Suspender Cable Inspection Using Advanced Robotic Technology at Arrigoni Bridge

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ABSTRACT: This paper covers the suspender cable inspection of Arrigoni Bridge 00524 using the advanced robotic technology - RopeScan®. This technology uses a Laser Vibrometer to determine the actual tension forces of the suspension cables under deadload conditions without any interference to traffic and minimal inconvenience to the traveling public.

INTRODUCTION

OVERVIEW

The Arrigoni Bridge is a thirty (30) span steel through arch structure carrying Route 66 over Route 9, the Providence and Worcester Railroad and the Connecticut River between Middletown and Portland, Connecticut. Opened in 1938, the bridge was the most expensive bridge ever built in Connecticut, at a cost of $3.5 million. Its two distinctive 600 feet (180 m) steel arches have the longest span length of any bridge in the state. The Connecticut River is the largest waterway in the state and the most important in this area. It is a major navigable river with some barge and recreational traffic. This location is an important crossing and because of its security and strategic concerns all work on the structure must be coordinated and cleared with the Department of Homeland Security and the Coast Guard in addition to the Town Police.

The bridge has a structure length of 3,428 ft., a curb to curb width of 44.8 ft. and two 4.8 ft. wide sidewalks along each side. The structure consists of twenty-eight (28) deck girder and floor beam approach spans with a reinforced concrete deck and two (2) 600 ft. tied steel thru truss arch main spans with a

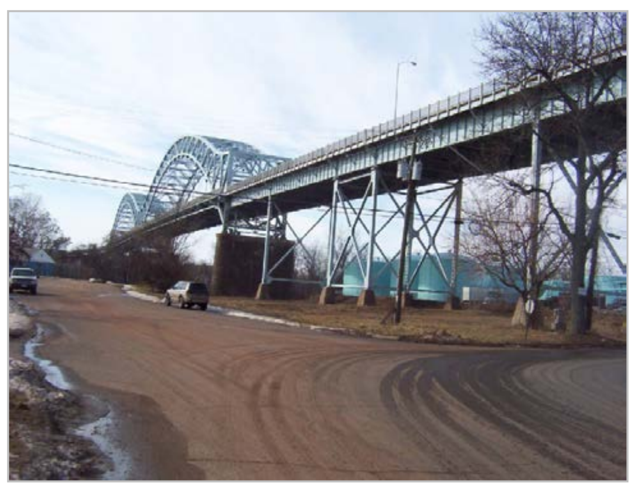


FIGURE 1 – Arrigoni Bridge, South Elevation from Portland Side

concrete filled steel grid deck. This bridge carries four (4) lanes of traffic (two each way) with no physical separation and no shoulders. The bridge was rehabilitated in 1994 and 2012 which consisted of structural steel repairs and replacement of the suspender cables and minor substructure repairs.

FIGURE 2 – Arrigoni Bridge, Middletown

The bridge receives the usual biennial NBIS inspections every two years, including visual inspections of the 14-inch diameter steel pins, the cable hangers and the zinc sockets at the ends of each hanger cable. For this in-depth inspection, it was desired to include the inspection of the steel suspender cables in the main spans using the non-destructive method which is electromagnetic in nature, more commonly known as; Magnetic Flux Leakage (MFL) and determining the tension forces of the suspender ropes which connect the bottom chords of the through-truss to the floor beams.

AI Engineers, Inc., (AI) was tasked by the Connecticut Department of Transportation (ConnDOT) to perform the testing of the suspender cables in the mains spans (spans 10 and 11) using the non-destructive method which is electromagnetic in nature and determining the tension forces of the suspender ropes which connect the bottom chords of the through-truss to the floor beams of the bridge. AI reached out to various Non-Destructive Testing (NDT) firms to determine what kind of expertise each would bring to bear on this important task.

