced by traffic as well as thermal gradients in the pavement slab. The CF-1 composite dowel showed a shear load capacity of 85 kN and a moment resistance of 3840 N-m. Comparing these numbers to a theoretical shear load, P_t, of 10.0 kN and a bending moment, M_{max} of 243 N-m plus 500 N-m due to a high thermal gradient, it can be seen that the dowel load capacity is almost 5 times greater.

Cost of FRP and composite dowels

At the present time, the cost of solid 38mm dowel bars and of composite pipe dowels is about 20 to 30% higher than that of epoxy coated steel compared to other non-corrosive alternatives such as stainless steel which range from 100% to 400% the cost of epoxy coated steel. Excluded in this comparison is the savings in shipping costs due to the lightweight of FRP. Glass FRP has the lowest cost of all fiber-reinforced polymer products and with the increase in production and market demand the industry will reach more economically viable and competitive pricing levels.

CONCLUSIONS

The presented research investigates the use of alternative dowel materials and construction to produce longer lasting joints in rigid pavements. The laboratory research and field testing provided the following conclusions.

GFRP dowels subjected to FWD tests in the field showed that LTEs of GFRP dowels are comparable to those produced by steel dowels, providing that the diameter of the GFRP dowel is 20-30% larger than the steel dowel. The larger diameter results in a reduction in bearing stresses which in turn reduces the potential for faulting. GFRP-2 which has the highest shear strength of the three tested GFRP bar types, produced a joint stiffness and LTE that are the closest to the control steel bars. These findings are based on results obtained after only eight months of service. Therefore, it will be imperative that further testing of the joint load transfer be conducted after several more years to determine the longer-term performance of the GFRP dowels.

The materials used to manufacture the concrete-filled GFRP dowels were products that are already in commercial use, and were not designed specifically for this investigation. These materials can be designed to provide required strength for both shear and bending loads and provide an optimal dowel design. Changes in properties such as fiber orientation, number of layers, and thickness of the FRP tube can greatly affect the strength and performance of the dowel. The combined properties that will produce an optimum composite dowel have been outlined. Through the use of widely accepted theoretical pavement design formulas, it was found that the large diameter composite dowels cut bearing stresses nearly in half. The dowels tested in this investigation showed to have sufficient shear and bending strength to resist loads applied in the field. Calculated shear loads and bending moments due to estimated traffic axle loads were significantly less than values obtained through laboratory testing of the dowels.

Although the research does not endorse any of the tested systems for direct use in pavements, there is an opportunity to design and implement optimal dowel designs using FRP bars and tubular sections.

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