INVESTIGATION OF DOWEL BAR RETROFITTING ON PCC PAVEMENT RESPONSES

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ABSTRACT

Load transfer across transverse cracks is critical to maintaining satisfactory performance in PCC pavements. As a result of this, the use of dowel bar retrofitting is an essential rehabilitation alternative for PCC pavements.

Finite element analysis was used in a parametric study including variables such as PCC thickness, temperature gradient, and subgrade support. Discontinuities were modeled solely with aggregate interlock as well as in combination with dowels. In both cases, load transfer efficiency and the critical slab tensile stresses were computed to examine the immediate theoretical benefits.

Analytically, little change in slab tensile stress was exhibited when retrofitted at an LTE_{δ} level below 70-80% depending on the pavement thickness, subgrade support, and temperature gradient. Analytical results were verified using field data from four retrofitted dowel sites.

OVERVIEW

Load transfer across transverse cracks is critical to the maintenance of satisfactorily performing PCC pavements. In an ideal situation, both sides of a crack or joint should share in supporting the load as it is transferred from one side of the crack or joint to the other. By doing this, deflections and their ensuing damage to the pavement can be reduced [1].

In 1933, Benkelman [2] noted that when the crack faces of two slabs are held firmly together, the aggregate interlock can be expected to function permanently as a load transfer mechanism. While this may be true to a certain extent, wear of the aggregates and opening of the joints due to time and traffic can cause loss of load transfer capacity. However, this type of load transfer is highly dependent on material properties of the concrete, such as coarse aggregate type, mix design, and gradation [3].

Low severity shrinkage cracks can also develop into mid-slab structural fatigue cracks through a loss of load transfer. Raja and Snyder [4] note that abrasion of the crack faces and opening of the cracks over time can lead to intrusion of water and incompressibles into the cracks. This phenomenon can lead to a loss of load transfer, resulting in increased slab deflections, pumping, faulting, and spalling at the crack.

Loss of load transfer across transverse cracks results in increased internal tensile stresses in the pavement and can lead to more fatigue cracking and loss of structural integrity in the pavement [5].

Many older PCC pavements have initially relied on aggregate interlock for load transfer at engineered joints. Transverse cracks that have formed between these joints have relied on aggregate interlock to maintain the adequacy of the pavement structure. With the United States Interstate Highway system deteriorating, a method for increasing load transfer at these joints and cracks was needed. A rehabilitation method of retrofitting dowel bars at these transverse cracks and joints was then experimented with.

Since the early 1980's, many states have utilized dowel bar retrofitting with much success. Over time, dowel bar retrofit construction has been refined to combat problems with overconsolidation of the concrete covering, spalling of the sawed slots, and misalignment of the dowels.

IMPORTANCE OF DOWEL BAR RETROFITTING

Dowel bar retrofitting can be utilized as either a preventive or corrective maintenance tool for PCC pavements. Mamlouk et al. [6] defines preventive maintenance as "the planned strategy of cost effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional conditions of the system without necessarily increasing structural capacity." Therefore, DBR as a preventive maintenance measure is applied only to pavements in a satisfactory condition in an attempt to eliminate or reduce the potential for future faulting, pumping, corner breaks, and spalling.

In the case of preventative maintenance, the dowel bar retrofit does not immediately benefit the pavement from a structural standpoint after the rehabilitation in terms of stresses or load transfer efficiency. However, the deterioration of stress and load transfer efficiency over time is widely believed to occur at a lesser rate, thereby increasing the structural life of a concrete pavement. While reliable deterioration models for DBR cracks do not exist at this time, field evaluation of dowel bar retrofits on a repeated basis has been occurring (most notably in Washington state [7,8]) for many years. These projects will eventually be used in part to assess the long-term benefits of dowel bars versus aggregate interlock as a means of load transfer.

Laboratory testing of dowel bar retrofits in cracked slabs is currently being conducted at the University of Minnesota using the Minnesota Accelerated Loading Facility (Minne-ALF). The goals of these tests are to determine the effects of selected design and construction variables, such as joint face texture, repair backfill material, and dowel material and length, on retrofit dowel load transfer system performance as well as to determine the variability in Minne-ALF test results [9]. The results of these tests will eventually be able to provide relative comparisons of the benefits of aggregate interlock and various design features in dowel bar retrofits.

Corrective maintenance is a necessary action conducted on a pavement to increase its performance to a satisfactory level. The defining distinction between preventive and corrective maintenance is the timing of the action as illustrated in Figure 1. When the rehabilitation occurs below a threshold set by a transportation agency, it is deemed as corrective maintenance. In general, there has not been clear threshold universally accepted by the pavement community for dowel bar retrofitting [10]. The corrective maintenance procedure for dowel bar retrofitting is similar to that of the preventive maintenance process except that faulted joints or cracks may need to be diamond ground.

In corrective maintenance cases, dowel bar retrofitting usually provides increased load transfer efficiency and reduced stresses at the cracks or joints, thereby reducing its potential for faulting and spalling distresses. While the performance of dowel bars which were inserted in corrective maintenance cases may differ than that of preventive maintenance cases, corrective maintenance provides an initial increase in performance and extended pavement life as seen in Figure 2. The performance of the pavement for any period of time can be maximized by increasing the total area under a curve similar to one from Figure 2.

In both preventive and corrective maintenance scenarios, DBR provides a mechanism by which cracks and joints may have prolonged load transfer and its associated benefits.

CURRENT METHODOLOGY

Most states select cracks and joints that are candidates for dowel bar retrofitting on a project basis. Each project would include many miles of structurally sound concrete pavement with unspalled, primarily transverse cracks that extend to the shoulder. All cracks (or joints if originally undoweled) that match these criteria would be retrofitted with dowel bars provided that the spacing allowed such rehabilitation. Severely spalled transverse cracks are normally treated

with full-depth patches since the concrete near the crack is not structurally adequate to hold dowel bars over time.

