INSTRUMENTED MONITORING AND MODELING OF WAS-339-2013
PRIOR TO, DURING, AND AFTER SUPERLOAD

SJN:14788(0)

Final Report Submitted to the
Ohio Department of Transportation

by

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April 2004
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EXECUTIVE SUMMARY

Several superloads were scheduled to cross a bridge at the Muskingum River along Route 339 near Marietta (WAS-339-2013) in the Summer of 2001. The largest of these (883,488 lbs. or 400,750 kg) was the biggest superload in recorded Ohio history. A new power plant was being constructed nearby and huge pieces of equipment were to be transported to the site. However, a BARS-based software analysis conducted by the Structural Engineering Office of the Ohio Department of Transportation revealed possible overload conditions in connection with these load/structure combinations. A permit would not be issued without further evidence of the actual load capacity of the bridge.

The bridge in question (WAS-339-2013) is a 2-lane, 6-span, 650-feet (198.250 m) steel-stringer bridge with a reinforced concrete deck, built in 1963, crossing the Muskingum River. The University of Cincinnati Infrastructure Institute (UCII) was contracted to instrument the bridge with strain transducers and conduct a series of controlled experiments with loaded dump trucks to determine the load carrying capacity of the structure. Linear superposition was used to then evaluate and verify the capacity of WAS-339-2013 for the superload passage.

In addition, a set of three of the superload passages were monitored. The various superload liveload responses measured were within 10% of the truckload-based predictions. A maximum stress of 10 ksi (44.50 kN) occurred at the piers and midspans of the bridge, with some temporary loss of the unintended composite action between the steel girders and the concrete decking. Minor permanent damage was observed (e.g., transverse cracking in the roadway). The loads arrived without incident.
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</tr>
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</tr>
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<tr>
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</tr>
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<td>Effective Area of the Concrete Decking, in ratio ( n_{eff} ) to the steel strength, using the specified ( b_{eff2} ), for the location under consideration</td>
</tr>
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<td>Area of the Steel Reinforcement, for the location under consideration</td>
</tr>
<tr>
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</tr>
<tr>
<td>AASHTO</td>
<td>American Association of State Highway and Transportation Officials</td>
</tr>
<tr>
<td>ACI</td>
<td>American Concrete Institute</td>
</tr>
<tr>
<td>ASCE</td>
<td>American Society of Civil Engineers</td>
</tr>
<tr>
<td>ASD, ASM</td>
<td>Allowable Stress Design or Method</td>
</tr>
</tbody>
</table>
Effective Width of the Concrete Decking, AASHTO Spec. 10.38.3

Effective Width of the Concrete Decking Derived by Analytical Method 2

Width of the Girder Flange, for the location under consideration

Bridge Analysis and Rating System

Capacity, in regards to bearing a load

Centerline, line to denote the geometric center between two parallel lines

Depth or Height of the Girder, for the location under consideration

Design Value, as specified by the plans or by design analysis

Deadload (i.e., the effect of self weight)

Distance between Truck Axle # and (#-1) (e.g., d2 is distance between truck axles 2 and 1)

Distribution Factor, as per AASHTO Spec. 3.23.2.2

Young's Modulus of Elasticity for Concrete Decking

Young's Modulus of Elasticity for Steel

Force or Weight of Truck Axle # (e.g., f2 is the weight of truck axle 2)

Yield Force for the Concrete Decking

Cut-Off Frequency, of the lowpass filter to remove high frequency noise

Natural Frequency, first/lowest vibrational mode of the bridge

Feet, unit of Length

Yield Force for the Steel Girder

Yield Force for the Steel Reinforcement

Finite Element Model

Fast Fourier Transform, a processing algorithm for frequency domain representation of a measured time signal

Federal Highway Administration

Height or Depth of the Girder, for the location under consideration

Design Load Designations, as per AASHTO Spec. 3.7

Design Load investigated, as per AASHTO Spec. 3.7.6

Hertz, unit of Frequency

Effective Inertia of the Composite Section Derived by Analytical Method # from Truckload Measurements, in ratio n_eff to the steel strength, for the location under consideration

Effective Inertia of the Concrete Decking, in ratio n_eff to the steel strength, using the specified b_eff, for the location under consideration

