USE OF THE TOTAL STATION FOR SERVICEABILITY MONITORING OF BRIDGES WITH LIMITED ACCESS IN MISSOURI, USA

W. Merkle[1], J. J. Myers[1]

[1] Center of Infrastructure Engineering Studies (CIES), Department of Civil Engineering, University of Missouri-Rolla, Rolla, MO 65409, USA

Abstract: As new technologies are increasingly applied to civil infrastructure, the need for structural monitoring systems becomes more critical. Serviceability, or deflection, is very important in monitoring the health of not only a structural system, but also in analyzing the affects of a new technology applied in the field.

A major initiative by the Missouri Department of Transportation (MoDOT) to repair and retrofit five bridges in Missouri required serviceability monitoring through a series of load tests. For these tests, surveying equipment was employed in attempt to make serviceability measurement more practicable since most of the bridges had issues related to limited access for traditional monitoring equipment. Until recently, surveying equipment would not have produced the accuracy required for structural monitoring use; however, manufacturers of this equipment have developed new technologies to increase the accuracy of the instrumentation. The major component used in this study, the total station, can measure deflection accurate to 0.2 millimeters. This monitoring system is much easier to set up and use, reducing labor and time requirements. The system has almost no site restrictions. This paper will discuss the implementation of the total station and contrast its use to traditional load testing monitoring equipment.

Introduction: Load testing is an effective means of evaluating the performance of a structure [1]. In the case of bridge rehabilitation with new strengthening technologies, diagnostic load testing is required to verify the effects of remediation on the bridge [2]. Protocol for load testing should be carefully planned; however, no guidelines for load testing currently exist – testing procedures are to be determined by the organization performing the test [1].

The origin of this study spun out of a current research project at the University of Missouri – Rolla, “Preservation of Missouri Transportation Infrastructure: Validation of FRP Composite Technology through Field Testing”, referred to as the Five-Bridge project herein. The project retrofits five structurally deficient Missouri bridges with Fiber Reinforced Polymer (FRP) composites as the primary strengthening material. Load testing was to be carried out in effort to verify that the FRP strengthening systems were performing as expected [2]. All five bridges were scheduled for load testing biennially for five years following strengthening.

Four of the five bridges were multiple span, simply supported, reinforced concrete Tee-Beam structures. Their tested spans were ten to twenty-five feet high, some spanning water several feet deep. Because of these existing site conditions, traditional serviceability monitoring techniques, like using LVDT systems, would be extremely difficult; the search for a better system was initiated. Figure 1 shows one tested bridge span, with the monitored points fifteen feet above the river below. The fifth bridge was a continuous two-span reinforced concrete slab structure; these spans were only several feet above a dry rocky creek bed, ideal for a comparison between monitoring systems.

Traditional land surveying techniques utilized many components, with the Total Station as the principal device. The total station (Figure 1) was set atop a secure tripod in a location with an unobstructed view of the field targets. Reference points (Figure 2), or backsites, were set in place to transfer a horizontal angle or an elevation from the reference point to the total station, and then from the total station to the targets (Figure 3). The reference points also served to check that the total station had not moved. The reference point was simply a prism mounted atop a secure tripod; the targets were simply prisms fixed atop a metal rod (range pole). In the case of load testing, the prisms were fixed to points on the tested structure.

Figure 1: Leica TCA 2003 set up for Load Testing

Figure 2: Reference Point

Figure 3: Target (Prism) on a bridge

The total station obtained three-dimensional coordinates of every target by measuring a horizontal angle, vertical angle, and distance between points. The Leica TCA 2003 [3] could measure angles accurate to 0.5 arc-seconds (1/7200 degrees) and distances to nearly 1 millimeter, depending on atmospheric conditions. With a horizontal angle, vertical angle, and distance – coordinate geometry was used to transfer three-dimensional coordinates to a target. The total station automatically recorded the coordinates with a point number, point description, date, time, and atmospheric conditions.