Cracks or joints can be selected for dowel bar retrofitting on the basis of falling-weight deflectometer (FWD) testing. An FWD is a device that applies an impulse load, using a circular load plate, to a pavement while measuring the resulting pavement deflections through a series of sensors. When one side of a crack or joint is loaded by the FWD, the other side will respond as well. The amount of response on the unloaded side of the joint or crack is proportional to its load transfer capability. The response of the unloaded side to the load side is termed deflection load transfer efficiency (LTE_δ) and can be computed using equation (1):

$$\mathbf{LTE}_\delta = \frac{\delta_U}{\delta_L} \times \mathbf{100\%} \quad (1)$$

where:

LTE_δ	=	deflection load transfer efficiency, %
δ_U	=	deflection on the unloaded side of a crack or joint
δ_L	=	deflection on the loaded side of a crack or joint

Use of LTE_δ assumes that the amount of load transfer across a crack is directly proportional to the relative deflections of the unloaded to loaded sides of the crack [8]. With high LTE_δ levels, deflections and stresses are shared by both sides, thereby reducing both factors.

ANALYTICAL MODELING

Finite element analysis was conducted using ISLAB2000 on pavement sections representing ranges of variables, which are typical of concrete pavements including the following:

- Modulus of subgrade reaction (k): 27.1, 67.9,108.6 kPa/mm
- Concrete thickness (h): 152, 203, 254, 305, 356 mm
- Aggregate interlock factor (AGG): 1.0 to 6,900 MPa
- Temperature difference (ΔT): 0, -8.3, +8.3°C

To model aggregate interlock joints, the AGG parameter is modeled as a one-degree of freedom (vertical) per node spring stiffness. This one-degree of freedom only allows for the modeling of shear across a discontinuity. The spring stiffness is controlled by the AGG value in units of force/length^2. In this finite element program, the stiffness is converted into units of force/length of joint as a means of load transfer across a discontinuity. This program also has the ability to model slab liftoff due to curling/warping, thereby increasing stress from loads on unsupported locations.

Other material and geometric properties were set at constant values for this analysis. These constant values included the following:

- Slab length: 9.1 m

- Slab width: 3.7 m
- Elastic Modulus: 27,600
- Poisson Ratio: 0.15
- Coefficient of Thermal Expansion: $7.9*10^{-6}$ mm/mm/°C
- Unit Weight: 2,400 kg/m^3
- Dowel Bar Properties
    - Diameter: 32 mm
    - Elastic Modulus: 138,000 MPa
    - Poisson's Ratio: 0.20
    - Dowel Length: 46 cm

A 40 kN load was placed on one side of a modeled crack to simulate the load placed by an FWD while testing for deflection load transfer efficiency. The same matrix of parameters was analyzed with and without dowel bars in order to characterize the benefits of a simulated dowel bar retrofit. To simulate the dowel retrofits, two sets of three dowel bars were placed at mid-depth in the wheel paths at 0.3 m spacings as illustrated in Figure 3. The elastic modulus of the patching mix that covers the embedded dowel bars was assumed to be the same as that of the rest of the concrete. All of the pavements in this analysis assumed no contribution to the load transfer occurred from a shoulder. This is usually the case when either an asphalt or gravel shoulder is present, which is the case in the vast majority of older PCC pavements.

For all cases without dowel bars, the load transfer efficiency was analytically found for different levels of AGG. The same cases were then evaluated with dowel bars in addition to the same levels of AGG. This method of analysis assumes that cutting slots for the retrofit dowels achieved no loss of aggregate interlock. The load transfer efficiencies in both cases were then compared to analytically assess the increase in load transfer due to dowels. Figure 4 provides an example for LTE_δ with respect to AGG for both before and after a dowel bar retrofit for the case of h = 203 mm, k = 67.9 kPa/mm, and $\Delta T = 0°C$. Figure 5 shows the principal tensile stresses at near the crack for before and after a dowel bar retrofit for the same levels of h, k, and ΔT as in Figure 4.

In Figure 4, there is a distinct separation between the curve representing aggregate interlock as the sole means of load transfer and the curve representing aggregate interlock with the benefit of retrofit dowels to aid in load transfer. This break represents the point where dowels aid in increasing LTE_δ for a given crack or joint. In this case, the break is near an LTE_δ of 91%. If a dowel bar retrofit occurs when LTE_δ is greater than this level for h = 203 mm, k = 67.9 kPa/mm, and $\Delta T = 0°C$, these analytical trends would suggest that no immediate benefit in LTE_δ would be realized. This is important to note for a transportation agency that is considering using dowel bar retrofitting as a rehabilitation method.

Figure 6 shows the same data as in Figure 4, but instead avoids the immeasurable parameter of AGG to determine LTE_δ after a dowel bar retrofit from the initial LTE_δ for the case of h = 203 mm, $\Delta T = 0°C$, and various levels of k. From Figure 6 (and for other similar curves for different

levels of h, k, and ΔT), it is seen that a significant improvement in LTE_δ can be achieved through dowel bar retrofitting. Increases of up to 85% can be achieved in LTE_δ, theoretically.

Figure 6 also illustrates that the increase in LTE_δ is dependant on the modulus of subgrade reaction. Lower levels of subgrade support generally provide greater increases in LTE_δ. The loaded side's deflection is highly dependent on the load level and less so by the subgrade support. Therefore, the deflection levels are similar for a reasonable range of k-values. However, the unloaded side deflections are based lesser on the magnitude of load on the loaded side and more so on the subgrade support. Since the subgrade is weaker, the unloaded side can deflect more under the same load transfer level. Since LTE_δ is a derived term based on deflections, the higher deflection of the unloaded side for softer subgrades equates to higher LTE_δ calculations.