Effective Inertia of the Concrete Decking, in ratio n_eff to the steel strength, using the specified b_eff2, for the location under consideration

Inertia of the Steel Girder, for the location under consideration

Effective Inertia of the Composite Section, in ratio n_eff to the steel strength, for the location under consideration

Impact Factor, as defined by AASHTO Spec. 3.8.2.1

Inch, unit of Length

Cubic Inch, unit of Volume

Ratio of Moment Arms from the Section Centroid to the Sensor Locations Derived by Analytical Method # for the Section from Truckload Measurements, for the location under consideration

Scaling Factor for Analytical Bridge Rating, as recommended by NCHRP Manual for Bridge Rating Through Load Testing, Lichtenstein

Ratio of Moment Arms from the Girder Centroid to the Sensor Locations for the Section from Truckload Measurements, assuming Noncomposite Action, for the location under consideration

Kilogram, unit of Force
kip  One Thousand Pounds, unit of Force
kN   Kilo-Newton, unit of Force
ksi  Kips per square inch, units of Stress
L    Span Length, for the span under consideration
L    Liveload (i.e., the effect of traffic load)
lbs  Pounds, unit of Force
LF#  Load Factor, for load # (e.g., 1 = Deadload, 2 = Liveload)
LFD  Load Factor Design
LRFD Load and Resistance Factor Design
m    Meter, unit of Length
m/s  Meters Per Second, unit of Speed
M#   Moment Derived by Analytical Method # for the Section from Truckload
      Measurements, for the location under consideration
Mij  Moment for Girder I under load in lane J
M\text{ASinv} Yield Moment with the Inventory Safety Factor, for the location under
      consideration
M\text{ASopr} Yield Moment with the Operating Safety Factor, for the location under
      consideration
M_{d}  Moment for the Concrete Decking from Truckload Measurements, assuming
      Noncomposite Action, for the location under consideration
M_{DL}, M_{DLoad}  Deadload Moment, as determined by analysis and given deadloads,
      assuming Noncomposite Action, for the location under consideration
M_{D\text{Eff}} Effective Deadload Moment, as determined by scaling the determined
      deadload moment \( M_{DL} \) by the ratio of section moduli \( S_{LL} / S_{DL} \), for
      the location under consideration
M_{s}  Moment for the Steel Girder from Truckload Measurements, assuming
      Noncomposite Action, for the location under consideration
M_{SDL}, M_{SDLload} Superimposed Deadload Moment, as determined by analysis and given
      deadloads, assuming Noncomposite Action, for the location under consideration
M_{SDL\text{Eff}} Effective Superimposed Deadload Moment, as determined by scaling the
      determined deadload moment \( M_{SDL} \) by the ratio of section moduli
      \( S_{LL} / S_{SDL} \), for the location under consideration
M_{Ult#}, M_{Ultimate#} Ultimate or Plastic Moment Derived by Analytical Method #, for the
      location under consideration
MEGADAC Data collection system, Optim Electronics, Germantown, MD
MPa  Mega-Pascals, unit of Stress
mph  Miles Per Hour, unit of Speed
N    North, compass direction
n_{\text{eff}} Strength Ratio of the elastic moduli, \( E_s / E_c \)
N_{\text{f}} Number of the Steel Reinforcement, for the location under consideration
NAxis Neutral Axis, location of zero stress in the section under bending
NBIP National Bridge Inventory Program
NCHRP National Cooperative Highway Research Program
NDT Nondestructive Testing
NL   Number of Traffic Lanes
NRC National Research Council
ODOT Ohio Department of Transportation
P#  Axial Force Derived by Analytical Method # for the Section from Truckload Measurements, for the location under consideration
P#? Location on Girder ? at Pier # (e.g., P12 is Girder 2 at Pier 1)
P_d Axial Force in the Concrete Decking from Truckload Measurements, for the location under consideration
P_s , P_{Partial} Axial Force in the Steel Beam from Truckload Measurements, assuming Noncomposite Action, for the location under consideration
P_{sc} , P_{Full} Axial Force in the Steel Beam from Truckload Measurements, assuming Full Composite Action, for the location under consideration
PC Personal Computer
psi Pounds per square inch, units of Stress
Pt Point, abbreviation
RCA Remaining Composite Action Index, defined as the ratio of the axial force in the steel beam to that predicted for a fully composite section
RF Rating Factor
S Girder Spacing
S# , S_{LL} Section Modulus Derived by Analytical Method # for the Section from Truckload Measurements, for the location under consideration
S#? Location on Girder ? at Span # (e.g., S12 is Girder 2 at Span 1)
S_{ij} Section Modulus for Girder I under load in lane J
S_{DL} Section Modulus for Steel Girder, determined by its geometry, assuming Noncomposite Action, for the location under consideration
S_{SDL} Section Modulus for Steel Girder, determined by its geometry, assuming Composite Action and material strength ratio of 3 n_{eff}, for the location under consideration
SAP90 Structural Analysis Program 1990, Computers & Structures, Inc., Berkeley, CA
SDL Superimposed Deadload
sec Seconds, unit of Time
SF Safety Factor of ASD, per Table 6.6.2.1-1 of the AASHTO Manual
t_d Thickness of the Concrete Decking, for the location under consideration
t_f Thickness of the Girder Flange, for the location under consideration
t_w Thickness of the Girder Web, for the location under consideration
TRB Transportation Research Board
UCII University of Cincinnati Infrastructure Institute
ue Microstrain, unit of Strain
UIL Unit Influence Line
V Velocity of the Test Truck
WAS-339-2013 The Bridge Specimen, under test and analysis
x Longitudinal Location, relative to Forward Abutment of Bridge
y# Vertical Location of Neutral Axis Derived by Analytical Method # for the Section from Truckload Measurements, for the location under consideration
y_a Vertical Location of Neutral Axis of Compressive Stress Zone in the Concrete Decking, as per AASHTO Spec. 10.50.1.1, for the location under consideration
y_{bg} Vertical Location of Sensor on Bottom Flange of Girder from Truckload, for the location under consideration
y_c Vertical Location of Neutral Axis of Noncomposite Concrete Decking from Geometry, for the location under consideration
<table>
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$y_{naz}$</td>
<td>Vertical Location of Neutral Axis of Section from Truckload Measurements, for the location under consideration</td>
</tr>
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<td>Vertical Location of Neutral Axis of Noncomposite Girder from Geometry, for the location under consideration</td>
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1. PROJECT OVERVIEW AND MOTIVATION

