Dynamic Load Allowance of a Prestressed Concrete Bridge through Field Load Tests

Eli S. Hernandez[1] and John J. Myers[2]

[1] PhD Candidate, Missouri University of Science and Technology, Rolla, MO, United States
[2] PhD, PE, Missouri University of Science and Technology, Rolla, MO, United States

ABSTRACT: The load capacity of a bridge can be obtained by means of a series of diagnostic load tests. The dynamic load allowance or impact factor is a parameter used to establish a bridge's flexural capacity during the capacity evaluation process. Bridge A7957 was built using normal-strength self-compacting concrete and high-strength self-compacting concrete. The objective of this study was to compare Bridge A7957's dynamic load allowance obtained by experimental and analytical methods proposed in three different design and evaluation codes. To attain this objective, Bridge A7957 was instrumented with accelerometers at different locations. For different dynamic tests, the spans' response was measured with accelerometers and a laser vibrometer. The dynamic load allowance was obtained experimentally and analytically using current design and evaluation codes. The impact factors obtained analytically resulted in larger values compared to the experimental results. This difference might have repercussions in the assessment results of bridge structures.

1 INTRODUCTION

Load rating is defined as the capacity evaluation procedure employed to estimate the carrying capacity of a bridge structure to withstand loads without suffering damage or undergoing collapse. Field testing presents a very accurate visualization of the live-load carrying capacity of a bridge because it provides an in-service, as-built characterization of the bridge's response. Field testing has largely confirmed reserves of strength capacity in existing bridges despite their age and existing condition. Sources that explain these differences are diverse and may be attributed to field parameters that are not considered during the design or capacity evaluation of a bridge's structure. The dynamic load allowance (DLA) or impact factor (IM) is one of the parameters that can be verified by means of a field load test [AASHTO (2010), Cai et al. (2003)]. Most design codes takes into account the dynamic load effects, by increasing in some fraction the magnitude of the static live load applied to a bridge structure. An accurate estimation of the DLA yields safe and rational load ratings of existing bridge structures. The complex nature of the factors affecting the DLA makes it difficult to estimate its value during the design and strength evaluation process of a bridge [Barker et al. (2013)].

The main objective of this study was to obtain the dynamic load allowance of Bridge A7957 by using analytical and experimental methods to quantify differences that may arise when both type of approaches are employed in bridge design and evaluation. To achieve this goal, the dynamic response of Bridge A7957's exterior spans was recorded with accelerometers and a laser vibrometer. The DLA was computed using the analytical provisions dictated by the American Association of State Highway and Transportation Officials (AASHTO) Standard Specification [AASHTO (1992)], the LRFD Bridge Design Specification [AASHTO (2012)] and the Ontario Highway Bridge Design Code (OHBDC) [OMTC (1983)]. The experimental DLA was estimated by comparing the measured dynamic and static response of the bridge structure. The following sections detail the instrumentation plan, and the static and dynamic tests conducted on Bridge A7957 to estimate its DLA before opening the structure to traffic.

2 ANALYTICAL AND EXPERIMENTAL DYNAMIC LOAD ALLOWANCE

In terms of analytical computations, design codes have traditionally proposed expressions to estimate the dynamic load allowance (or impact factor) as a function of the span length (L) or the fundamental frequency of the bridge. The AASHTO Standard Specifications [AASHTO (1992)] presented an expression to estimate the impact factor in terms of the span length as follows:

$$IM = \frac{15.24}{L + 38} \leq 0.30 \tag{1}$$

In 1994, the AASHTO LRFD Bridge Design Specifications [AASHTO (2012)] replaced the term impact factor used in AASHTO (1992) with the term dynamic load allowance. A DLA value independent of the span length was adopted as equal to 0.33 (33% of the static live load) for bridge components other than deck. In 1983, the Ontario Highway Bridge Design Code (OHBDC) presented an approach that estimates the DLA in terms of the fundamental frequency of the bridge structure as Figure 1 illustrates.

