

# **LABORATORY EVALUATION OF CONCRETE-FILLED GFRP DOWELS IN JOINTED CONCRETE PAVEMENTS**

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## **Abstract**

For decades, smooth, round, steel dowels have been used to transfer traffic wheel loads across the joints of concrete pavements. These dowels are subjected to shear and bending stresses due to thermal gradients in the pavement slabs in addition to the traffic loads. Over time, the concrete pavement joints become damaged due to the corrosion of the steel dowels as a result of the use of de-icing salts. As well, the small diameter, high strength, steel dowels create high bearing stresses in the concrete surrounding the dowels which causes the concrete to crush and spall locally. This eventually causes the dowels to become loose which is the major cause of pavement joint faulting. Dowel materials such as stainless steel, stainless clad, and glass-fibre reinforced polymer (GFRP) have been introduced in recent years as possible solutions to the corrosion problem. The size of the dowels has remained the same, typically 38 mm (1.5") in diameter for high-trafficked roads, which does not solve the bearing stress problem and costs can be very high for stainless steel.

In order to address both the corrosion and bearing stress problems, large-diameter concrete-filled GFRP tube dowels have been introduced. Experimental work at the University of Manitoba examined and compared the performance of four dowel types including 38 mm epoxy coated steel, 38 mm solid, pultruded GFRP dowels, and two sizes of concrete-filled GFRP tube dowels having diameters of 50.8 mm and 63.5 mm each. The dowels, which were cast in full-scale depth concrete slabs, were instrumented with strain gauges and small linear variable displacement transducers (LVDTs) attached to the dowel by small steel rods extending down through a small slot in the concrete. Behaviour of the dowels was evaluated based on measured displacements and performance over one million load cycles.

Tests showed that the concrete-filled GFRP tube dowels exhibited considerably lower displacements and therefore, lower bearing stresses than the smaller 38 mm steel and pultruded GFRP dowels. After one million load cycles, the concrete-filled dowels and the concrete slab showed no signs of fatigue damage and exhibited great potential for use in jointed concrete pavements.

## **1.0 Introduction**

There is a great demand for better designed, longer lasting jointed concrete pavements. For almost a century, smooth, round, steel dowels have been used to transfer vehicle loads across concrete pavement joints. These dowels are subjected to shear and bending stresses due to thermal gradients in the pavement slabs in addition to the traffic loads. The dowels are also subjected to harsh corrosive environments due to de-icing salts used in colder climate regions. The corrosion problem of steel has led to the need to find alternative dowel materials.

The pavement joints are designed to allow the slabs to expand and contract under changes in temperature requiring the dowels to move within the concrete slab. The volume change associated with corrosion of steel causes the joints to lock up and the concrete surrounding the dowels to crack. The epoxy coatings placed on steel dowels for the purpose of preventing corrosion are easily damaged allowing for the intrusion of corrosive agents. Stainless steel dowels have been used to prevent corrosion, however, the cost of these bars can be as much as six times the cost of an epoxy-coated steel dowel.

In recent years glass fibre-reinforced polymers (GFRP) have been introduced as a promising alternative material to steel. GFRP are not affected by de-icing salts, provides good strength, and do not require surface de-bonding agents like its steel counterpart. Use of 38-mm diameter pultruded GFRP dowels, similar in size to the epoxy-coated steel dowels, has been increasing and tests have shown them to perform comparably to steel in the field<sup>(2)</sup>. GFRP has a higher tensile strength than steel, however, it has a significantly lower elastic modulus. The problem with the lower elastic modulus is that the dowel bar will bend and deflect more easily than steel under load causing higher concrete bearing stress in the critical region that is closest to the joint face. Damage to the concrete surrounding the dowels due to high bearing stress is already common with steel dowels. High bearing stresses produced by the dowel cause the surrounding concrete to crush and spall off, thereby causing the dowel to become loose. 'Dowel looseness' is a common cause of joint faulting which occurs when one slab deflects more than its adjacent slab under traffic loads.

It is known that bearing stress can be reduced by increasing the size of the dowel bar<sup>(3)</sup>. Using larger solid steel or GFRP dowels will increase costs and therefore may be less feasible for use in concrete pavements. Large-diameter concrete-filled GFRP tube dowels have recently been suggested as a possible solution to this problem. There is no

available information on the performance of this type of dowel, however, tests at the University of Manitoba<sup>(1,7)</sup> have shown them to exhibit good potential for use in concrete pavement joints. The required strength for shear and bending of the dowel is provided mainly by the FRP tube alone as the concrete core becomes cracked under load. The concrete or grout core of the dowel provides internal support to the shell preventing the tube from collapsing under traffic loads. The concrete-filled GFRP dowels combine bearing stress-reducing size with non-corrosive material properties and are cost effective than solid GFRP dowels of the same size.

## 2.0 Background

### 2.1 Design of Concrete Pavement Joints

Pavement joint design methods were first developed by B.F. Friberg<sup>(3)</sup> and were based on closed-form linear-elastic solutions for an infinitely long beam in an elastic mass solved by Timoshenko and Lessels<sup>(11)</sup>. The deflection of a beam in an elastic mass is calculated using the following equation:

$$[1] \quad y = \frac{e^{-\beta x}}{2\beta^3 E_d I_d} \{P_t \cos \beta x - \beta M_o (\cos \beta x - \sin \beta x)\}$$

Friberg applied Timoshenko's elastic solution to a dowel bar of semi-infinite length embedded in concrete. The peak deflection measured at the joint face of the slab is determined by setting  $x = 0$  in Equation [1] and obtaining the following equation:

$$[2] \quad y_o = \frac{P_t}{4\beta^3 E_d I_d} (2 + \beta z)$$

where  $\beta$ , the relative stiffness of the dowel embedded in a concrete mass, is given by:

$$[3] \quad \beta = \sqrt[4]{\frac{Kb}{4E_d I_d}}$$

- K = modulus of dowel support (K-value)
- b = diameter of the dowel (width of beam)
- $E_d, I_d$  = elastic modulus and moment of inertia of the dowel
- $P_t$  = load transferred by the dowel
- z = the width of the gap between the two slabs.