SCOPE OF WORK

AI prepared a scope for approval by the Department to complete the proposed inspection. The scope approved by the Department was in two sections, one regarding the work to be completed by AI, the prime consultant and one the specialized testing company for the testing of cables.

Scope of Work for Prime Consultant (AI)

- Perform data collection and all pertinent work necessary for the completion of the testing program
- Review existing scope of work, revise and finalize for the Department's approval
- Solicit, obtain and analyze quotes for the Departments' approval
- Coordinate with the Department and other Contractors, Subcontractors
- Coordinate with Homeland Security, the Coast Guard, State police, the Police Departments of Middletown and Portland
- Get Contractors' personnel approved
- Provide oversight of the testing process: a senior engineer (Team Leader) from AI must be present during the entire testing procedure
- Prepare and submit reports to the Department

Scope of Work for Contractors

Examine the entire length of each

- suspender cable (Total 17 x 4 x 4 – 272 vertical with lengths ranging from minimum 6 ft., up to 100 ft.)

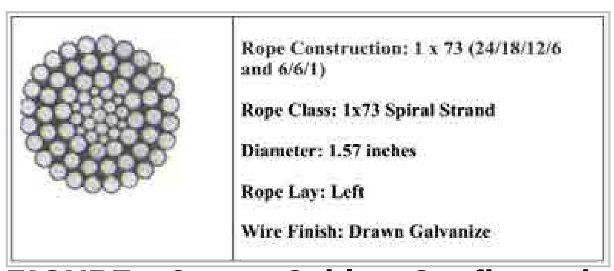


FIGURE 3 – Cable Configuration (Typical

- Electromagnetic inspection of suspender cables using state-of-the-art digital instrumentation
- Using the method which will be able to detect all damage mechanisms frequently occurring in wire ropes, both internal and external, i.e. broken wires, corrosion, wear, fatigue, abrasion, etc.
- Maximum sensitivity of the method should be 0.2% to 0.5% of the metallic cross section
- The extent of the inspection was from sidewalk level to the top attachment
- Recording data digitally for analysis, permanent record and future reference
- Cable vibration measurements (tension force in cable) using the latest state-of-the-art structural testing system
- Determination of tension force, resonant and natural frequencies of each cable
- Providing results in graphical and tabular including acceleration history, power spectral diagram plot and linear regression fit line for a much more in-depth look at each of the cable behavior

CONTRACTORS

The scope of work was sent out with requests for quotes to several potential bidders. Several responses were received, and AI analyzed the quotes and recommended for approval by the Department.

Infrastructure Preservation Corporation (IPC) of Washington, DC was selected to perform the non-destructive testing of the cables due to their state-of-the-art RopeScan Robotic Inspection System and Laser Vibrometer Type PSV-150 for tension force measurements.

PRE-INSPECTION & TESTING

DATA COLLECTION

AI obtained and reviewed the following:

1. Existing structure plans
2. Most recent inspection reports
3. Most recent load rating reports
4. Previous cable testing reports
5. Recent maintenance memoranda
6. Correspondence of previous repair/rehabilitation

PLANNING

Proper planning and scheduling of the cable inspection activities promotes the effective and efficient completion of this monumental task. AI started the process by reviewing the documents collected as stated above and conducted site visits in order to get familiar with the structure.

AI coordinated with IPC team and scheduled the testing with the help of providing one of AI's Team Leader (senior engineer) to oversee the entire testing process. Also, AI coordinated with the Town police and notified in advance about the testing during the day and nighttime.

SECURITY

AI coordinated with the Coast Guard and Homeland Security regarding the scheduling of the inspection operations over an important navigable river. All the names of the personnel from AI and the contractor anticipated to participate in the inspection operations had to be submitted to the Coast Guard for prior security clearance and approval.