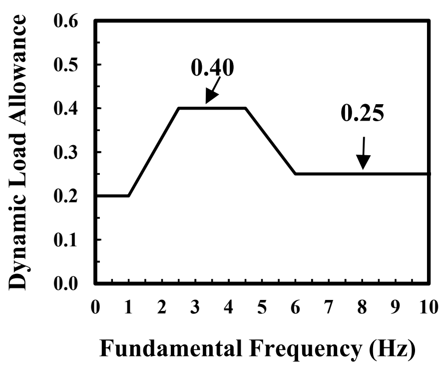

Figure 1. DLA vs. fundamental frequency [data from OMTC (1983), Paultre et al. (1992)].

Bakht et al. (1989) reported several definitions found in the literature to experimentally obtain the DLA. As reported by Deng et al. (2015), the DLA is commonly defined as the ratio of the maximum dynamic and static responses regardless of whether the two maximum responses occur simultaneously. Equation (2) presents this definition.

$$DLA = \frac{R_{dyn} - R_{sta}}{R_{sta}} \tag{2}$$

Where R_{dyn} = maximum dynamic response and R_{sta} = maximum static response. According to Paultre et al. (1992, McLean et al. (1998) and Deng et al. (2015), the estimation of the static response can be obtained by: (1) conducting a quasi-static test where vehicles move across the bridge at a low speed between 5–16 km/h; (2) filtering the measured dynamic response with a low-pass filter to eliminate the dynamic components of signal; and (3) using finite element models (FEM) to calculate the static response when the vehicle weight and loading position are known. In this study, the first option was employed to estimate Bridge A7957's DLA.

3 BRIDGE A7957 DESCRIPTION

Bridge A7957 is a three-span, continuous, precast-prestressed (PC/PS) concrete bridge (Figure 2) with a 30-degree skew angle (Figure 3), and excellent road surface condition. Each span has PC/PS concrete Nebraska University 53 (NU53) girders [Hernandez et al. (2015), Hernandez et al. (2016)]. The first span's girders are 30.48 m long and fabricated with conventional concrete (CC), specified by the Missouri Department of Transportation as a Class A mixture, with a compressive strength of 55.2 MPa. The second span's girders are 36.58 m long and fabricated with high-strength self-consolidating concrete (HS-SCC) of 68.9 MPa. Girders in the third span are 30.48 m long and employ normal-strength self-consolidating concrete (NS-SCC) with a design compressive strength of 55.2 MPa. The superstructure is supported by two abutments and two intermediate bents [Figure 2(a)] with nominal compressive strength of 20.7 MPa.

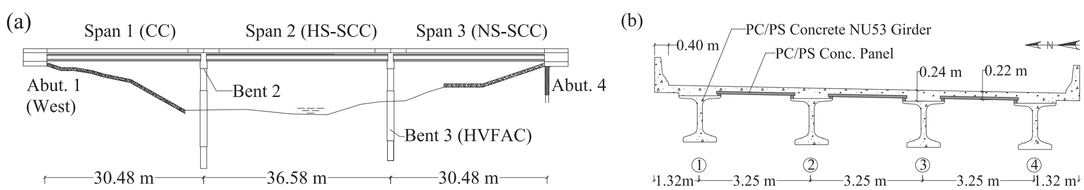

Figure 2. Bridge A7957. (a) Elevation. (b) Cross-section.

4 FIELD TEST EQUIPMENT

The instrumentation was designed to collect: (1) the static vertical deflection at midspan of girders 1–4 (spans 1 and 3); (2) the dynamic vertical deflection at midspan of girder 3 (spans 1 and 3); and (3) girder 3 and 4's vertical acceleration at midspan locations (Figure 3). The sensors employed and details pertaining to their installation are depicted in the next subsections.

4.1 Automated total station

An automated total station (ATS), Leica TCA 2003, was used to estimate the girders' deflection during the static test conducted on the first and third spans. The ATS recorded the coordinates of targets (prisms) placed at the exterior-span girders' bottom flange (midspan sections), as illustrated in Figures 3 and 4. The ATS has an accuracy of 1 mm ± 1 ppm (distance measurements) and 0.5 arc-seconds (angular measurements). The accuracy of the ATS has been reported as 0.1 mm in vertical deflection measurements [Merkle et al. (2004)].