The modulus of dowel support, K, is a constant representing a force per unit area that would cause a unit deflection.

Figure 1 shows the deflected shape of the dowel bar calculated by Equation [1].

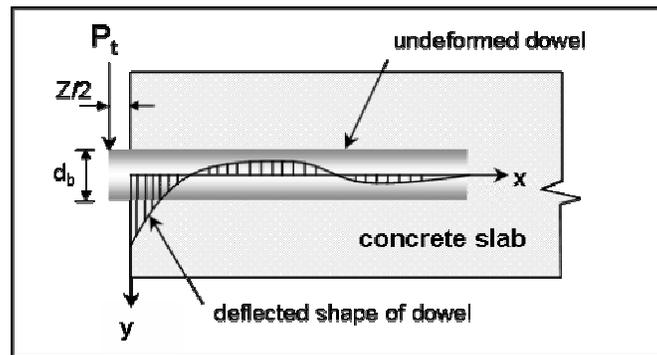


Figure 1: Deflected shape of a dowel bar

In Equation [1], the bending moment in the dowel,  $M_o$ , is caused by the eccentricity of the applied load,  $P_t$ , which would result from the adjacent slab being loaded, and is calculated from the following equation:

$$[4] \quad M_o = P_t \frac{z}{2} = \text{bending moment at the face of the surrounding mass}$$

The bearing stress along the dowel/concrete interface,  $\sigma_b$ , is obtained by multiplying the deflections calculated from Equation [1] by the modulus of dowel support or ‘K-value’ as shown in the equation below.

$$[5] \quad \sigma_b = Ky$$

The maximum load transferred by a dowel,  $P_b$ , across the pavement joint is determined by a concept known as ‘dowel group action’<sup>(4)</sup>. Dowels that cross the joint within a 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. The number of adjacent dowels that experience load is determined by the relative radius of stiffness of the slab-subgrade system<sup>(12)</sup> as:

$$[6] \quad \ell = \sqrt[4]{\frac{E_c h^3}{12(1-\nu^2)k}}$$

where,  
 h = thickness of concrete slab  
 $E_c$  = modulus of elasticity of concrete slab  
 $\nu$  = Poisson’s ratio of concrete  
 k = modulus of subgrade

The modulus of dowel support, K, is a parameter that incorporates the elastic properties of the surrounding mass which is the concrete in this case. The K-value expresses the bearing stress in the concrete developed under a unit deflection of the dowel bar. The Timoshenko-Lessels analytical expressions adopted by Friberg for calculating the deflections of the dowel and the bearing stress in the concrete are highly dependant upon this elastic parameter. The selection of a K-value in design can greatly affect the predicted deflections and bearing stresses. Determination of the correct K-value has been shown to be practically impossible as it can vary with load level, concrete strength, dowel diameter and several other factors<sup>(5,6,10)</sup>. Early theoretical approaches by Friberg estimated the K-value to range from 82 to 409 GN/m<sup>3</sup> depending on the properties of the dowel-slab system.

### 2.1.1 Research on Dowels for Concrete Pavements

A recent study at the University of Oklahoma<sup>(6)</sup> investigated the load-deflection behaviour of a dowel bar embedded in concrete using an experimental approach. The deflected shape of a dowel bar was monitored under load using a set of LVDTs connected to rods leading up through small vertical shafts in the concrete slab.

The measured dowel deflections were compared with predicted calculations using the elastic theory. Correlation between the two methods was found to be highly dependant upon the value of the modulus of dowel support. It was found that the back calculated K-value was considerably larger than the early estimates of 82 to 409 GN/m<sup>3</sup> provided by Friberg. For Mannava, K-values required to match experimental results ranged from 240 to 1250 GN/m<sup>3</sup> depending on the load level, concrete strength, and other characteristics of the test specimens.

### 2.1.2 GFRP Dowel Research

Glass fibre-reinforced polymer (GFRP) dowels have been recently introduced as a possible solution to the corrosion problem posed by steel dowels. In addition to their non-corrosive properties, GFRP dowels have a low pull-out force, thereby eliminating the need to grease the dowels before paving the concrete. Glass fibre-reinforced polymer has a higher strength than steel, however, the modulus of elasticity is lower. The lower modulus results in a lower flexural stiffness for the GFRP dowel compared to the steel. As seen in Equations [1] and [3], the magnitude of displacement of the dowel in the concrete slab is dependent upon the flexural stiffness ( $E_d I_d$ ) of the dowel. A lower stiffness will result in higher dowel displacements which will in turn result in a greater bearing stress at the joint face of the slab. The bearing stress in the concrete can be reduced, however, by increasing the size of the dowel.

There were two studies conducted at the University of Manitoba on the use of glass fibre-reinforced polymer dowels in jointed concrete pavements. The first study<sup>(1)</sup> investigated the use of 38-mm (1.5”) diameter pultruded GFRP

dowels for concrete pavement. This study involved extensive laboratory tests of full scale concrete slabs and resulted in a field application for GFRP dowels. The second study<sup>(7)</sup> investigated the use of large-diameter (60 mm) dowels comprising pultruded and filament wound GFRP tubes filled with concrete. The latter study involved strength testing of the dowels to determine if a concrete-filled GFRP dowel was suitable for use in concrete pavements. The larger dowel was selected as a possible solution to the bearing stress problem outlined earlier.