Several superloads were scheduled to cross a bridge over the Muskingum River (WAS-339-2013 near Beverly, OH in Washington County, ODOT District 10) in the Summer of 2001. The largest load (883,488 lbs. or 3,930kN) was the biggest superload in recorded Ohio history. A BARS-based analysis conducted by ODOT's Structural Engineering Office has revealed possible overload conditions in connection with these load/structure combinations. The University of Cincinnati Infrastructure Institute (UCII) was contracted in June 2001 in order to help the Ohio Department of Transportation (ODOT) evaluate the safety of the steel-stringer bridge for superload passage. This effort was to augment the BARS model-based analysis conducted by ODOT's Structural Engineering Office. The load in question was a generator to be used in the construction of an electric power generation facility by Duke Energy. Burkhalter Rigging, Inc. was the hauler contracted for the load.

Truck, proof, or other load testing of highway bridges has usually been reserved as an area of academic research due to the complexities, cost, and disturbance to service of such a field experiment. However, when a structure's computed capacity is less than the desired level of performance, it is usually beneficial to the owner to objectively identify the actual structural response to controlled loading experiments. The constructed bridge will have many inherent mechanisms to resist the applied load and which are generally not considered in the analysis of its capacity. These identified mechanisms include the actual load distribution, impact factor, unintended composite action, participation of superimposed deadload, material properties, unintended continuity, participation of secondary members, effects of skew, effects of deterioration and damage, unintended bearing restraint, and environmental effects such as thermal stresses [Lichtenstein, 1998]. The AASHTO Manual envisions the future use of diagnostic tests under truckloads for load rating [AASHTO, 1994a].