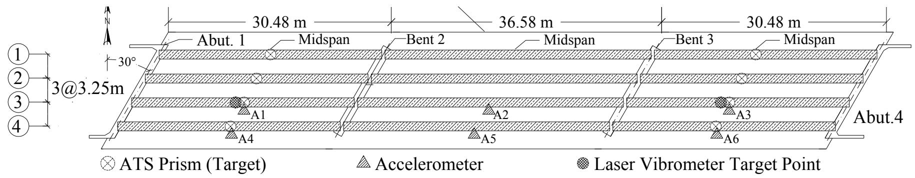

Figure 3. Instrumentation layout.

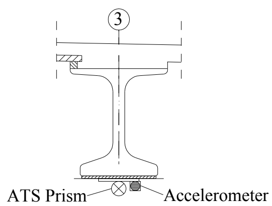

Figure 4. Girder 3's instrumentation (midspan sections).

4.2 Accelerometers

Six accelerometers were deployed on Bridge A7957 to record the vertical acceleration at midspan sections of PC/PS concrete girders 3 and 4 (Figure 3). Figures 3 and 4 show details of the recording equipment used at the girders' bottom flange (midspan sections).

4.3 Remote sensing vibrometer (RSV-150)

A RSV-150 (Figure 5), was utilized to collect the dynamic bridge response (vertical deflection) of the exterior spans' girder 3 (midspan sections). The RSV-150 has a bandwidth up to 2 MHz for nondestructive test (NDT) measurements and can detect the vibration and displacement of distant structures.

Figure 5. Remote sensing vibrometer (RSV-150).

5 FIELD TEST PROCEDURE

Large-scale static and dynamic tests were conducted on Bridge A7957. The following subsections describe the test procedure and load configurations planned to obtain the maximum static and dynamic response of the bridge superstructure.

5.1 *Static test*

For this study, static load tests were conducted on Bridge A7957's exterior spans. An H20 dump truck was used to obtain the maximum static response of the bridge superstructure. Quasi-static tests were conducted by passing the truck at a crawl speed of 16 km/h. Figure 6 shows the average truck's dimensions and weight. Figure 7 illustrates the load configuration applied to spans 1 and 3 during the static tests 1and 2.

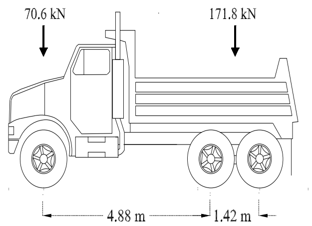

Figure 6. H20 truck detail.

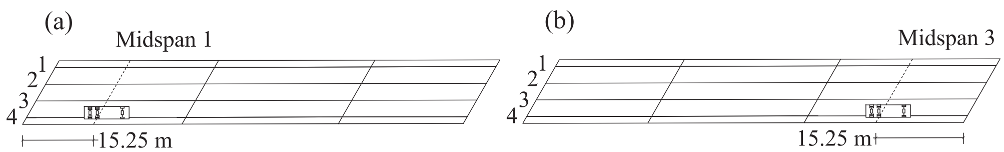

Figure 7. Static test configurations. (a) Static test 1. (b) Static test 2.

5.2 *Dynamic test*

Speeds ranging from 16 km/h to 96.6 km/h were used during the dynamic load tests. For each test, the truck speed was increased at a rate of 16 km/h until the maximum speed of 96 km/h was attained. The maximum dynamic and static responses were compared to estimate the experimental dynamic load allowance. Experimental data was recorded with the RSV-150 at a sampling rate of 120 Hz. The truck was driven over the south side of the bridge (along the west–east and east–west directions), separated 0.60 m from the safety barrier's edge.