FIELD WORK

Electromagnetic Inspection of the Steel Suspender Cables

The purpose of this MFL inspection was to establish the overall condition of the suspension ropes, determine the presence any abnormal condition, such as; the presence of corrosion, loss of metallic section, broken wires, and the extent of same, within metallic area of the suspender ropes, and locate & document any and all issues of concern within the suspension ropes for future comparison within a comprehensive inspection report. The nondestructive method utilized was electromagnetic in nature, more commonly known as; Magnetic Flux Leakage (MFL).

IPC under the supervision of one of the AI Team Leader (senior engineer) performed the testing of the suspender ropes located in Spans 10 and 11 which connect the bottom chords of the through-truss to the floor beams. All MFL testing was performed by a certified Level II inspector and a mechanical engineer.

Testing Equipment

IPC performed the inspection using its RopeScan Robotic Inspection System. RopeScan is a stand-alone, battery operated, self-propelled wireless inspection system. It uses a clamshell approach to attach to the ropes. It is remote controlled and transmits test data to the ground station while scanning the rope for real-time viewing. RopeScan's tractor system can scan 70ft per minute with a mount and dismount time of one minute.

FIGURE 4 – RopeScan Testing System

A hand-held remote control was used to ascend and descend of RopeScan as it performs an inspection using MFL. The average time to test four ropes was approximately 20 minutes.

On-Site Calibration

RopeScan was calibrated at the beginning of each day. A small wire representing a 1.2% section of the rope was attached to the outside of the rope. As RopeScan passed over the calibration rod the screen reflected an amplitude equal to the 1.2% increase in mass. This represents 0.4842 sq. inches of the rope.

FIGURE 5 – Showing On-Site Calibration

Testing Procedure

The ropes were tested in sequence from Rope 1 through Rope 4 in each bundle. Each rope was scanned twice to ensure redundancy during post-processing. RopeScan ascended the rope and tested the rope during it descend. All distance measurements start at the top of the rope and increase as RopeScan descended. As the instrument moved along the cable, the operator, on an associated computer screen, watched the section properties of the cable in real time and could identify and locate where a single wire had broken or had section loss.

All scans were verified before each rope bundle. The entire length of each cable except the cables supporting ladders was inspected and documented.

Post Processing

The scans were processed independently and then compared. Indications on one scan that shows up in the second scan in the same location indicates a flaw in the rope. The flaw is then processed to determine broken wires and loss of metallic area.

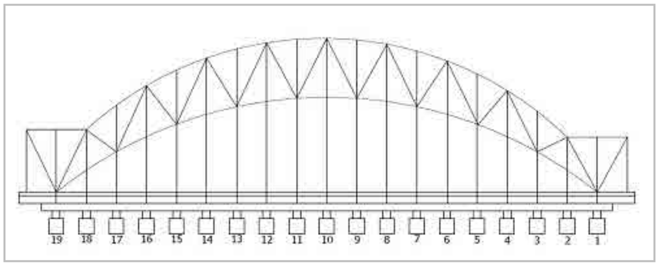


FIGURE 6 – Span 10, North Elevation (Schematic View)

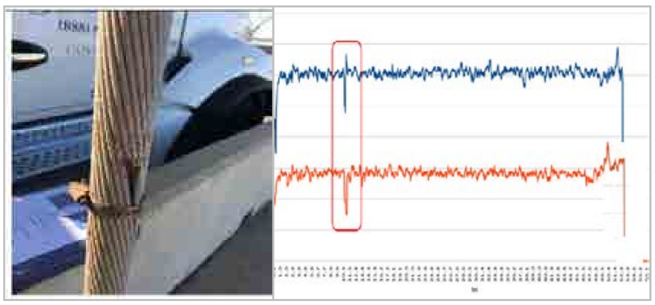


FIGURE 7 – RopeScan Indicating a Broken Wire on Cable

Verification of Testing Data

The testing data for broken wires (as shown in Figure 7) or any flaws in the cables was then verified against the field visual observations at the time of inspection and a previously conducted similar study/testing in 2007 on this bridge. On comparison it showed the testing was able to detect all the broken wires and flaws in the cables as noticed in 2007 testing and visual findings (including any new findings) at the time of inspection. The comparison further proved the reliability and precision of testing data. The Department was notified of the above findings and a re-evaluation of the load rating with the reduced section is in process.