FIELD VALIDATION OF ANALYTICAL RESULTS

To justify the analytical models produced using finite element analysis, FWD data from actual dowel bar retrofit sites were utilized. FWD data from both before and after the dowel bar retrofits were utilized from both Michigan and Washington state sites.

Michigan Dowel Bar Retrofit Sites

In the state of Michigan, the dowel bar retrofit sites include the following:

- I-69, Eaton County, South of Lansing, MI
- I-75, Monroe County, North of Toledo, OH
- M-14, Washtenaw County, East of Ann Arbor, MI

With the exception of some cracks on the I-69 site, the Michigan sites have been primarily preventive maintenance projects with the intention to increase the LTE_δ of tight transverse cracks over the design period of the dowels.

The trend in Figure 7 was developed by analyzing a dowel bar retrofit with h = 229 mm, the design thickness of the I-69 pavement. The backcalculated k value for this site was 67.9 kPa/mm and was modeled as a Winkler foundation. Each triangle in Figure 7 and the following figures represents a crack retrofitted with dowels and non-destructively evaluated using an FWD. The analytical trend corresponds well with the field-tested cracks at all levels of LTE_δ. Unlike the other Michigan sites, several cracks on the I-69 site exhibited low levels of LTE_δ before dowel bar retrofitting to help substantiate the predicted trend for the entire range of LTE_δ values.

The I-75 site was designed to be a 279 mm PCC pavement serving as the main north-south interstate route in Michigan. Backcalculation procedures again estimated a modulus of subgrade reaction value near 67.9 kPa/mm for use in modeling this site. The trend developed using these values in modeling the dowel bar retrofit is seen in Figure 8. As a preventive maintenance section precaution by the Michigan Department of Transportation, the expected values of LTE_δ after the dowel retrofit should be very near the initial high values of LTE_δ. The data points and

trend in Figure 8 demonstrate that little loss or gain in LTE_δ is realized initially following dowel retrofitting in these cases. The benefits of these dowel bar retrofits are based upon expected long-term preservation of load transfer across these cracks.

As with the I-75 site, the M-14 site in Michigan was a preventive maintenance measure. The PCC layer was designed to be 229 mm thick with an asphalt shoulder. A modulus of subgrade reaction was found to be near 67.9 kPa/mm again using backcalculation of mid-slab FWD tests. However, Figure 9 illustrates a very poor correlation between the cracks tested using the FWD and the predictive trend. In over 80% of the cases, the cracks exhibited lower levels of LTE_δ after the dowel bar retrofittings than before any rehabilitation occurred.

A visual observation of the M-14 site in Figure 10 reveals a problem with spalling of the grout material covering the retrofit dowels, which may have lead to this discrepancy. Without a solid base of concrete for the dowel bars to bear against as loads cross these cracks, the retrofits could not provide added load transfer. An investigation of the rehabilitation construction found that there was a problem controlling the consistency of the grout material as it came out of the mobile mixer. The mix was originally very dry, so water content was increased on site. This resulted in a variable consistency with many of the fines rising to the surface after vibration. This reduced the air voids near the surface, thereby increasing delamination potential and decreasing freeze-thaw resistance. A petrographic investigation of cores taken from the site by the Michigan Department of Transportation revealed that the top 25 to 38 mm of the grouting material had very few air voids and led to the premature delamination [6].

Washington State Dowel Bar Retrofit Sites

The Washington State Department of Transportation set up a PCC Pavement Rehabilitation Test Section on I-90 west of Cle Elum, WA, which included some sections retrofitted with dowel bars as a rehabilitation technique for transverse cracks. This site was a 229 mm thick plain jointed concrete pavement resting on a crushed stone base with an asphalt shoulder [7]. A modulus of subgrade reaction of 108.6 kPa/mm was assumed since no information of the level of stiffness of the subgrade was found. This assumption tended to correlate well with the tested transverse cracks as seen in Figure 11 although some scatter was noticed in the data. However, in general, the predictive trend did forecast the increase in LTE_δ due to the dowel bar retrofits.

BENEFITS OF SELECTIVE RETROFITTING

Analytical trends like the ones from Figures 4-6 can help transportation agencies set thresholds for levels of LTE_δ in order to gain the maximum benefit of existing load transfer at a crack. As discussed earlier, the break between the two curves in the example in Figure 4 represents the point where dowel bar retrofits start to have immediate impact on LTE_δ analytically. Therefore, as a corrective maintenance measure, the threshold using FWD testing for LTE_δ would be set at a point less than this level (in this case LTE_δ = 91%). Also in Figure 4, a distinct drop in the difference between aggregate interlock only and the curve representing both aggregate interlock and dowels occurs around LTE_δ = 80%. Consequently, an ideal threshold value to trigger a dowel bar retrofit would be this level of load transfer for these particular levels of h, k, and ΔT.

Figure 5 can also be used as a guide to set threshold values by limiting the maximum tensile stress analytically. When the LTE_δ is below a level of 75-80%, the critical values of tensile stress in the concrete tend to remain near the same levels. Therefore, no significant benefit can be gained by waiting for the crack performance to deteriorate past those levels. A transportation agency could set the threshold near LTE_δ =75-80% for this level of h, k, and ΔT (when testing the pavement using the FWD) to activate a dowel bar rehabilitation action.

In contrast, AASHTO [11] recommends that load transfer restoration should be considered when transverse cracks or joints exhibit LTE_δ levels below 50% under acceptable testing temperatures. The Federal Highway Administration [12] recommends that this threshold value be 60%. It is the conclusion of this study that thresholds for dowel bar retrofitting should be based on the levels of h, k, ΔT and accompanied by a visual survey. The use of a blanket threshold value would not necessarily maximize the reductions in stress achieved through load transfer restoration.