6 TEST RESULTS

The vertical deflection measured at midspan locations of the end spans 1 and 3's girders are shown in Figure 8. Although both exterior spans have the same geometry (Figure 2) and were subjected to the same truck load, a 5% difference was observed between the deflection responses recorded at both spans' midspan. The difference might be attributed to two possible sources: first, a slight variation on the application of the truck load on each span; second, the accuracy of the ATS might have affected the measured deflection values due to the low level of load applied during the test. This difference may be corrected in future tests by taking caution regarding the location of truck loads. In addition, the level of load applied needs to be relatively high so that the error of ATS measurements is kept low during data recording. Moreover, Girder 3's static deflection at midspan (Figure 8) was compared to the quasi-static response recorded with the RSV-150 when the test truck was passed at a crawl speed of 16 km/h. This comparison was performed to verify if the recorded quasi-static deflection was representative of the bridge's static response and may be utilized to estimate the dynamic load allowance.

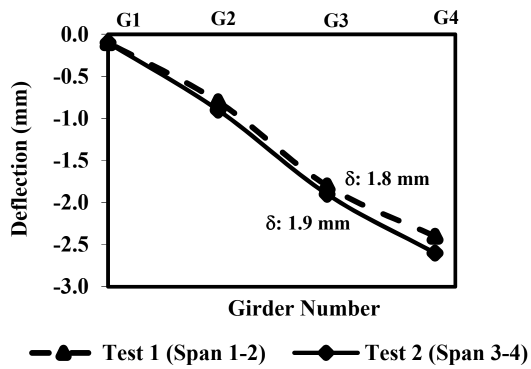

Figure 8. Vertical static deflection (girders' midspan).

Figure 9(a) presents the acceleration response collected with sensor A1 (Figure 3) installed at midspan of girder 3. This acceleration data was recorded when the truck was driven from west to east at 96 km/h. Figure 9(b) presents the fundamental frequency estimated from Fast Fourier Transformation (FFT) applied to the recorded acceleration data shown in Figure 9(a). The fundamental frequency corresponds to a value of 3.125 Hz. Using the approach proposed by the OMTC (1983), the estimated fundamental frequency yields a dynamic load allowance value of 0.40 (see Figure 1).

(a) (b)

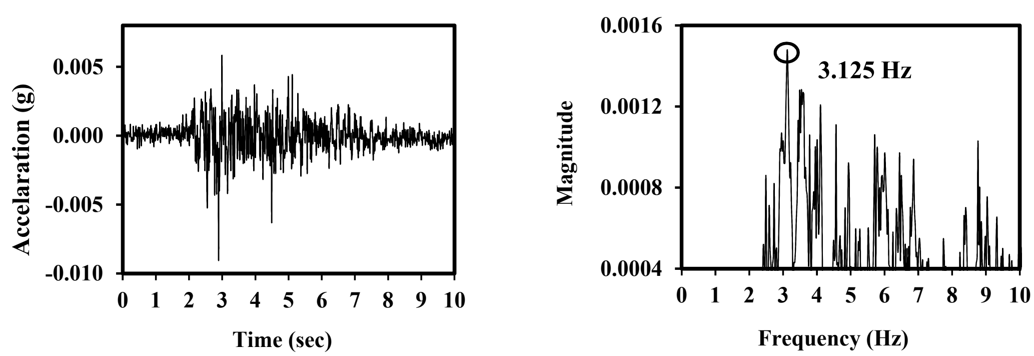

Figure 9. Dynamic response. (a) Measured acceleration. (b) Natural frequency extracted through FFT.

Figure 10 shows that the quasi-static deflection recorded with RSV-150 was close enough to the static deflection collected with the ATS (1.77 mm vs. 1.80 mm). Consequently, the quasi-static response of the spans was assumed to be the maximum static deflection of girder 3's midspan and was employed to estimate the exterior spans' DLA for the different truck speeds employed during the dynamic test. In addition, Figure 10 presents the maximum dynamic deflection (2.08 mm) measured with the RSV-150 corresponding to a truck speed of 96 km/h. The experimental DLA was estimated with Equation (3).

$$DLA^{exp} = \frac{{D_{dyn}}^{max} - {D_{sta}}^{max}}{{D_{sta}}^{max}} \tag{3}$$

Where DLA^{exp} = experimental dynamic load allowance; ${D_{dyn}}^{max}$ = maximum dynamic (measured) vertical deflection (mm); and ${D_{sta}}^{max}$ = maximum static deflection obtained from passing the test truck at a crawl speed (mm).