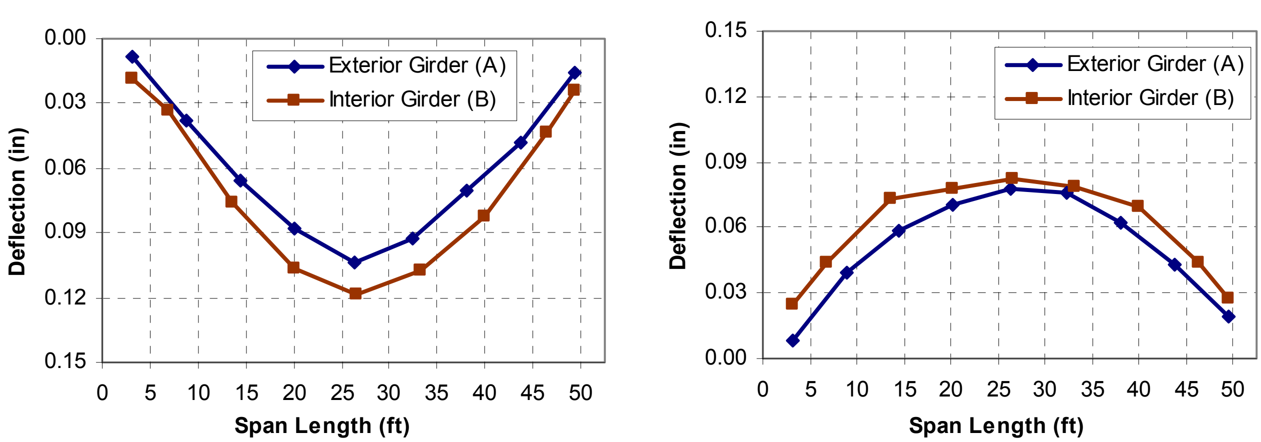
While past load testing showed that Surveying Equipment was not accurate enough to measure small deformations [4], recent advances in technology have made it possible to use surveying equipment to monitor deformation in structural monitoring applications. The new and more accurate Leica TCA 2003 Total Station could measure deformation accurate to 0.2 mm at close range (less than 50 m), making it comparable to traditional systems that use LVDT's. The Leica Total Station was made even more accurate through the use of robotics – the instrument rotated on the horizontal and vertical axes by itself. The instrument also recognized and locked onto targets automatically. The user manually located the targets at the start of testing, and the Total Station automatically relocated the target and measured deformation. Because the instrument was extremely sensitive to vibration and movement, automation helped eliminate human error associated with physical contact during instrument operation.

Procedure Development: While traditional surveying techniques were used as a base for operating the equipment, the higher accuracy required for structural monitoring demanded extra measures to assure desirable results. Most of these additional measures were fairly obvious; the goal was to reduce or eliminate the possibility of undesired instrument and target movement. First, three reference points were used instead of one. Using even more reference points was always a possibility; however, there has never been a discrepancy between all three reference points during testing to date. Second, the tripods holding total station and reference points were firmly set in stable soil. The tripods were far away from all moving objects, mainly people and vehicles, as the slightest ground vibration could induce small settlement or instrument maladjustment. Lastly, the targets were securely fastened to the monitored structure. Again, common sense helped to reduce errors in the field.

The first round of load testing for the Five-Bridge project yielded several issues in using surveying equipment for structural monitoring. First, as mentioned above, the total station was extremely sensitive to movement. The slightest nudge to the instrument or its tripod could displace and rotate the instrument. Keeping the instrument in almost perfectly level was fundamental when monitoring vertical deformation. The instrument automatically stops monitoring if the vertical adjustment (plum) was moving or out of range. Error within this range rarely happened; however, eliminating the error was easily done during data analysis when necessary.

Traditional surveying transferred elevation from one point to another; in the case of structural monitoring, elevation was relative to the instrument. During testing, the instrument located the reference points, followed by all monitored points, and relocated the reference points again. The process was repeated as the structure was loaded and unloaded. During data analysis, the first step was to compare the reference point checks. Instrument or reference point movement was very obvious during data analysis and the error was eliminated, if necessary, by adjusting elevations and transferring this adjustment to the monitored points.

Load testing took much more time using the Total Station because it takes more time to measure (locate all points), compared to LVDT systems. This will be discussed more in depth in the next section. Because of the length of time required to complete a load test, five hours in some cases, the effects of changing thermal gradients were considered and compensated for [5]. Initially, the baseline was established with no-load measurements on the structure at the beginning and end of the load test – done to verify that the monitored points themselves had not moved. Depending on weather conditions and site parameters, a sunny day induced a changing gradient from morning to afternoon. This caused a camber (upward deflection) relative to initial baseline measurements. Often the magnitude of this camber was a large fraction of the deformation under loading, making thermal effects significant in load testing for the project. Figure 5 illustrates the results of load testing bridge X-495 in Iron County, Missouri in July 2003; (a) shows the net camber from start to finish of testing; (b) shows the deformation under a specific load case (truck stop). Assuming that the change in thermal gradient was linear throughout the test, the baseline can be adjusted accordingly for each load case. To verify this assumption, the structure's temperature was taken using a thermal temperature gun, measuring along the depth of the structure in various locations.