By using the predictive LTE_δ trends developed using the finite element method, a transportation agency could use non-destructive evaluations of potential rehabilitation candidates in order to make more efficient use of existing load transfer in transverse cracks in corrective maintenance situations. This will result in construction savings by reducing the amount of dowel bars placed if every transverse crack in a PCC pavement was retrofitted.

From 1993-1997, the Washington Department of Transportation granted contracts for dowel bar retrofits ranging from $34.40 to $42.33 per dowel placed with a total of over 300,000 dowels retrofitted over this period [8]. Assuming that one-third of the retrofits could be avoided, a potential savings of more than $3,000,000 over this period could be achieved.

SUMMARY

A history of load transfer at joints and cracks was reviewed and the importance of dowel bars as a means of restoring load transfer was discussed. In previous field studies, dowel bars tended to have better immediate and long-term benefits in comparison to other load transfer devices. The cost and ease of construction has also improved since the initiation of dowel bar retrofits in the United States in the early 1980's.

Using a finite element program designed for use with rigid pavements, analytical trends were developed for a variety of pavement thicknesses, levels of subgrade support, and temperature differences in the concrete slab during FWD testing. Examples of these trends were discussed for Figures 4-6. While these trends may infer that high quality aggregates are not necessary, the sustained load transfer from these aggregates can delay the need for DBR action.

With the exception of the M-14 site in Michigan, the developed trends tended to predict the increase in LTE_δ due to dowel bar retrofitting with relative accuracy for both the Michigan and Washington State sections. The reason for the discrepancy between the analytical trend and the FWD testing results for the dowel bar retrofits on M-14 in Michigan was investigated.

Plots, like the ones in Figures 4-6, were shown to be tools to set thresholds for selective dowel bar retrofitting activities. This method has the benefit of increased cost savings and efficiency over a method of selection that would result in all transverse cracks being retrofitted for a particular site.

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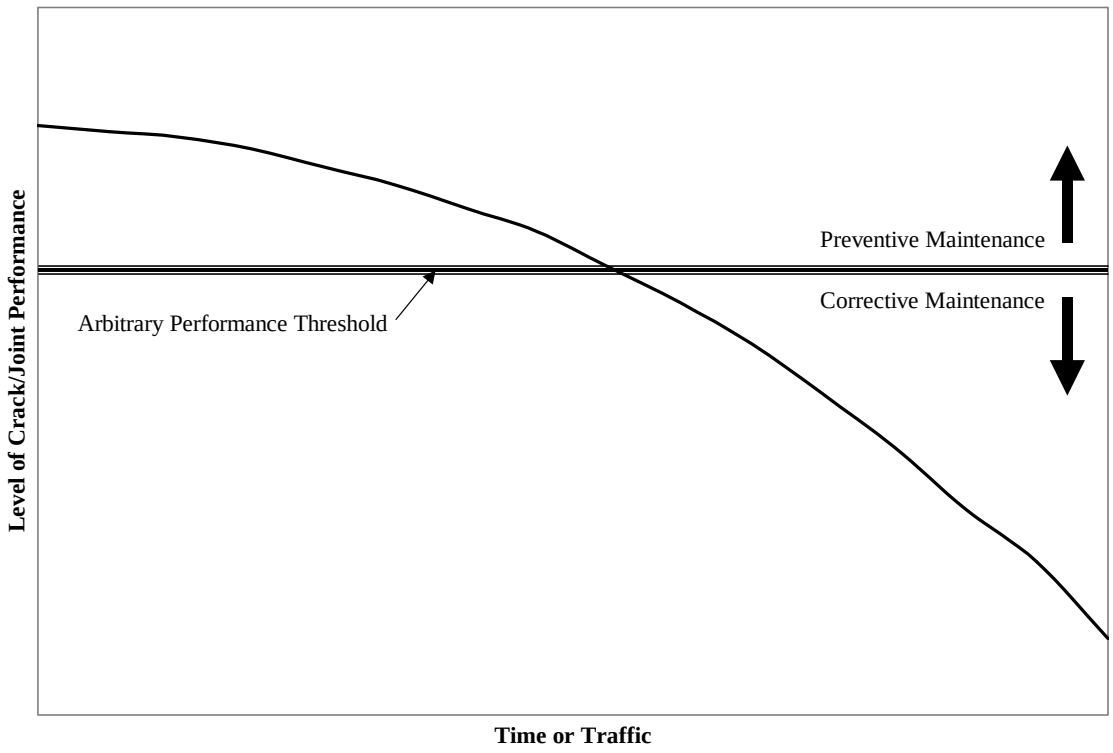

Figure 1. Distinction Between Preventive and Corrective Maintenance.