### 3.0 Experimental Program

#### 3.1 General

The experimental program was conducted to study the performance of various dowel types under simulated vehicle axle loads. The dowels, cast into full-scale depth concrete slabs, were loaded in shear by a steel loading device. The mechanism simulated the effect of an adjacent slab being loaded and transferring that load across the joint via the dowel bars. The elastic solutions by Timoshenko show that lower dowel deflections produce less bearing stress in the concrete. Reduction of bearing stresses will result in less damage to the concrete over time. By measuring the dowel deflections, it is possible to determine the optimum dowel design for use in concrete pavement joints.

The experimental program comprised two phases. Phase I involved static and cyclic loading of four slabs, each cast with a different type of dowel. The slabs were loaded up to a service level of 12 kN and then unloaded. This force represented the largest load applied to a single dowel under an 80 kN Equivalent Single Axle Load (ESAL). Monotonically loaded static tests were conducted initially and repeated after four sets of 250,000 load cycles for a total of 1,000,000 cycles for each slab specimen.

The second phase, Phase II, comprised four additional slabs that were loaded monotonically until failure of the dowels. The steel dowels, which have a significantly greater stiffness, were loaded until the strain in the bar reached yield. For all tests, the dowels and slabs were instrumented to measure load-deflection and load-strain responses as well as plot the deflected shape of each dowel under load.

#### 3.2 Dowels

Four types of dowels were tested in this study. These are a 38-mm (1.5") diameter epoxy-coated steel dowel, a 38-mm pultruded GFRP dowel, and two sizes of concrete-filled GFRP tube dowels with outside diameters of 50.8 mm and 63.5 mm (2" and 2.5"). The GFRP tube thickness for both dowel sizes was 6.2 mm (1/4"). All dowels were 456 mm (18") in length. Figure 2 shows a photo of the four dowel types. The 38-mm steel and GFRP dowel bars tested are typical of those most commonly used in the field today.



**Figure 2: Dowel Bars Tested**

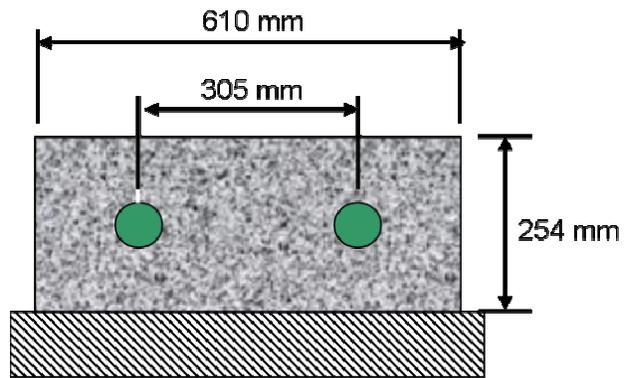
The 38-mm diameter epoxy-coated steel dowels tested in this study comprised mild steel with a yield strength of approximately 300 MPa. The elastic modulus was 200,000 MPa with a poisson's ratio of approximately 0.3.

The 38-mm GFRP dowels comprised 70% pultruded glass fibres / 30% resin by volume as provided by the manufacturer. The GFRP dowels had an elastic modulus of approximately 40,000 MPa. As provided by the manufacturer, the peak tensile and shear capacities for the 38-mm diameter GFRP dowel were 630 kN and 146 kN respectively.

The GFRP tubes used for the concrete-filled dowels comprise layers of continuous strand mat that provide multi-directional strength and pultruded layers that provided strength in the longitudinal direction. The GFRP tubes have a vinyl-ester resin that is corrosion resistant and fire retardant. The composition of the tubes is 70% glass fibres by volume and 30% resin. A synthetic veil on both the inner and outer layers of the tube provides additional protection against corrosion and alkalis. As provided by the manufacturer, the GFRP tubes had an elastic modulus of approximately 19,000 MPa, a tensile strength of 207 MPa, and a poisson's ratio of 0.33. The concrete core had a 28-day compressive strength of 48 MPa. The main purpose for the concrete core was to provide internal support to reduce ovalizing and prevent crushing of the surrounding GFRP tube.

### 3.3 Test Specimens

A total of eight concrete pavement slabs were constructed. There were two sets of four slabs containing a pair of each of the four types of dowels. The two dowels in each slab were placed at mid-depth and were spaced 305 mm (12") on centre as shown below in Figure 3.



**Figure 3: Pavement Slab Test Specimen**

The dimensions of the slabs were 610 mm x 610 mm x 254 mm thick (24" x 24" x 10") and the thickness is typical of a freeway or expressway pavement. The dowels were embedded 229 mm or half their length into the slab. For each slab, one of the dowel bars was instrumented with electrical resistance strain gauges to measure flexural strains. The second dowel cast into the slab was prepared for measuring vertical displacements using LVDTs. A small shaft was cast in the slab above one of the dowels in each slab. This shaft, which lead down from the top of the slab to the top of the embedded dowel bar, was used to facilitate measuring the dowel deflections using small extension rods connected to the LVDTs attached to the top of the pavement slab. During the tests, the protruded ends of the dowels were loaded directly by a steel cross-head eliminating the need to cast an adjacent slab. The main objective of not having an adjacent slab was to have the joint face open for visual monitoring of possible damage. The steel cross-head that applied load directly to the dowels was placed at a specified distance from the concrete joint face (12.5 mm). This simulated the loading conditions for a worst-case scenario where a large pavement joint opening exists.