Conversion: 1 in. = 25.4 mm; 1 ft = 0.305 m

Figure 5(a): Net Camber

Figure 5(b): Load Test – 2^{nd} Stop

System Comparison: Before implementation, many advantages and disadvantages were known about using the Surveying Equipment in place of LVDT's for load testing project bridges. After the three case studies comparing the two systems, even more issues became apparent.

Setup time of the LVDT system at the bridge site had long been a problem. For spans clearing less than fifteen feet above stable soil, setup time easily took several hours. The soil under the tripods must be compacted, the tripods and LVDT's must be assembled and wired, and the LVDT's must be calibrated prior to use. For a bridge span over deep water or average span height above fifteen feet, scaffolding was mandatory for the LVDT's – adding much more time and effort. For this worst case, the Surveying Equipment was set up in about forty-five minutes (Figures 6 and 7). Every component (soil, scaffolding, and tripods) supporting the LVDT introduces error to the system. Target height and site conditions were practically irrelevant with the Total Station.

Figure 6: Testing Tall Spans

Figure 7: Mounting the Targets

The LVDT system was designed for laboratory use and adapted to be used in the field. Using this system in the field required much more time, effort, and manpower for both preparation and testing. While two people or more set up the Surveying Equipment, one can set up and operate the equipment without much additional effort. Site conditions were critical when using the LVDT system. The electronic equipment required significant wiring and a generator as well. The electrical components were very sensitive to the weather, mainly water, which created obvious problems for load testing bridges. The Surveying Equipment was designed for outdoor use; all components were rugged and waterproof, including the Total Station. The Total Station measured accurately regardless of weather conditions.

Testing time was where the LVDT system regained popularity. If twenty points were monitored on the structure, the Total Station took over twenty minutes to measure while the LVDT system took only a few minutes. If the bridge was heavily travelled, then the road could feasibly be closed for long periods of time. If a twenty-four hour sustained load test was chosen, recommended for in-situ testing by the American Concrete Institute (ACI), then the issue of additional measuring time with the Total Station was eliminated [6]. For rapid load testing, the structure would be loaded and unloaded cyclically multiple times [5]. Rapid load testing was not feasible with the Total Station because of the time required to measure every point.

The LVDT system monitored all points continuously; this was not possible with the Total Station. Continuous monitoring of LVDT's allowed for real-time output. Any equipment problems were noticed during testing and corrected. Real-time monitoring was also not possible with the Total Station; any problems during testing were well documented and later corrected during data analysis. Continuous monitoring allowed for dynamic load testing with LVDT's [7]; again this was not possible with the Total Station.

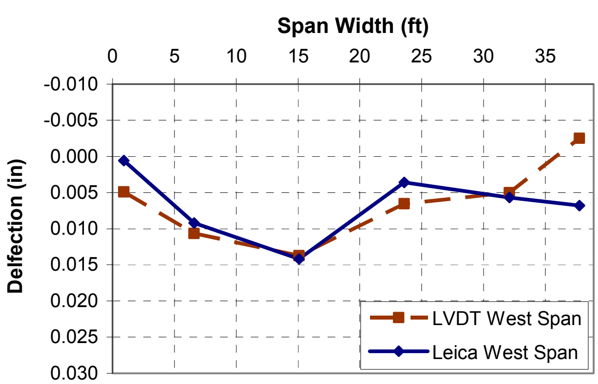
The Total Station used in testing has an internal error directly associated with how accurately it can measure angles and distances. For load testing instrumentation monitoring deformation, it was recommended that LVDT systems have an accuracy of 0.00254 mm (0.0001 in.), or 0.0254 mm (0.001 in.) if dial gages were used instead [2]. For tall spans, it was obvious that the tripods and scaffolding holding LVDT and dial gage instruments would have an error associated with movement due to sway, poor footing, or slipping. More support complexity introduces more error into the system.

Case Study – Field Test 1: The first field test took place at bridge Y-298 in Pulaski County, Missouri. This bridge was chosen for a comparison study due to the easy access underneath the structure, which made setup of the LVDT system relatively easy. Figures 8 and 9 illustrate the low clearance of the substructure, as well as the setup of the LVDT and surveying systems. Setup time for the surveying equipment took about fifteen minutes; setup time for the LVDT system took over sixty minutes.