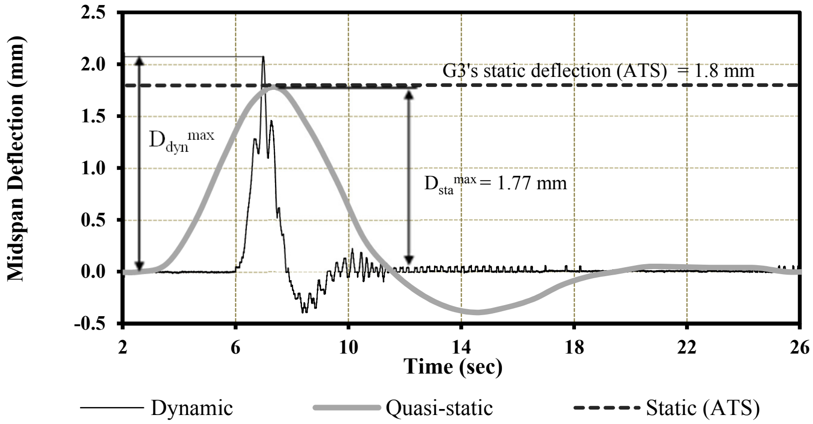

Figure 10. Maximum static and dynamic vertical deflection.

Table 1 lists the bridge's dynamic and static maximum deflection recorded for the different speeds (row 1) employed during the dynamic tests (see rows 2 and 3). In addition, the experimental DLA corresponding to different truck speeds are listed in row 4 using Equation (3). The experimental dynamic amplification factor, DAF^{exp}, was estimated as follows:

$$DAF^{exp} = (1 + DLA) \tag{4}$$

Table 1. Dynamic load allowance

Speed (km/h)	16	32	48	64	80	96
D_{dyn}^{max} (mm)	1.77	1.79	1.79	1.77	2.03	2.08
D_{sta}^{max} (mm)	1.77	1.77	1.77	1.77	1.77	1.77
DLA^{exp}	0.000	0.010	0.010	0.000	0.150	0.175
DAF^{exp}	1.000	1.010	1.010	1.000	1.150	1.175
DLA*	0.33	0.33	0.33	0.33	0.33	0.33
IM (spans 1, 3) *	0.222	0.222	0.222	0.222	0.222	0.222
IM (span 2) †	0.204	0.204	0.204	0.204	0.204	0.204
DLA (OHBDC)	0.40	0.40	0.40	0.40	0.40	0.40

* According to AASHTO LRFD. † According to AASHTO Standard Specifications

The DLA obtained with AASHTO (2012) and the impact factor computed with AASHTO (1992) are listed in rows 6-8. Row 9 presents the DLA estimated as a function of the bridge's fundamental frequency as proposed by OMTC (1983). The maximum value of the experimental DLA was estimated as 0.175 and corresponds to a truck speed of 96 km/h. By comparing the maximum experimental DLA to the values obtained using the different design specifications [AASHTO (2012), AASHTO (1992) and OMTC (1983)], it was determined that the analytical methods provide conservative values compared to the experimental approach. These results implied that the experimental approach is more appropriate to conduct a capacity evaluation of existing bridges. Values obtained with AASHTO (1992) were closer to the experimental values of the impact factor, IM.

7 CONCLUSIONS

The dynamic load allowance of Bridge A7957 was obtained from field measurements and by using three design specifications. The DLA obtained with the design specifications resulted in larger values compared to the experimental values. This disparity might be attributed to the presence of in-situ factors not considered by the theoretical methods proposed in current design and evaluation codes. Current bridge design specifications intend to estimate the value of the impact factor based on several assumptions as an attempt to cover a large spectrum of bridges fabricated with different materials, span lengths, dynamic characteristics, and road surface conditions. The impact factors obtained from field load tests implicitly consider in-situ parameters such as unintended support constraints and continuity, skew angle, and interaction soil-structure that may contribute to improve the bridge's dynamic response behavior. More importantly, the variation between the experimental and analytical DLA values may have repercussions in the rating factor of existing bridge structures. More research should be conducted to isolate the sources of these variations.

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