The concrete used for the pavement slabs was supplied by a local mixing plant and had a specified 28-day compressive strength of at least 35 MPa. Results of the cylinder tests showed the strengths to be significantly higher (in the range of 46 MPa or greater). The compressive strength of the concrete was 53 MPa at the time of testing for Phase I. The concrete strength had increased to approximately 58 MPa at the commencement of Phase II tests.

### 3.3.1 Instrumentation

#### 3.3.1.1 Dowel Bar Deflection

A short narrow slot was cast in the concrete slab above one of the two dowels to allow small LVDTs to measure the dowel displacements at specified distances along its top surface. The slot measured approximately 6 mm wide and 60 mm long parallel to the direction of the dowel bar. The size of the slot was kept small in order not to affect the behaviour of the dowel. A compact support fixture was manufactured to house the LVDTs in a way that would allow for several displacement measurements to be taken within close proximity to each other. The LVDTs were held in place by the device and measured the displacement of the dowel using stainless steel extension rods resting against the top surface of the dowel bar. A total of five LVDTs were required to measure displacements over a 50 mm long section of the dowel bar extending from the joint face where displacements are highest. The locations of the five points were zero (at the joint face), 10, 20, 35, and 50 mm inward from the joint face as shown in Figure 4. The LVDTs had a total travel of 6.35 mm and an accuracy of 0.001 mm. This high level of accuracy was required as the expected displacements at service loads ranged between zero and 0.1 mm.

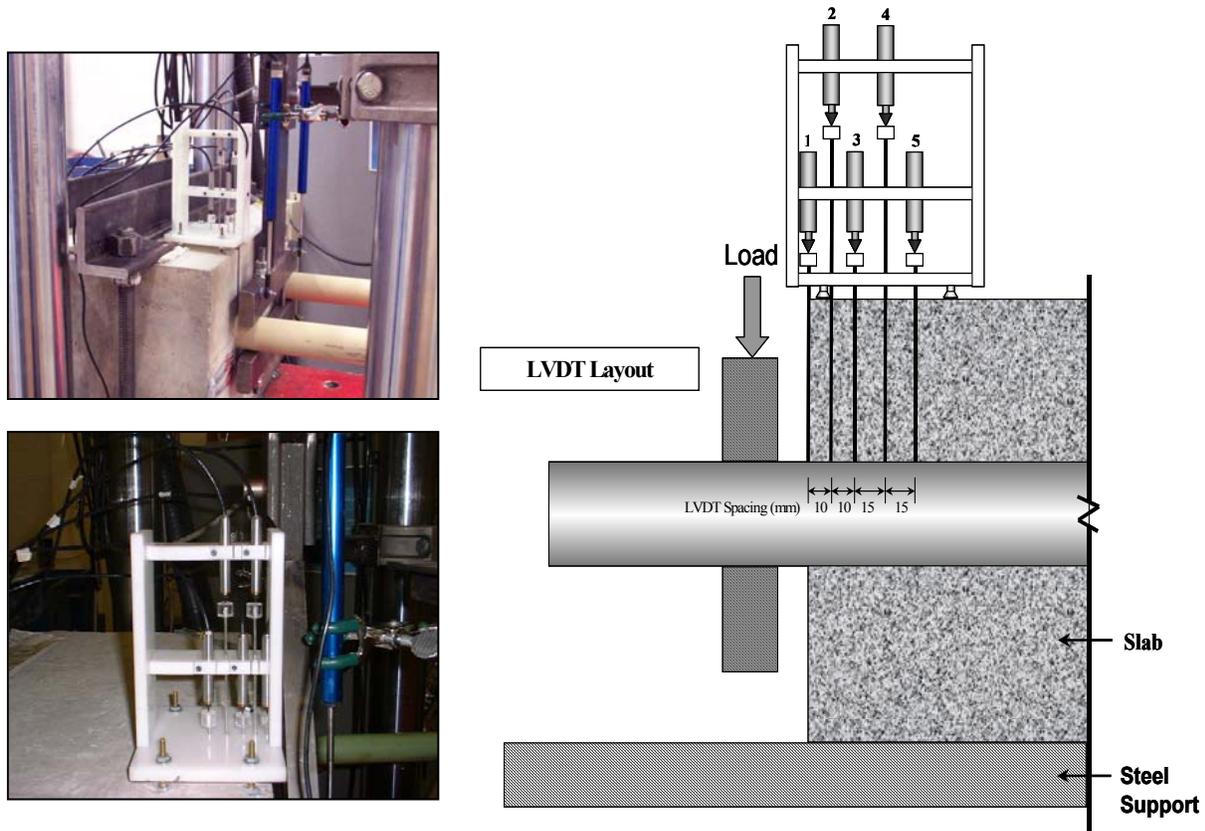
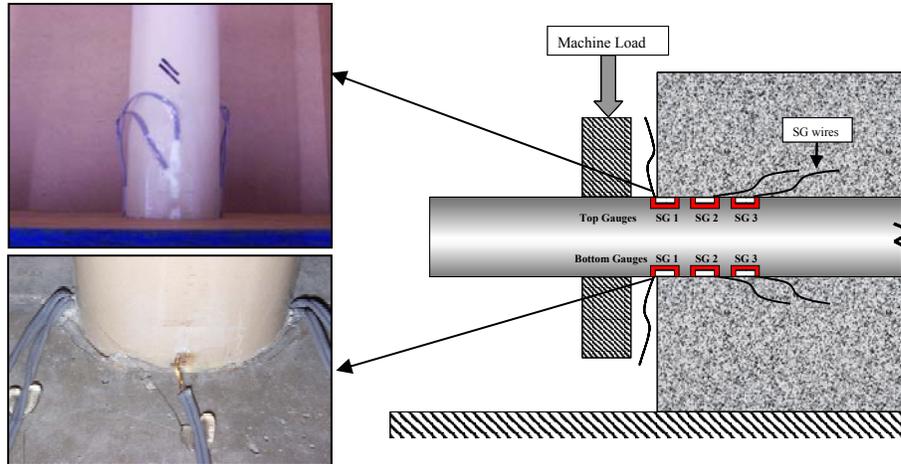