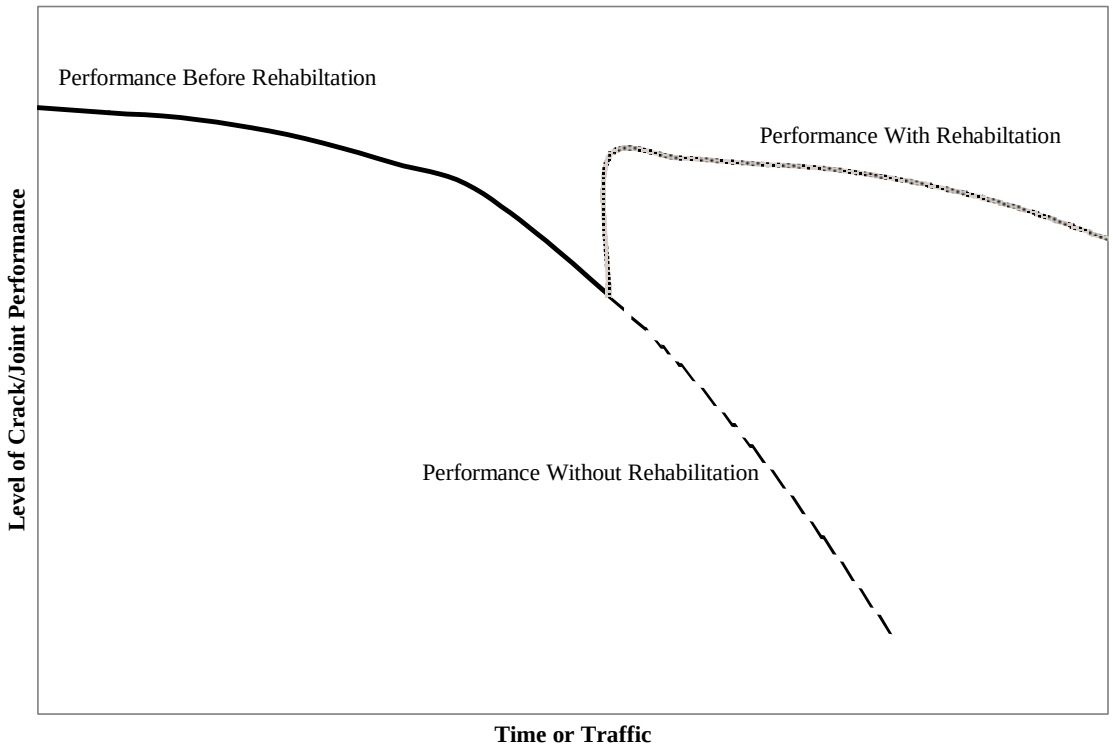

Figure 2. Comparison of Performance Benefits of Rehabilitation Over Time.

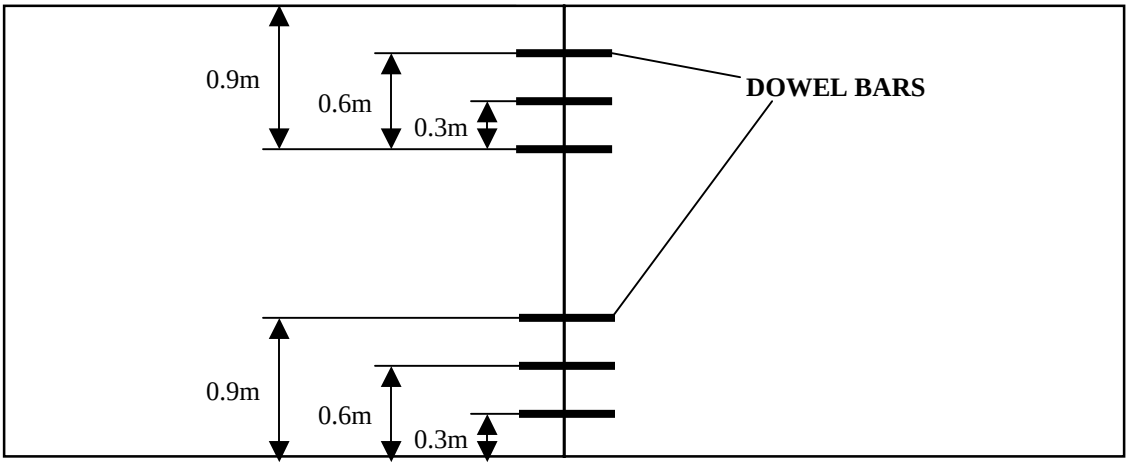

Figure 3. Dowel Bar Retrofit Locations for Finite Element Modeling.

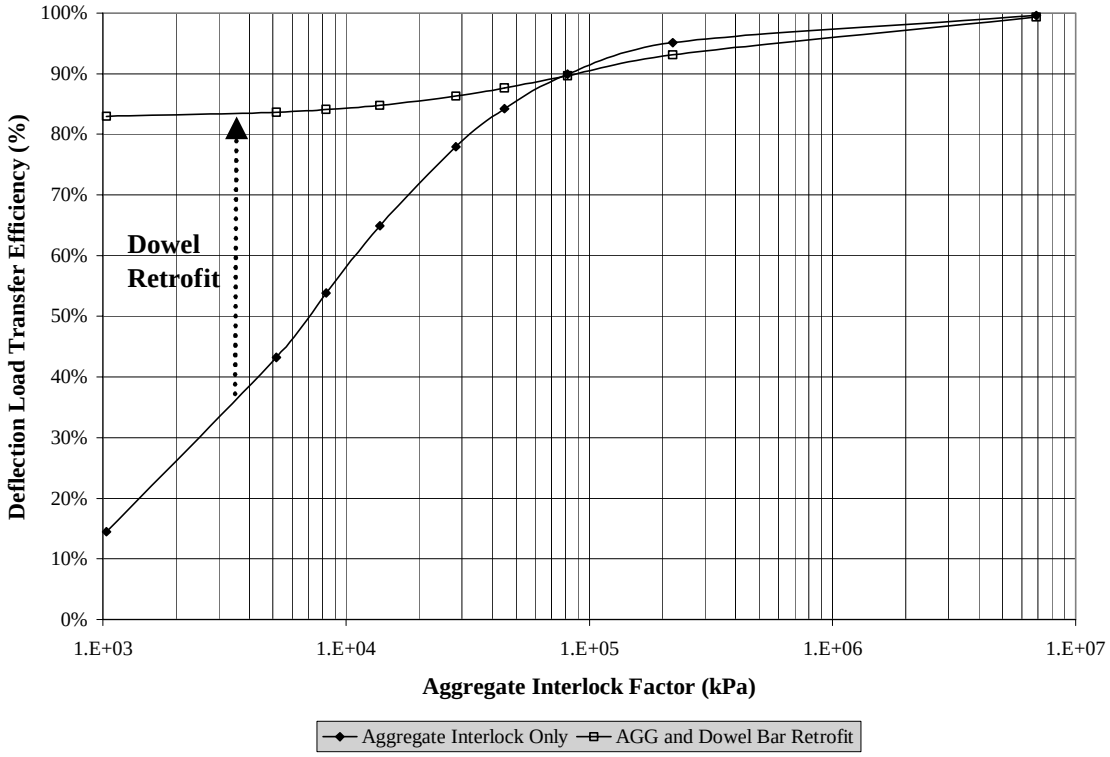

Figure 4. Example of LTE_{δ} Increase for Given Levels of AGG.

