Long Term Monitoring of Bridges Using a Robotic Tacheometry System

Eli S. Hernandez, Nestore Galati, John Myers and Antonio Nanni

Department of Civil, Architectural and Environmental Engineering
University of Missouri-Rolla, Rolla, MO 65409
ehd36@umr.edu, cies@umr.edu

Abstract

Field-testing is an important topic in the validation of new infrastructure as well as in the assessment of obsolete and deficient infrastructure. There is a need for accurate and inexpensive diagnostics methods that enable the prediction of the actual load carrying capacity of bridges through load testing. A major difficulty in testing bridges is the measurement of vertical deflections. The use of instruments such as mechanical dial gauges, linear potentiometers, and linear variable differential transducers (LVDTs) is usually not feasible. Access under a bridge structure is usually limited, which requires erecting temporary supports to mount the measurement instruments to the ground. These difficulties can be eliminated by using a Robotic Tacheometry System (RTS) (Total Station), which offers the capability to measure the spatial coordinates of discrete points on a bridge without having to touch the structure.

INTRODUCTION

Robotic Tacheometry Systems, RTS, also called Total Stations (Fig. 1), have been used to measure the movement of structures and natural processes with good results [1,2]. Leica Geosystems [3] quotes accuracies of better than 1mm for their bridge and tunnel surveys where a remote system is used to log measurements six times daily via a modem, with measurements still possible at peak times. Hill and Sippel [1] used a total station and other sensors to measure the deformation of the land in a landslide region. Kuhlmann and Glaser [2] used a reflectorless total station to monitor the long-term deformation of bridges. Measurements were taken of the whole bridges every six years, and statistical tests were used to confirm if the points had moved. Merkle [4] used the total station during the first stage of a 5-year monitoring program to conduct in-situ load testing prior to and after the strengthening of five existing concrete bridges, geographically spread over three Missouri Department of Transportation (MODOT) districts. Hernandez [6] utilized an RTS to conduct a series of nondestructive load tests to measure the deflections of four bridges located on US Highway 151 in Fond du Lac County, Wisconsin. The objective of this program was to evaluate the response of the bridges under service loads and to calibrate the analytical results obtained by the Finite Element (FEM) simulations. The advantages of
using an RTS include the high accuracy as quoted above; the automatic target recognition, which provides precise target pointing [1]; and the possibility of measuring indoors and in urban canyons [2]. Some disadvantages of using an RTS include the low sampling rate, measurement problems in adverse weather conditions [1], and the necessity of a clear line of sight between the total station and the prisms, which makes it difficult to read target coordinates in some cases. A research project aiming to evaluate the feasibility of RTS systems to measure vertical deflections is described here. Five bridges, geographically located in Missouri, were subjected to field load tests. This research describes the systematical methodology developed to measure lateral deflections as well as experimental results and the field validation of this measuring technique.

LONG TERM MONITORING OF FIVE BRIDGES

Field strengthening, using composite materials, of five existing bridges located in Missouri took place during the summer of 2003. The bridges are identified as follows: Bridge P-962 (Dallas County), Bridge X-495 (Iron County), Bridge X-596 (Morgan County), Bridge T-530 (Crawford County) and Bridge Y-298 (Pulaski County). Construction was successfully performed under a team-oriented, design-build-verify format involving UMR, Structural Preservation System, and MoDOT. The various combinations of composite technologies used for each bridge are summarized in ref. [6].

The different strengthening techniques adopted on each bridge required a monitoring program to be conducted biannually during five years [6, 7]. The following sections describe the load test procedure for one of the five bridges (Bridge P-962). The same monitoring methodology was executed for the other four bridges, leading to similar results. The plan involved the load testing of one span of each bridge (three spans in the case of Bridge P-962) by using two H20 dump trucks provided by MoDOT (Fig. 2). To date, seven series of load tests have been conducted. The first three series of load tests were conducted by Merkle and Myers (2003-2004), and more details are found in ref. [4]. The vertical deflection of the interior and adjacent exterior girders was monitored at nine points per girder along the length of the span, and the remaining exterior girder was monitored at one point over mid-span (Fig. 3). The vertical deflections values were obtained for five different loads’ configurations (stops) planned to maximize the stresses of the different superstructures. The trucks were loaded up to 60 kip each, with most of the weight carried by the rear axles. In the case of Bridge P-962, Table 1 summarizes the total truck weight loads as reported by MoDOT personnel.
### Table 1  Truck Axle Loads, Bridge P-962