Figure 4: LVDT dowel-deflection measuring system

#### 3.3.1.2 Dowel Bar Flexural Strain

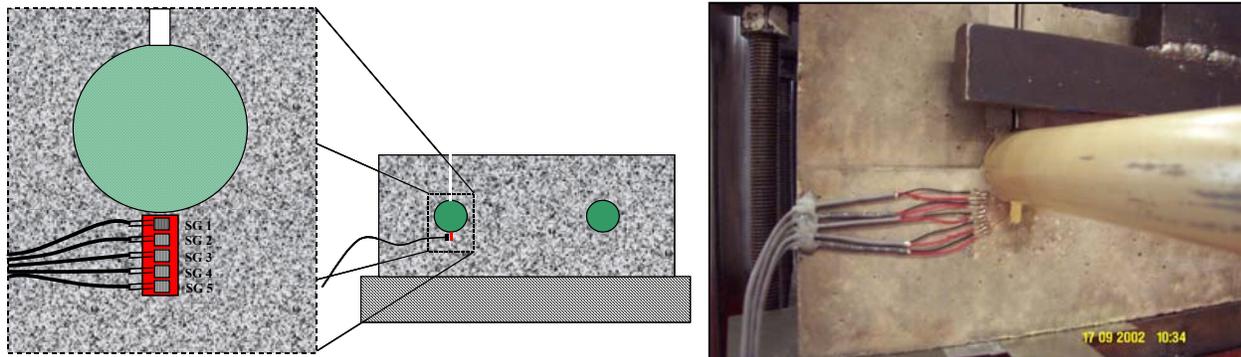
One of each pair of dowels in every slab was instrumented with 3-mm gauge length electrical resistance strain gauges to measure longitudinal strains due to bending. A total of six gauges were placed on each bar, three on the top and three on the bottom, at distances 3 mm, 19 mm and 38 mm (1/8", 3/4", and 1.5") inside of the face of the concrete as shown on the diagram in Figure 5. In theory, the maximum bending moment that would occur in the bar under load would exist within the region instrumented with strain gauges.



**Figure 5: Strain gauge layout for measuring bending strains**

### 3.3.1.3 Concrete Strain

Strain gauges were selected to monitor the behaviour of the concrete loaded by the dowel bar above. In theory, when load is applied to the dowel, a series of bearing stress bulbs form beneath it decreasing in magnitude with distance below the dowel. In this study, a series of five small 2-mm strain gauges were used in an attempt to capture this strain gradient. Each strain gradient gauge contained five 2-mm length strain gauges spaced 2 mm on center. Figure 6 shows a photograph of one of these gauges and a diagram showing the placement of the gauge on the concrete slab.



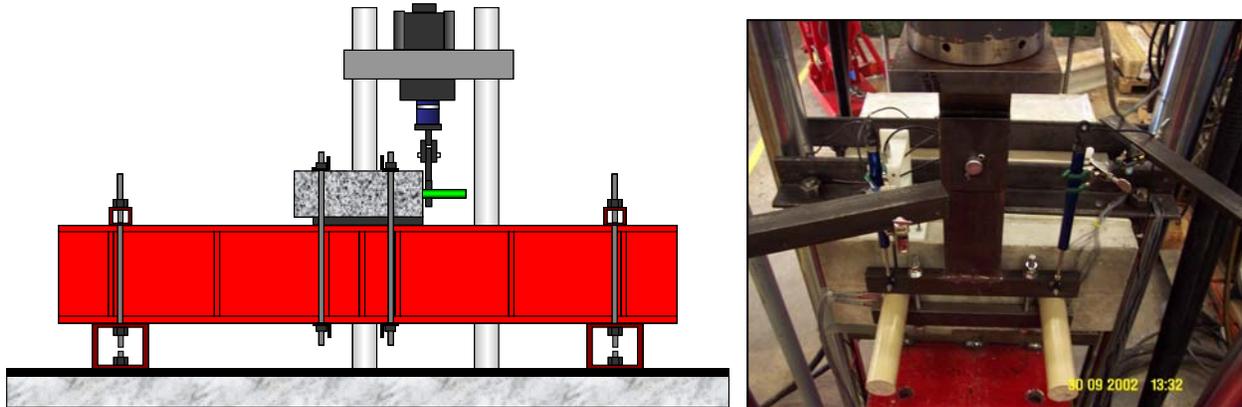
**Figure 6: Layout of strain gauges on concrete slab face**

This paper focuses only on the deflections of the dowels. Results for dowel and concrete strain will be discussed in future publications. Based on the elastic solutions presented earlier, the dowel deflections are most important because they can be related directly to bearing stress at the dowel/concrete interface. The reduction of bearing stress is essential for improving pavement joint design.

### 3.4 Test Set-up

For all tests, the concrete pavements slabs were anchored down to a large rigid support beam as shown in Figure 7 below. The beam was raised off the ground by placing it across two steel 254 x 254 mm square hollow steel sections and then anchored to the floor using tie-down bars. In theory, the deflection of the dowel bar within the concrete slab is unaffected by the amount of base support. Therefore a rigid base (beam) could be used instead of a compacted granular material. Using the rigid beam reduced the overall stroke of the test machine allowing for a higher frequency to be used during cyclic testing. It also eliminated the complexities of setting up a simulated

subbase material to support the pavement slab. The slabs were loaded using an MTS 1000 kN capacity closed-loop servo-hydraulic testing machine.