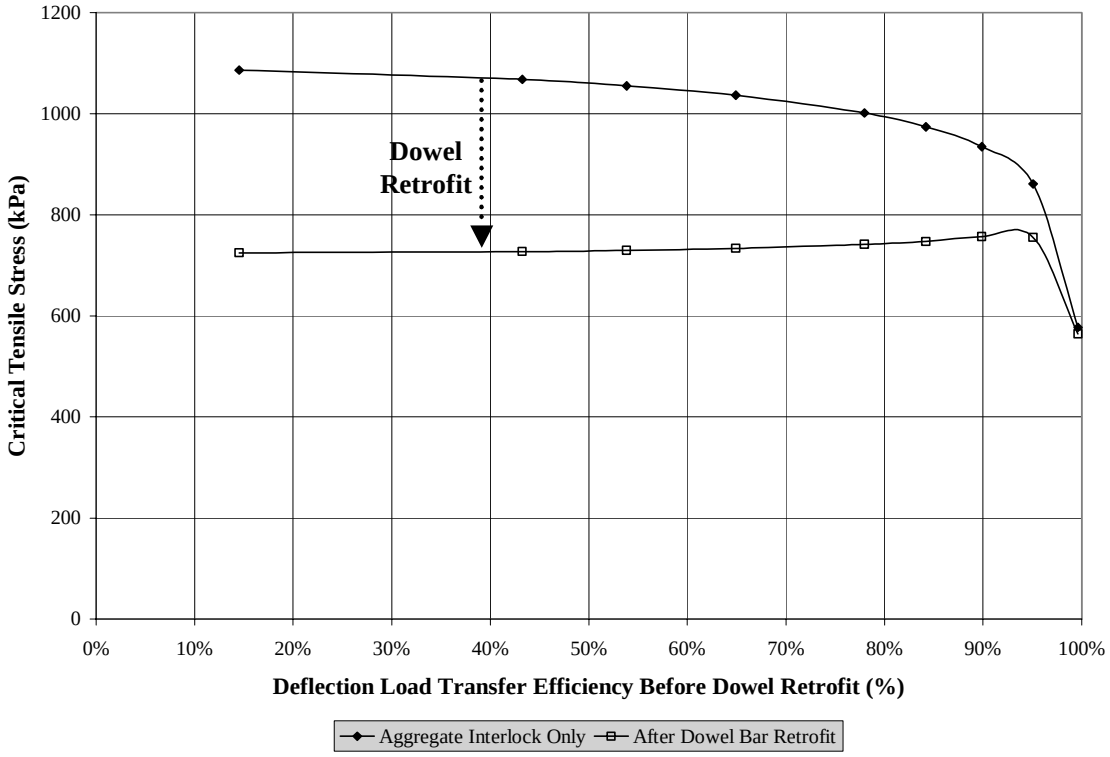

Figure 5. Example of Reduction in Critical Tensile Stresses By Using Retrofit Dowels.

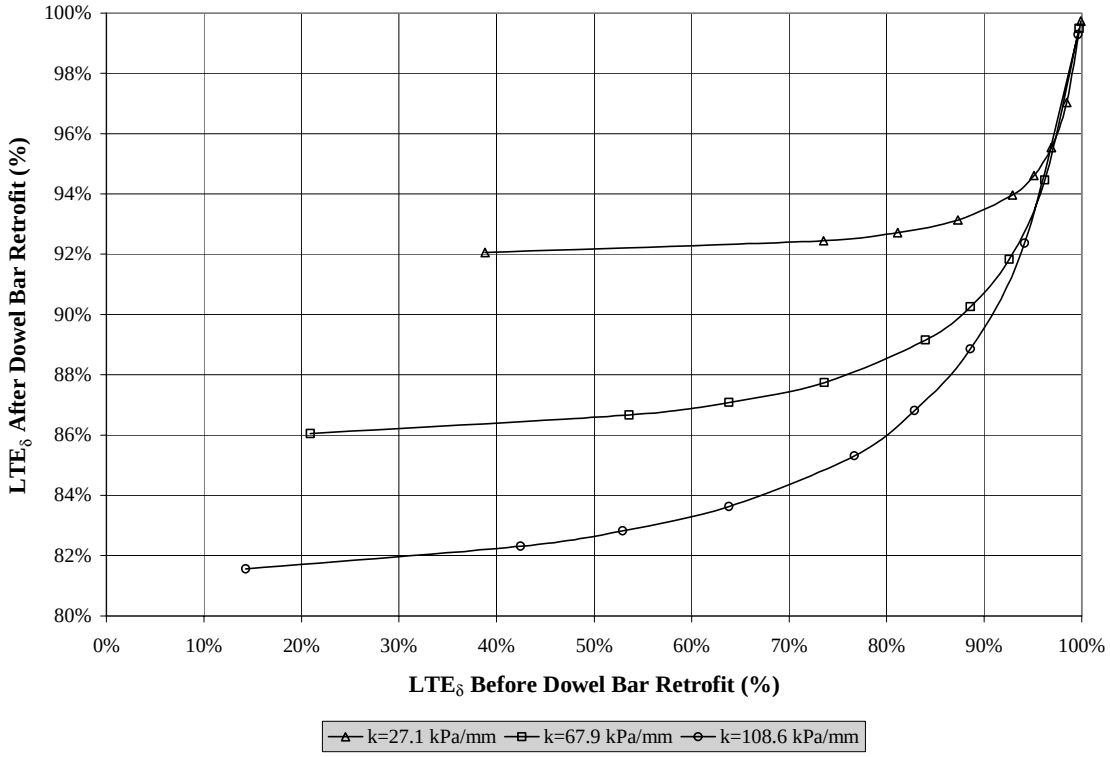

Figure 6. Example of Final LTE_δ for Given Levels of Original LTE_δ.