Figure 8: LVDT's and Prisms

Figure 9: Total Station setup

The load test of bridge Y-298 consisted of four truck stops. During each stop, overloaded MoDOT H20 dump trucks were parked on the bridge in a specified location. Deflection was measured with both systems, in six locations per span, or twelve total locations. However, the LVDT system was only capable of measuring ten points. The Total Station took over ten minutes to measure while the LVDT system took only a few minutes. The time taken by the total station is only a function of how many points are being monitored. The LVDT system measures instantaneously; however, several minutes are allowed initially for the bridge to stabilize under loading [2]. This was ignored with the total station because it spent the first minutes measuring reference points. Figures 10 and 11 illustrate the results of two stops over the west span of the bridge. The plots were typical for all four truck stops during this load test.



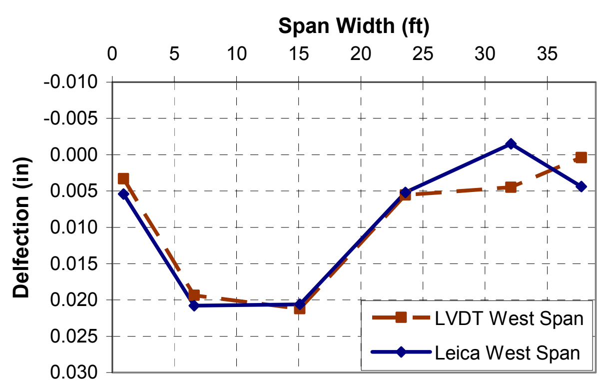


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Figure 10: Stop 1 – West Span Deflection

Figure 11: Stop 2 – West Span Deflection

Forty samples were taken for this comparison between LVDT and Surveying systems. The (absolute) variances between the two systems were as follows: average: 0.076 mm (0.003 in.), median: 0.051 mm (0.002 in.), maximum: 0.305 mm (0.012 in.). The internal accuracy of the total station was 0.051 mm (0.002 in.) for this test. Discrepancy between systems may be due to the setup of the LVDT supporting tripods (Figure 8) – a stable tripod base was fundamental to have acceptable readings. In this case where the tripods sat on rock, slipping was possible but unlikely.

Case Study – Laboratory Test: The first laboratory test utilized three deformation – monitoring systems (String Transducers, LVDT's and Surveying Equipment). The goal of a laboratory comparison was to minimize error by testing under ideal conditions. While the Surveying Equipment was primarily designed for field use, the String Transducer and LVDT systems were not. Stable footings low to a concrete floor (i.e. no tall tripods, no scaffolding), organized equipment (Figure 12), and climate control helped eliminate potential error associated with using equipment outside the laboratory. The Surveying Equipment was adapted to laboratory use without incident (Figure 13).


Figure 12: Laboratory Test Setup

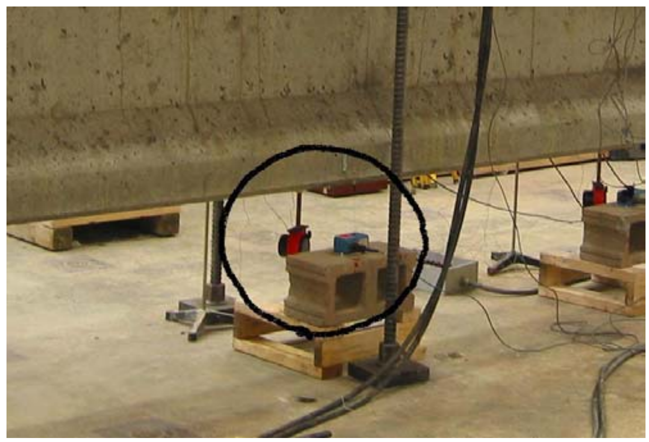


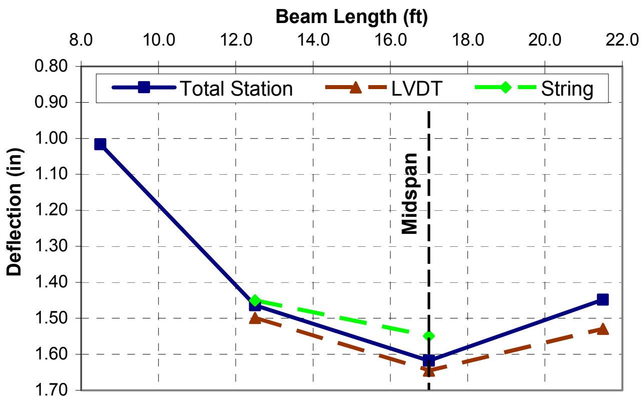
Figure 13: String Transducer and Mounted Prism

The specimen tested was a 10.4 meter (34 ft.) prestressed concrete I-beam. The I-beam was loaded with two load cells, shown in Figure 5. While the String Transducer LVDT systems were set to monitor deflection continuously, the total station could only measure when the load was constant. The Total Station was set to measure three times throughout the test; the results of one measurement are shown in Figure 14. Some LVDT's and String Transducers were not functioning properly, so they were removed from this analysis.