<table>
<thead>
<tr>
<th>Load Test</th>
<th>Date</th>
<th>Truck 1 (kips)</th>
<th>Truck 2 (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rear Axles</td>
<td>Front Axle</td>
</tr>
<tr>
<td>1</td>
<td>8/14/2003</td>
<td>38.72</td>
<td>13.36</td>
</tr>
<tr>
<td>2</td>
<td>11/17/2003</td>
<td>40.72</td>
<td>17.16</td>
</tr>
<tr>
<td>3</td>
<td>5/05/2004</td>
<td>41.28</td>
<td>13.98</td>
</tr>
<tr>
<td>4</td>
<td>11/10/2004</td>
<td>44.2</td>
<td>16.76</td>
</tr>
<tr>
<td>5</td>
<td>5/04/2005</td>
<td>44.96</td>
<td>13.70</td>
</tr>
<tr>
<td>6</td>
<td>10/20/2005</td>
<td>45.16</td>
<td>20.96</td>
</tr>
<tr>
<td>7</td>
<td>4/10/2006</td>
<td>45.32</td>
<td>14.42</td>
</tr>
</tbody>
</table>

### Equipment Description

The RTS used in this project is a Leica TCA2003 as shown in Fig. 1 (www.leica-geosystems.com). The instrument sends a laser ray to reflecting prisms (targets) (Fig. 1) mounted on the structure to be monitored. By means of triangulation with fixed reference points placed outside the structure, the RTS can determine how much the structure has moved in a three-dimensional array with an accuracy of 0.5 sec on angular measurements and 1mm+1ppm on distance measurements (in average atmospheric conditions).

![Fig. 1 Robotic tacheometry system (left), reference point (middle), target (right).](image)

### Load Test of Bridge P-962

Bridge P-962 (Fig. 2) is located in Dallas County, Missouri (MoDOT District 8). The bridge carries Route B over Dousinbury Creek and sees an average of 350 vehicles daily; load posting for trucks over 36 kip (18 ton) instructed them to travel fifteen miles per hour over the bridge. The bridge was built in 1956 as a Deck Girder/Reinforced Concrete Tee Beam Structure that has three spans, each 42.5 feet long on a 15 degree skew. All spans are simply supported over three Tee Beams spaced 9 feet on center and have a transverse beam at mid-span (Fig. 3). The deck slab is monolithically cast 6 in deep and 23.7 ft wide, and the roadway is 20 ft wide and striped as a two-lane bridge.
Load Test Procedure

The load test methodology followed on Bridge P-962 is described in this section to depict how vertical deflections are monitored by means of an RTS. Before the load test started, marks were made on the asphalt to indicate and ensure an appropriate placement of the trucks following the skew of the bridge (Fig. 4). Once the total station is leveled and acclimatized, initial readings are taken for each target. A “zero reading” (i.e. bridge without trucks) is taken to obtain the benchmark at the beginning (before stop 1) and at the end of the load test (after stop 5). These two reference readings help determine and correct any residual deformation produced during the load test from temperature effects. After the first “zero reading”, the trucks drove to the load configuration of stop 1. At each stop, before acquiring data, five minutes lapsed to allow stable readings. To assure stable measurements, three readings were taken for each target to average out any possible error. Once the readings were taken, the trucks moved to the next stop and the same procedure was repeated.

Fig. 2 Bridge P-0962 in Dallas County (left) and MoDOT dump trucks (right).

Fig. 3 Plan view, and target location details of bridge P-0962, Dallas County.
Load Configurations

Five load configurations were designed to produce maximum stresses on the span tested. The configuration of Stop 1 (Fig. 5a) was assigned to produce maximum shear at span 1. Both trucks were located side by side with their rear axles closed to one end of the span. Truck #1 was centered along lane 1 (Fig. 4), facing north, with the centroid of its rear axles over the first stop line. In a similar fashion, truck #2 was centered along lane 2, facing north, with the centroid of its rear axles over the first stop line. Stop 2 (Fig. 5b) was planned to produce maximum positive moment on span 1. Trucks #1 and #2 were oriented in a similar manner to Stop 1. Stop 3 (Fig. 5c) was designed to produce maximum shear on the north end of span 1. Trucks #1 and #2 were centered as for the configuration of Stop 1. Stop 4 (Fig. 5d) was intended to overload the exterior girder of span 1. Trucks #1 and #2 were centered over lane 2, back-to-back, at the second stop line (Fig. 4). Stop 5 (Fig. 5e) produced the overloading of the interior girder of span 1. Trucks #1 and #2 were centered along the bridge centerline, back-to-back, at the second stop line (Fig. 4). Stop 6 (similar to stop 2) (Fig. 5b) was designed to produce the maximum positive moment over span 2. In a similar manner, Stop 7 (similar to stop 2) (Fig. 5b) was intended to produce maximum positive moment over span 3. The picture of Fig. 2 shows the trucks aligned for Stop 2 of Bridge P-962.