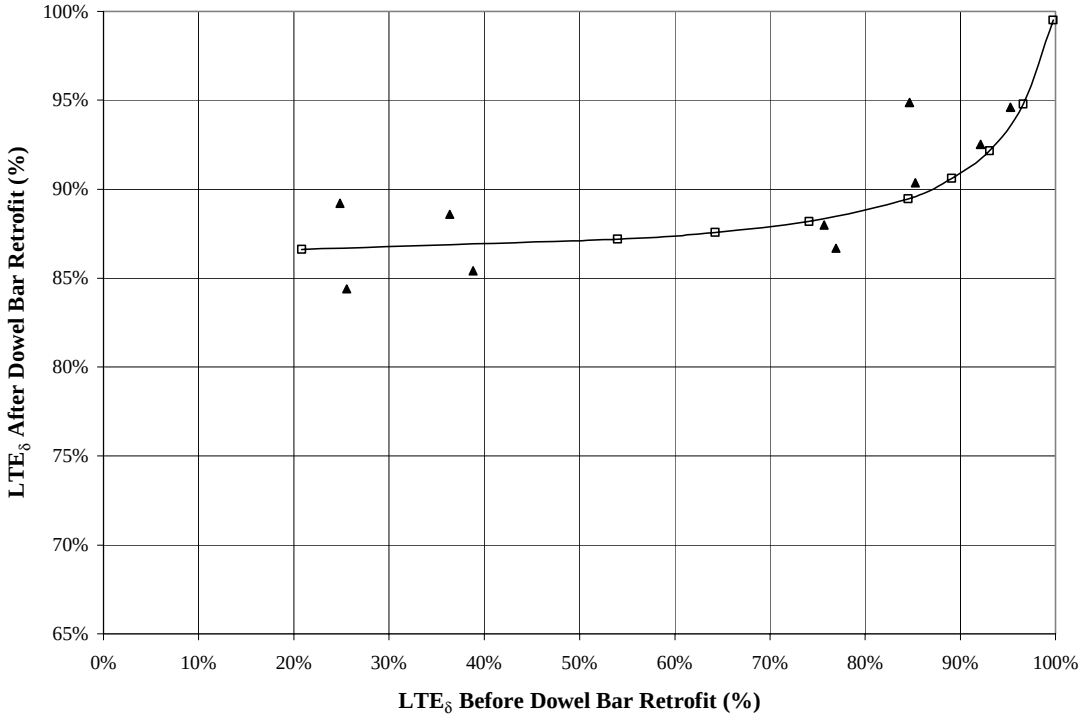

Figure 7. Field Verification of LTE_δ for Dowel Bar Retrofit Site on I-69 in Michigan.

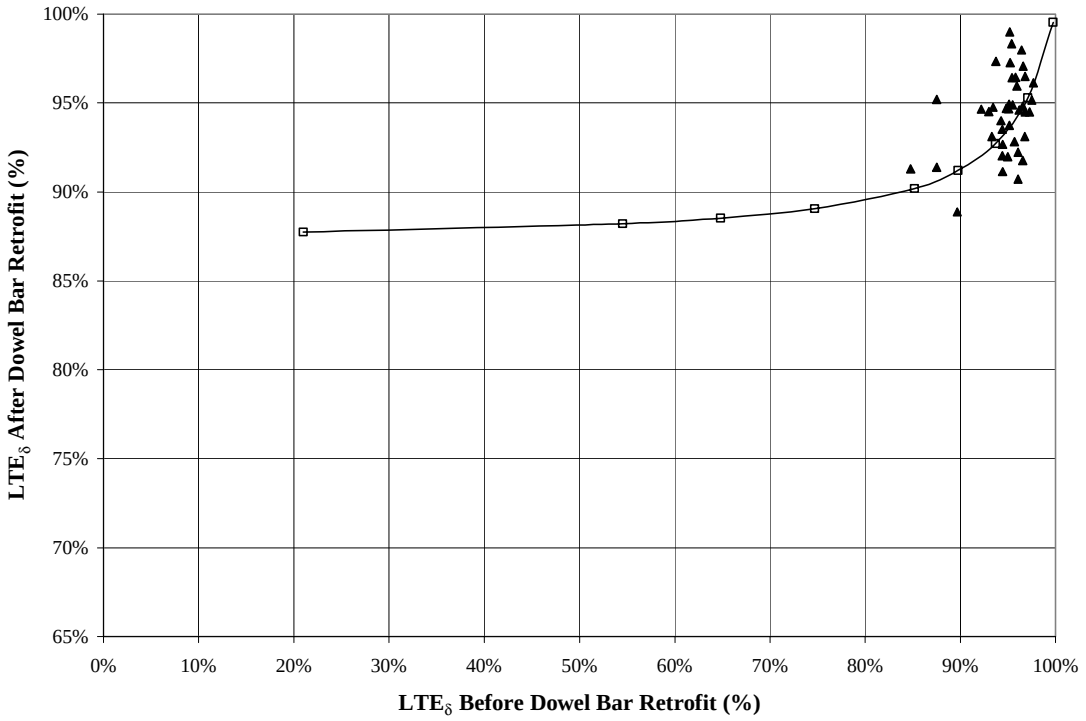

Figure 8. Field Verification of LTE_δ for Dowel Bar Retrofit Site on I-75 in Michigan.