**Figure 7: Test Set-up**

#### **4.0 Results and Discussion**

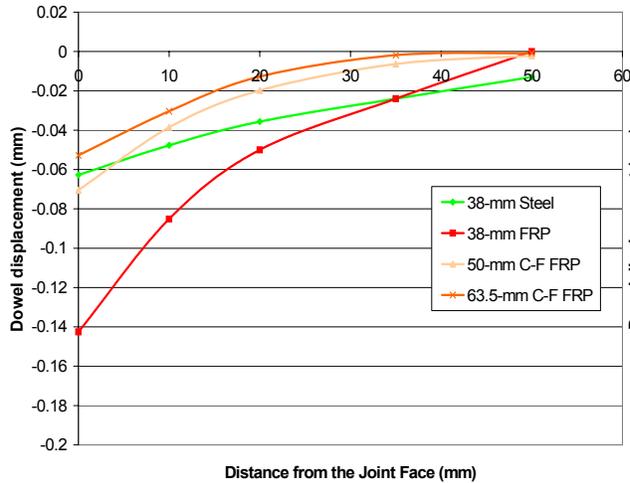
Two sizes of concrete-filled GFRP tube dowels were evaluated and compared with standard 38-mm diameter solid epoxy-coated steel dowels and pultruded GFRP dowels. This evaluation process involved the measurement of dowel bar deflections under static and cyclic loading, dowel strain due to flexure, and concrete strain in the pavement slab directly beneath the dowels. The results of the tests and subsequent discussion are provided.

#### **4.1 Deflected Shapes of the Dowels**

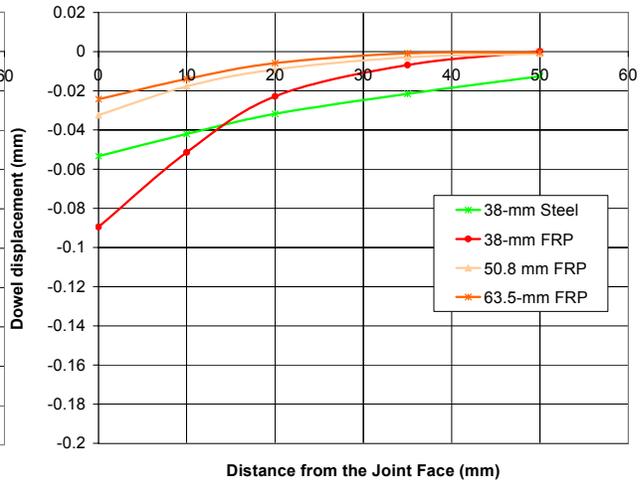
The primary objective of this study was to measure and plot the shape of each deflected dowel bar in order to capture the key differences in how the bars behave under simulated traffic loads. Of greatest importance was the measurement of the peak dowel displacements that occur at the edge of the joint or pavement slab face. This is an indirect measurement of the peak bearing stress that exists between the dowel and the surrounding concrete which is the fundamental factor in pavement joint design.

Figure 8(a) below shows the measured deflected shapes of the four dowel bar types tested in Phase I of this study at a service load of 12 kN. The values represent the displacement at the top surface of each dowel bar as the LVDTs were positioned above the dowels. In actual fact, the bottom surface of the bar, which is in contact with the underlying concrete, will have displaced a lesser amount than measured at the top surface of the dowel. This is due to transverse deformation or ovalizing of the dowel itself. The actual strength and stiffness of each dowel will affect the amount of transverse deformation each bar experiences. For example, a steel dowel has a much greater stiffness than a GFRP bar and will therefore deform less under load. In order to obtain the bottom dowel surface displacements, the transverse deformations of each dowel were subtracted from the top surface displacements provided in Figure 8(a). The bottom dowel surface deflected shapes are plotted in Figure 8(b).

It can be clearly seen that the concrete-filled GFRP dowels, which have significantly larger diameters, exhibit the lowest deflections. The 38-mm solid GFRP bar exhibits greater displacement than the 38-mm steel dowel due to the lower shear and flexural strength and stiffness. This lower strength and stiffness prevents the GFRP bar from transferring the applied load further along its embedded length, thereby, creating a greater concentration of force near the joint face. This causes greater deflection of the bar and therefore, higher bearing stress between the bar and the concrete slab. The larger diameter, concrete-filled GFRP bars have less strength and stiffness than the steel dowels, however, the load is spread out over a wider bar which reduces the force concentration.



(a) Top Surface of Dowel



(b) Bottom Surface of Dowel

Figure 8: Deflected Shape of Dowels at Service Load (12 kN)

The dowel deflections were measured again after each set of 250,000 load cycles up to 1 Million cycles. The magnitudes of the displacements were almost identical to the initial results shown above. Therefore, there was no indication of damage to the concrete pavement slab or any of the dowels after the cyclic loading based on dowel deflections.

#### 4.2 Dowel Deflections under Cyclic Loading

Figure 9 shows the dowel displacements at the joint face of the slab measured during cyclic loading in Phase I of the experimental program. The deflections are captured during a one second interval with 160 data points plotted per second. The dowels were loaded at rate of 5 Hz as can be seen by the five load pulses in the figure. The 38-mm GFRP dowel exhibited significantly higher displacement than the other dowels forcing a reduction in the load rate to 4.5 Hz. The reason for this was that the stroke of the hydraulic testing machine exceeded the limit for a cyclic loading rate of 5 Hz and had to be reduced.