![Fig. 4 Detail of truck stops for bridge P-0962](image)

![Fig. 5 Load configurations of bridge P-0962, Dallas County.](image)
TEST RESULTS

The internal girder’s vertical deflections for Stops 2 and 5 of the first seven series of load tests conducted on Bridge P-962 are shown in Fig. 6 and Fig. 7, respectively.

![Fig. 6 Experimental results for interior girder stop 2, bridge P-962.](image)

![Fig. 7 Experimental results for interior girder stop 5, bridge P-962.](image)

The recorded deflections were normalized by the weight of two H20 MoDOT trucks. Table 2 summarizes the normalization factors computed by using Equation (1) for each of the load tests.

\[
NF = \frac{TW_{test}}{2 \times W_{H20}}
\]

Where NF is the normalization factor, \(TW_{test}\) is the total weight of the trucks (Table 2) as reported by MoDOT personnel during each load test, and \(W_{H20}\) is the weight of an H20 MoDOT dump truck taken as 60 kip.
Load test 1 was executed before the strengthening of the bridges. The results obtained suggest that after the strengthening of the bridge (load tests 2 through 7), there was a slight increment of its stiffness and that the bridge has not experienced any significantly reduction of its stiffness. The plotted data exhibit a smooth transition from point to point and indicate that the readings are accurate; however, the results obtained for load test 6 indicate that some human error might have been present when the trucks’ weights were reported. The difference obtained is not in agreement with the total load applied (Table 2) to the bridge during load test 6. The differences between the results obtained can be attributed to several factors. Although enough care was taken to locate the rear and front axles of the trucks at the same location for the same stop of each load test, a slight variation is present because the axle configuration is not constant for each of the trucks. Other important factors that might influence the results are the way in which the load is distributed in the truck bed during the transportation of the load test vehicles, unknown thermal effects, and rebounding of the RTS during the recording of the experimental data.

CONCLUSIONS

1. The use of the RTS has been validated during the first seven load tests conducted for this monitoring program, confirming its cost-effectiveness for deflection measurement. The fact that the technology allows for non-contact measurement significantly enhances its versatility and gives an alternative that competes with traditional serviceability deflection methods.

2. The deflection data collected by the RTS indicate that the readings are accurate, and the consistency of the readings gives credence to their validity.

3. The strengthening systems implemented on these five MoDOT bridges apparently have not experienced a significant change of stiffness during the last six series of load testing.

4. The correlation of the experimental results is highly sensitive to a slight variation of the trucks’ axle configurations and/or an error committed when the truck’s weight was reported.

<table>
<thead>
<tr>
<th>Test</th>
<th>Truck 1 (kips)</th>
<th>Truck 2 (kips)</th>
<th>TW_{int}</th>
<th>NF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.08</td>
<td>60.26</td>
<td>112.34</td>
<td>0.936</td>
</tr>
<tr>
<td>2</td>
<td>57.88</td>
<td>54.44</td>
<td>112.23</td>
<td>0.935</td>
</tr>
<tr>
<td>3</td>
<td>55.26</td>
<td>55.74</td>
<td>111.00</td>
<td>0.925</td>
</tr>
<tr>
<td>4</td>
<td>60.96</td>
<td>59.54</td>
<td>120.50</td>
<td>1.004</td>
</tr>
<tr>
<td>5</td>
<td>58.66</td>
<td>58.82</td>
<td>117.48</td>
<td>0.979</td>
</tr>
<tr>
<td>6</td>
<td>66.12</td>
<td>66.12</td>
<td>132.24</td>
<td>1.102</td>
</tr>
<tr>
<td>7</td>
<td>59.74</td>
<td>59.48</td>
<td>119.22</td>
<td>0.994</td>
</tr>
</tbody>
</table>
ACKNOWLEDGMENTS

This project was made possible with the financial support received from the Missouri Department of Transportation (MoDOT), the UMR University Transportation Center (UTC) and the NSF Industry/University Cooperative Research Center based at UMR. Hughes Brothers, Seward, NE, Sigmatex, Benicia, CA, and Toray America, Decatur, AL, provided the FRP materials. Hardwire LLC, Pocomoke City, MD, provided the SRP material. Structural Preservation System, Chicago, IL, was the contractor and Co-Force America, Rolla, MO, was the designer. The authors would also like to thank Alexis Lopez, Travis Hernandez, Russ Quintero, Wesley Merkle, Filippo Masetti, and Andrea Rizzo for their assistance during the execution of the load tests of the five bridges described in this document.

REFERENCES