Tension Force Measurements of Suspender Cables

The objective of the measurement was to determine the actual tension forces of the suspension cables under deadload condition. To complete the task, the following criteria was developed:

- Measurement of the vibration signature of each cable at night time to reduce the influence factor of traffic load.
- Use forced excitation to reduce the measurement time to a minimum and to allow excitation of multiple modes.
- Use a stochastic subspace identification method (SSI) to overcome the frequency resolution limit of a fast fourier transformation (FFT) analysis unless very long measurement intervals are selected.

Method of Measurement and Analysis

All measurements were conducted by using a Laser Vibrometer Type PSV-150. The advantages of using a Laser Vibrometer versus accelerometer system is the speed of mobilization and the ease of use. While accelerometers must be physically mounted onto the structure to obtain a vibrational reading, a Laser Vibrometer only requires pointing of the Laser beam onto the location where the measurement shall be taken.

The measurement was contactless and locations up to 200m (600ft) distance was measured without physically attaching any device or target onto the object of interest.

FIGURE 8 – Tension Force Measurement of Suspender Cables

This allowed for a very quick mobilization on site and a very fast production rate, executing the measurements. The measurement for each cable consisted of the following steps:

- Locate the Laser Vibrometer Laser spot at approximately 1/3 point of the cable to be measured.
- Confirm at the Laser Vibrometer that there is a good noise-to-signal ratio, if necessary, adjust instrument and location.
- Check traffic situation and start the measurement only if there is no truck traffic and limited or no vehicular traffic.
- Initiate the forced excitation by hitting
- the cable to be measured with a rubber mallet 3 times with a spacing of approximately 1 second between blows.
- Wait approximately 1 second after the last blow to allow the induced shear wave to dissipate enough that the measurement can be started.
- Start the measurement with the Laser Vibrometer and observe the FFT analysis for immediate feedback if the measurement is showing multiple modes of the cable.
- Repeat the measurement at least 3 times to create 3 separate data sets for each cable to allow for data conclusiveness.
- Repeat measurement if required and move to next cable.

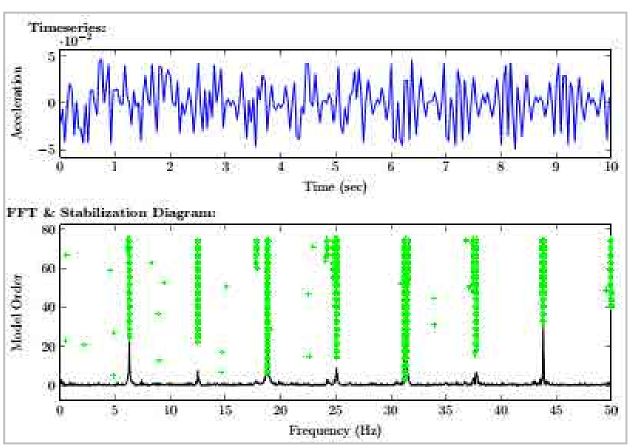
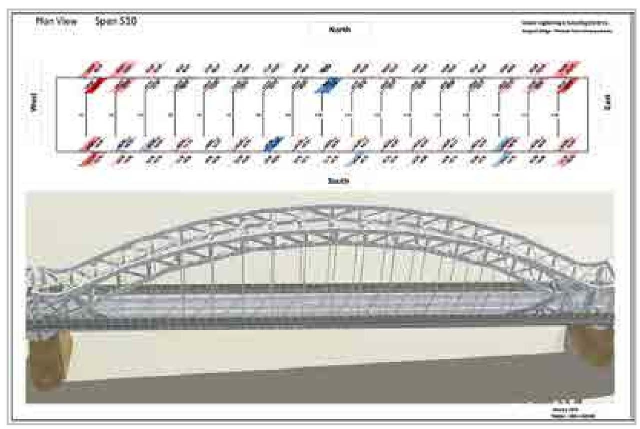