One conceptual signature that represents bridge condition and can be determined from a truckload test is the fundamental structural parameter of the unit influence line (UIL), the characteristic response at any instrumented bridge node due to the position of a unit load. Here, the unit load is defined to be a truck axle of one kip (4.45 kN) total weight and the loading path is considered to be that of a typical tandem or semi truck driven in the marked lane(s). Due to the concept of linear superposition, an influence line is especially helpful to a bridge engineer to understand the effects of various loads at different positions and/or orientations (e.g., point load, uniform load, etc.). For example, the response to a slowly moving vehicle can be determined by adding the weighted sum of influence lines corresponding to each axle weight, and vice versa.

UCII has demonstrated in past projects that the strain (or stress) influence line is a damage sensitive index by conducting truckload tests on decommissioned steel-stringer bridges that were loaded to various damage states [Levi, 1997a; Turer, 1997; Hunt, 1998; Hunt, 2000]. UCII has also shown that the influence line and its utility to estimate the future effects of proof or “superloads” can provide an accurate and conceptual health index for a structure [Hunt, 1998; Turer, 1999; Hunt, 2000; Lenett, 2001]. This project has further exemplified how the influence line can be reliably identified from several controlled loadings conducted weeks or months apart in order to track the condition of the structure. Most importantly, this project demonstrated how the measured truckload data can be used immediately (i.e. near real-time) after the experiment to provide a capacity rating for the instrumented section based upon the relevant AASHTO codes using custom software run on a laptop computer.
Several overloads were scheduled for this project, with three of the largest superloads scheduled for late Summer. A series of truckload experiments were conducted immediately before and after the first and lightest of the three overloads (629,800 lbs. or 2,801kN). In addition, the overload was monitored by UCII with the installed strain gages at various locations. For each gage location, for each test UILs were derived based on the test truck weight and axle configuration. Given the axle weights and spacings of the overload, the UILs were then used to simulate the overload responses with good results. Simulations were within 10% of actual stresses for the bottom flange of the critical regions, which indicated good predictive capabilities as well as a consistent linear behavior of the member. Some damage did occur to the unintended composite action between the girder and the decking which lead to increased stresses in the top flange at some of the pier bearings. Hence, all capacity ratings were calculated without composite action (which is as the bridge was designed).

The key research issues are defined as follows:

Rate WAS-339-2013 for the superload, using FE analysis, based upon plans, inspection reports, and site-visits by the researchers. Compare results against ODOT BARS analysis.

Generate a field calibrated FE model using data obtained from an instrumented truckload test. Use the calibrated FE model to check and verify the rating obtained above from the nominal FE model.

Extract unit influence lines from truckload data and rate the structure at the instrumented critical superstructure sections solely from truckload data together with basic principles of structural mechanics (as another further check of FE modeling).

Based on our best prediction capabilities, recommend possible measures, retrofits, etc. to help mitigate superload-induced damage.

Monitor the actual responses of WAS-339-2013 during the passage of the heaviest superloads and try to quantify the impact of the load on the life of the bridge.

After the superload passages, run a second round of field tests. The results of these will be compared against the baseline tests (conducted under item 2 above) for the purpose of quantifying changes in bridge state due to superload passage.

Of particular issue with this project were several issues:

Development of an optimal instrumentation plan to test and monitor the structure given its size, the need to maintain a practical sensor count, and the access issues presented by virtue of the fact that all six spans of the structure are over water. The symmetrical nature of the bridge design and truckload were employed to mitigate concerns regarding sensor suite size and installation.

Analysis of the structural rating and the need for any modification to either the structure, load configuration, or load path of passage given the relative dimensions of the load vehicle, span length, and the size of the per axle loadings.

Development of highly automated procedures for processing and computing results from modeling and truckload field test studies so that results could be provided to ODOT in a
highly expedited manner. In several instances the between load times were on the order of one week in which time field tests needed to be designed, run, results processed, and presented to ODOT Officials in time to make decisions about further load passages at the same time coordinating with local ODOT District personnel for access and temporary closure for testing, and the hauler for additional information and details on the loading configuration and set-up logistics.