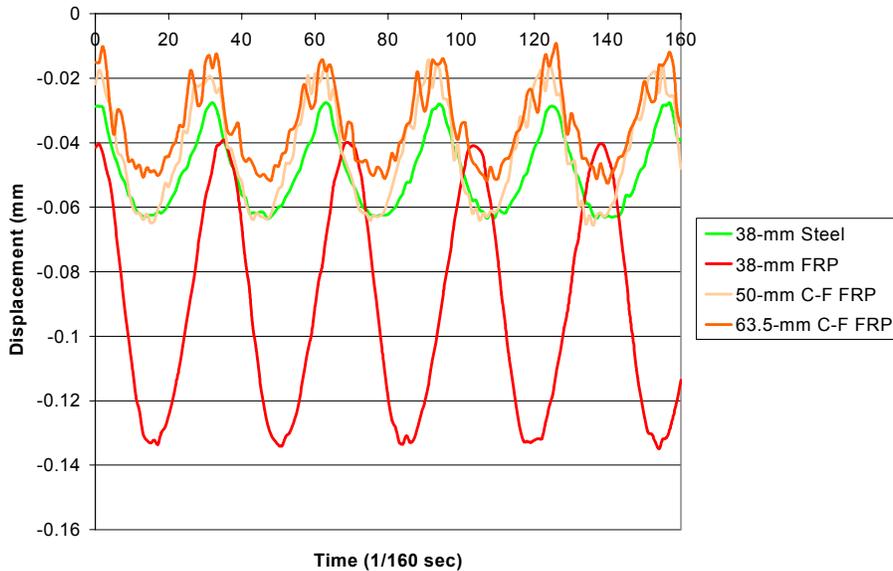


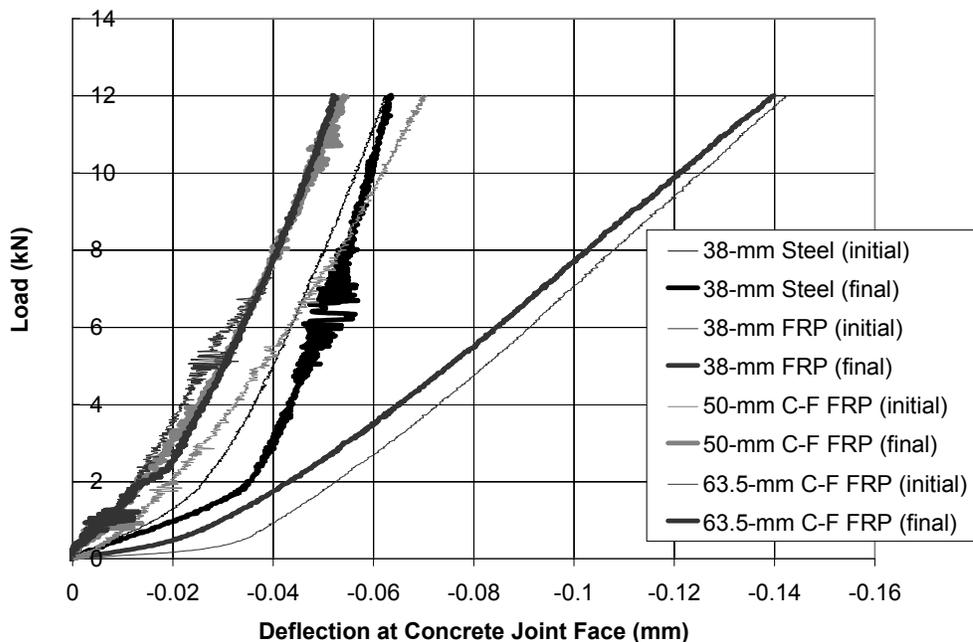
Figure 9: Displacement of dowels under cyclic loading (At service load of 12 kN)

The dowels were loaded in a haversine function in the compression range only. This was done to reduce the total stroke of the machine in order to achieve the fastest rate possible. In addition, the stroke was reduced even further by maintaining a minimum compression load on the dowels of approximately 10% of peak load. This is evident by the fact that the displacements in Figure 9 do not return to zero.

The peak displacements are similar to the values measured in the initial static test provided earlier. This indicated that the monotonically-loaded static tests provide accurate measurements of dowel displacements that would otherwise occur under dynamic load in the field.

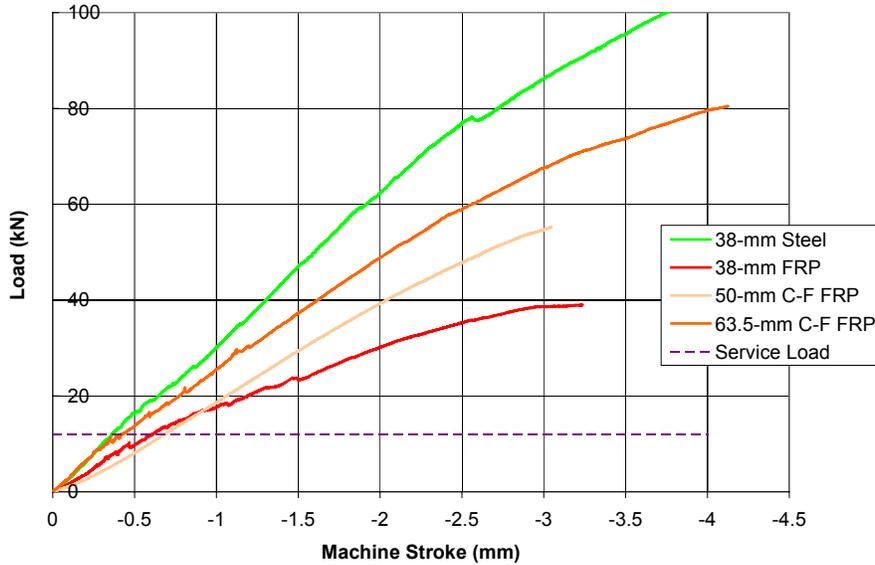
Figure 10 shows load versus deflection plots for each dowel type recorded before and after 1 Million load repetitions of 12 kN (service load). It can be seen that there is very little difference in the deflection between the initial and final loading of the dowels. The 50.8-mm concrete-filled GFRP tube dowel did show a significant difference after the first 250,000 cycles as it does in the figure below. The deflections after repeated loading were lower than those measured during the initial test. This appeared to be due to increased shear deflection of the dowel outside the joint due to the crack in the concrete core. This would cause a reduction in transverse deformation of the dowel resulting in a lower deflection measured from the top surface of the dowel. There was no indication of any wear or damage to the dowel of any kind.