For system comparison during the sampled measurements, the Surveying Equipment was compared to the LVDT system at three locations (nine total samples); the String Transducer system was compared at two locations (six total samples). The mean variance between the Surveying Equipment and LVDT system was 1.02 mm (0.04 in.); the mean variance between the Surveying Equipment and Sting Transducer system was 0.51 mm (0.02 in.); the mean variance between the LVDT and String Transducer systems was 1.52 mm (0.06 in.). At every instance, the measured deflection by the Surveying Equipment fell between the two laboratory systems. Variance between all three measuring systems was consistent, regardless of deformation magnitude.

Error could most likely be due to several sources. First, the string transducers, LVDT's, and prisms were not mounted as close to each other as possible, at a given comparison location. If the instrumentation was not located in the same proximity, torsion/rotation effects could influence the readings. Second, during testing when the load was held constant, it was noted that the load cells do not actually hold a constant load. This was plotted (Load versus

Deformation via LVDT's and String Transducers) after testing, which automatically sets the Surveying Equipment at a disadvantage. However, this does not account for the difference between String Transducer and LVDT readings. Compared to the variances between systems, internal error of the total station was negligible.



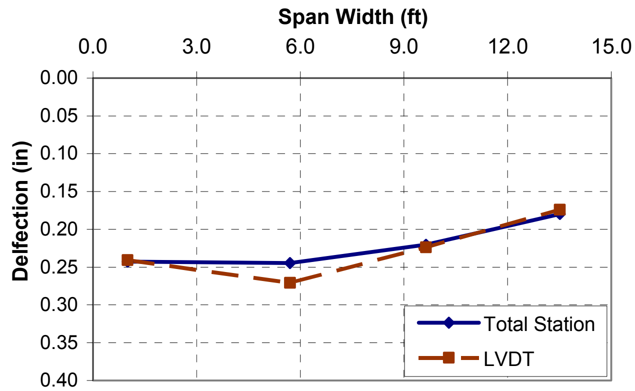


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Figure 14: Laboratory Test Results

Figure 15: Stop 1 – St. John's Street Bridge

Case Study – Field Test 2: The second field test took place at the St. John Street Bridge in St. James, Missouri. This bridge was similar to that in the first case study; there was easy access underneath the bridge and the single span was of low clearance. Unlike the first case study, this bridge had several inches of water and a mud bottom, which made securely setting the LVDT tripods difficult, thus adding to the setup time. For this comparison, the trucks were parked on the bridge twice in specified locations. Figure 15 above illustrates the results of both stops.

Deflection was measured in four locations by Surveying Equipment and the LVDT system (eight total samples). During data analysis, the LVDT at Span Width 1.68 m (5.5 ft) was found to be settling throughout testing (shown in Figure 15), so it was removed from comparison. The average variance between the two systems was 0.076 mm (0.003 in.); the average median was 0.051 mm (0.002 in.). The total station's internal error was 0.051 mm (0.002 in.) in this test, which was assumed to account for the variance between systems.

Conclusions: This paper has presented Surveying Equipment as an alternative means to monitor serviceability of structures during static load testing. With the appropriate equipment and procedure for setup and operation during testing, as well as an appropriate data analysis procedure, Surveying Equipment had an accuracy challenging that of traditional deformation monitoring systems using LVDT's.

While a major setback of using the Surveying Equipment was real-time monitoring. The University of Missouri – Rolla is currently building a new data acquisition system for field use; this new system will integrate several sensors including LVDT's, strain gages, inclinometers and the Total Station. This will make it possible to view data from the Total Station on site in real time during load testing, which will allow the load testing crew to correct any problems encountered immediately. The only major setback will continue to be that the Surveying Equipment cannot be used to monitor serviceability during a dynamic load test.

Future study will also test the application of Surveying Equipment to monitor rotation of a structural component under loading. Inclinometers as well as LVDT's placed horizontally are employed to measure rotation. With two targets at the same cross section, the Total Station can measure horizontal deformation (longitudinal and transverse) to find rotation.

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