Figure 1.1 provides the timeline according to which the project evolved and provides a breakdown of the activities undertaken by UCII on this project and the rapid turnaround achieved.
### Figure 1.1: Project Timeline

<table>
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<th>Task Name</th>
<th>Start</th>
<th>Finish</th>
<th>Duration</th>
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<td>Fri 6/22/01</td>
<td>Tue 6/26/01</td>
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<td>Mon 7/2/01</td>
<td>Thu 7/5/01</td>
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<td>13</td>
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<td>Fri 7/6/01</td>
<td>Sat 7/7/01</td>
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<td>Wed 7/11/01</td>
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<td>Wed 8/1/01</td>
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<td>Sun 8/19/01</td>
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<td>Mon 8/20/01</td>
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<td>28</td>
<td>Re-Run Analysis and Report to ODOT</td>
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<td>Wed 8/22/01</td>
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<td>Monitor 2nd &quot;Heavy&quot; Superload Event</td>
<td>Sat 8/25/01</td>
<td>Sat 8/25/01</td>
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<td>Sun 8/26/01</td>
<td>Sun 8/26/01</td>
<td>1 day</td>
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<tr>
<td>31</td>
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<td>Mon 8/27/01</td>
<td>Tue 8/28/01</td>
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<td>Analysis for Subsequent Superloads and Report to ODOT</td>
<td>Wed 8/29/01</td>
<td>Tue 9/4/01</td>
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2. BRIDGE SPECIMEN OVERVIEW

2.1 Description of WAS-339-2013 Bridge Specimen

The bridge under consideration here (Figure 2.1) is a 2 lane steel-stringer bridge with a reinforced concrete deck, built in 1963, crossing the Muskingum River in ODOT District 10. Its gross attributes are given as follows:

The bridge consists of 6 spans (89', 118', 118', 118', 118', 89' or 27 m, 36 m, 36 m, 36 m, 36 m, 27 m respectively) for an overall length of 650 feet (198 m) with a skew of 24 degrees.

The superstructure consists of a system of 5 variable depth, welded girders (4’8.5" to 7’10.5" or 1.435 m to 2.40 m) spaced at 8’3" (2.516 m), stub abutments, and rocker bearings at each pier and abutment.

The deck consists of an 8.5" (.216 m) reinforced concrete slab 39’ (11.895 m) wide (30’ or 9.150 m curb-to-curb) including a 1” (.025 m) monolithic wearing surface.

Various views of bridge layout, dimensions, and design details taken from the plans are given in Figures 2.2-2.4.

2.2 As-Is Visual Condition of Structure Prior to Superload Passage

As part of the NBIP, WAS-339-2013 receives bi-annual visual inspections. The most current visual inspection rated the overall condition of this structure at 7.

The research team obtained documentation on bridge plans and inspection reports from ODOT’s Office of Structural Engineering. In addition, the research team discussed the structure with local ODOT District 10 personnel. Finally, prior to instrumentation or testing, research team members also conducted a visual inspection of the structure using an ODOT snooper made available for truckload testing. The findings are reviewed below.

Pier Bearings and Abutments: The boundary conditions associated with the structures at pier bearings and abutments appeared to have been in relatively good shape. Rust and debris were noted at both abutments (Figure 2.5), and the rockers appeared to have been frozen in an expanded position.

From the underside, both abutments appeared to be clear of the abutment wall, but from then deck, it appeared as though both expansion joints were filled with debris and probably locked (Figure 2.5).

Girders: The girders appeared to be in good shape with no significant evidence or rust or sections loss (Figure 2.6). Welded connections at cross-frames, web/flanges, and stiffeners all appeared in good shape. Bolted connections at splices appeared in good shape. The bridge paint appeared to be relatively recent, but isolated areas of significant flaking/peeling of the paint was evident (Figure 2.6).
**Decking:** From the top surface the deck overlay showed extensive evidence of both longitudinal and transverse cracking primarily at the piers in the south side of the northbound lane (Figure 2.7).

From the underside, appeared to be relatively free of cracking and the connection between deck and upper flange of girder appeared to be in good shape for the most part (Figure 2.8).

**Sidewalks/Parapets:** The sidewalks and parapets appeared to be in generally good condition. It was noted the actual sidewalk thickness deviated from the bridge plans by about 1.5 inches (.038 m) on both sides of the bridge (Figure 2.9).
Reinforced concrete deck on steel girder
5 girders, 6 spans
89’, 118’, 118’, 118’, 118’, 89’ (27.1 m, 36.0 m, 36.0 m, 36.0 m, 36.0 m, 27.1 m) span lengths
2 lanes, 38’ (11.6 m) wide
built in 1963