FIGURE 9 –Cable Frequency Analysis Report

The data sets were analyzed individually, and the best dataset was selected for final analysis. Modal frequencies were extracted by using a stochastic subspace identification (SSI) method in parallel to a classic FFT analysis as shown in Figure 9. The frequencies obtained from the SSI method were used to develop a linear analysis by minimizing the least squares. The result from the linearization of the modal frequencies was the first mode of the cable. This first mode frequency was then used to calculate the tension force by utilizing the taut string theory equations and further conversion to Kips. The design forces (38 Kips) for the cables were taken from the cable shop drawings. Figure 10 shows the tension force for each cable with forces shown in red are greater than 38 kips and those shown in blue



are less than 38 kips.

FIGURE 10 – View of Bridge with Cable Force Indication

Verification of Results

The results were compared to a 2013 study conducted by University of Connecticut (UConn). The study assumed certain parameters (cable length, cable parameters, etc.) in the calculations which were altered during our calculations. Also, the 2013 study used a simple FFT analysis for the determination of natural frequencies (modes) of the cable assemblies, our frequency calculation was based upon an SSI method to obtain those frequencies. While both methods are equally acceptable it was important to eliminate all external factors during the measurement. The 2013 data was acquired during daytime where live load (traffic) may have increased the tension forces in the suspender cables with a dynamic component. The dynamically changing loads will result in a dynamic response of the natural frequencies and therefore in a modal frequency band for each mode in the measurement. In addition, a longer measurement will capture all dynamic events during the data acquisition window. Typically, longer measurements are required using FFT analysis for a reasonable frequency determination. Determining the actual 1st mode frequency with linear optimization will therefore result in a potentially shifted 1st mode, depending on the live load influences. We executed the measurements at night time with very low (vehicular) traffic influence (or no traffic influence) and the suspender cables were excited by forced excitation. This allowed to minimize the data acquisition time and minimize the live load influence to obtain a narrow-banded frequency response from the cables. This resulted in significant variations between the 2013 study results and existing results.

The results were also compared with the design forces (calculated from the shop drawings) and showed variations since 1935 to the time of inspection which were within+/-5% of the actual forces the cables experience under dead load conditions as shown in Figure 11 (as an example for one of the cable). This proved that the methodology used in data acquisition during the testing is reliable and precise.

Span	Cable	Bundle ID	Calculated T-Force	Design Load (Deadload)	Over/Under	Total per Cable Bundle	Over/Under
			Kips	Kips	Kips	Kips	Kips
				Per cable (152/4)			Per bundle
10	S8	1	37.87	38	-0.1		
		2	39.94	38	1.9		
		3	29.77	38	-8.2		
		4	50.62	38	12.6	158.2	6.2

FIGURE 11 –Comparison of Tension Forces

CONCLUSIONS

The steel suspender cables tested and inspected were found to be in fair to good condition. Over 93% of the cables tested showed less than 1% cross-section loss. For the remaining 7% of the cables, signs of broken wires, loose wires and moderate corrosion were observed. The testing results were validated against the 2007 testing findings for reliability and precision. There were no indications that required immediate attention. Through the tension force test, variations found in some of the cables between the design forces from 1935 to the time of inspection. Some of the cables exceed the 38Kips design load with some of the cables showing loads of more than the design loads while other cables in the same bundle show a lower tension force. This is due to the reason that the cable bundles were not equally loaded, and an unequal load distribution is present.

AUTHOR

Muhammad Asif Iqbal, PE is the quality control / quality assurance manager and assistant project manager for the Connecticut DOT Biennial Bridge Inspection Program by AI Engineers, Inc. of Middletown, CT.

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