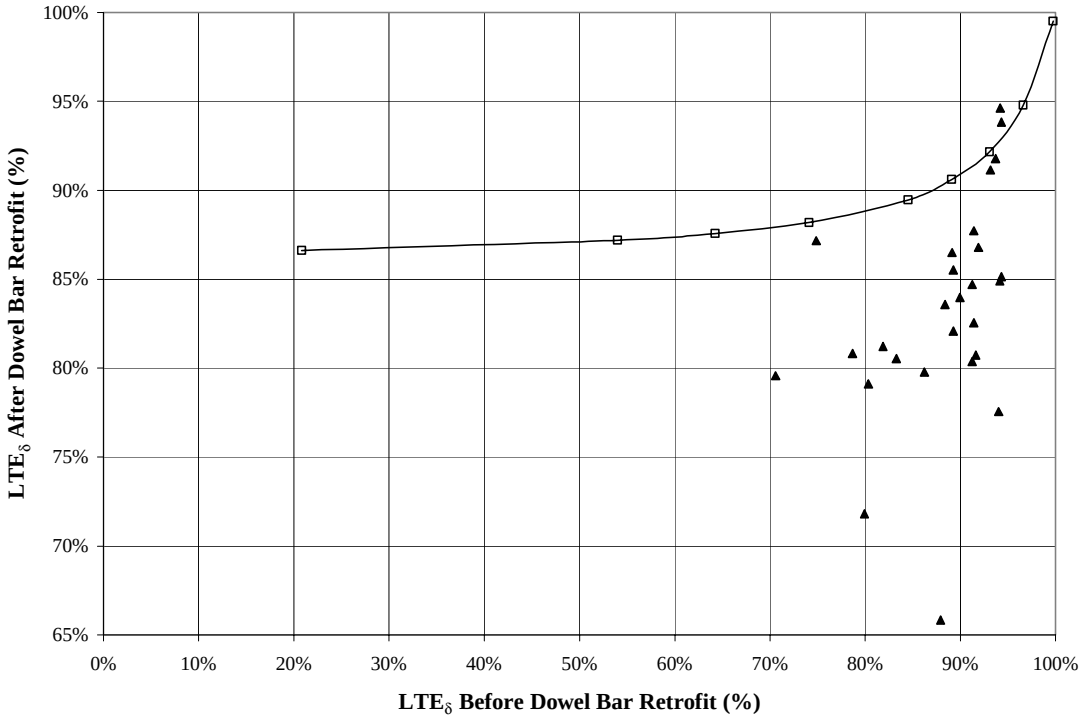

Figure 9. Field Verification of LTE_δ for Dowel Bar Retrofit Site on M-14 in Michigan.



Figure 10. View of Spalling in Grout Covering of M-14 Dowel Bar Retrofit Site.

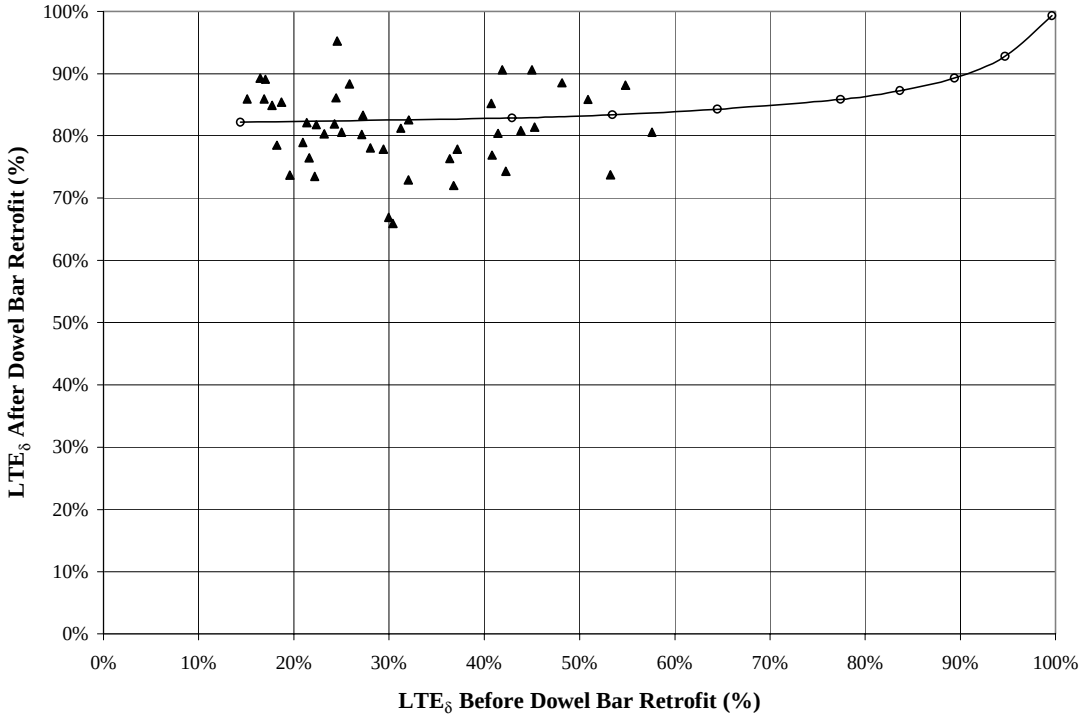

Figure 11. Field Verification of LTE_δ for Dowel Bar Retrofit Site on I-90 in Washington.