The dynamic loading up to one millions cycles for each dowel type in the experimental program showed all four dowels to withstand the load without any significant signs of damage. Similarly, the concrete around each dowel showed no visual signs of damage. It should be noted that the ideal conditions of the laboratory tests do not take into account the effects of environmental factors such as freeze-thaw and expansion and contraction at the joints.



**Figure 10: Load-deflection plots up to service load before and after 1 Million load cycles**

In the second phase of testing, Phase II, the dowels were loaded to failure. Figure 11 shows a load versus stroke graph for each of the four dowel types. Damage was observed for both of the 38-mm dowels. The 38-mm pultruded GFRP dowel caused a large flake of concrete to spall away just under the dowel at a load level of twice the service load or 24 kN. This dowel reached a maximum load of 39 kN. The epoxy-coated steel dowel exhibited slight spalling of small concrete flakes at a much higher load of 80 kN. The loading was ceased when all six strain gauges on the dowel registered a yield strain in the steel ( $\epsilon_y = 0.002$ ). The concrete-filled dowels produced no signs of damage to the concrete slab before the dowels themselves failed under load. The 50.8-mm and 63.5-mm C-F GFRP dowels had peak failure loads of 55 kN and 80 kN respectively.



**Figure 11: Load versus machine stroke - Dowels loaded to failure (Phase II)**

## 5.0 Conclusion

In this study, the performance of concrete-filled GFRP dowels in concrete pavement joints was investigated and compared with the performance of 38-mm epoxy-coated steel and solid pultruded GFRP dowels. An experimental program comprising two phases was carried out. In Phase I, four pavement slabs were tested under static and cyclic loading at service load. Phase II involved the testing of four additional slabs where the dowels were loaded up to failure.

The study showed that the concrete-filled GFRP tube dowels are a feasible alternative to steel dowels for use in jointed concrete pavements. This study showed the significance of using larger diameter dowel bars to reduce bearing stress in the concrete. The need for larger-diameter dowels is greater when using GFRP dowels because of the low shear strength and flexural stiffness.

The concrete-filled GFRP tube dowels, especially the larger 63.5-mm tubes, were found to perform the best in this study. The deflections and resulting bearing stresses were the least for the four dowel types and the performance over the set of one million load pulses was excellent. The concrete-filled GFRP dowels exhibited lower deflections than the 38-mm GFRP dowel as expected because of the larger diameter. The 50.8-mm concrete-filled dowel and 38-mm epoxy-coated steel dowel exhibited similar peak displacements near the joint face of the slab, however, the displacements dissipated with distance away from the joint face more rapidly for the concrete-filled dowel. The concrete-filled dowels proved to have ample strength for use in concrete pavement joints and are capable of withstanding the repeated traffic loads.

Benefits of the concrete-filled GFRP dowels include:

- GFRP tubes are non-corrosive which prevents locking of pavement joints.
- The synthetic veil surrounding the GFRP tube along with a vinyl-ester resin, provide protection against the alkali environment of the concrete.
- The large diameter reduces bearing stress significantly
- The high strength and durability provide excellent resistance to repeated traffic loads.
- They are a lower cost alternative to using stainless steel (approx. 1/3 the cost of 38-mm solid stainless steel dowel)
- The smooth outer surface of the GFRP tube eliminates the need to apply de-bonding agents prior to paving to prevent the dowel from locking in the joint.
- Although not part of this study, it is expected that the low stiffness and large diameter will require a shorter dowel length which is preferable for dowel retrofitting.

There will be limitations on the thickness of the pavement slab when using concrete-filled GFRP dowels. They are not recommended for use in pavement slabs that are less than four times the diameter of the dowel. Further work will need to be conducted to determine the minimum pavement slab thickness for each concrete-filled dowel size.

The 38-mm pultruded GFRP dowels produced the greatest deflections and bearing stresses in the concrete compared to the other dowel types. This was due to the small diameter and low flexural stiffness. The GFRP dowel exhibited ample strength and durability for use in concrete pavement joints, however, the concrete bearing stress is most critical in design. In order to reduce the bearing stress, the pavement joint will require either shorter dowel spacing (more dowels to share the load) or larger dowels or a combination of both. Both of these options will increase costs, however, the cost of using stainless steel will be even greater.

The 38-mm epoxy-coated steel dowels performed better than the 38-mm GFRP dowels in this study, however, the effects of corrosion and other environmental factors were not incorporated. There is no question that the problem of dowel corrosion must be eliminated and one of the most economical ways to eliminate the problem is to use GFRP.

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