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EXPERIMENTAL STUDY ON DETERMINING DAMPING RATIO OF STEEL BRIDGES

Muharrem AKTAS[1], Serdar KUYUK[2], Cemal YILMAZ[3], Elif AGCAKOCA[4], Erkan ÇELEBİ[5]

ABSTRACT

Damping property of a light-weight structure is especially required in design stage when dynamic response is considered. Since damping ratio cannot be directly derived from other structural properties; an experimental study is essential on completed structures of similar characteristics. Damping ratio calculated from existing structure is not sufficient for direct use in new design but it is the only way so far. This study aims to identify the damping ratio of a scaled steel pedestrian bridge. Main goal is to prove amplitude dependency of damping ratio for such structures.

Tested bridge span is in 6.84 m length and 0.90 m wide. All the members are connected with bolts and the bridge is pin supported. Bridge was initially imposed with an initial deflection at mid span and released to make damped free vibration. Acceleration records were taken for the case of eight different initial displacement applied prior to free vibration. The damping ratio calculated after applying each initial amplitude value provides information about the sensitivity level of the structure's damping ratio. Damping ratio is calculated with log decrement equations by using both displacement and acceleration records. However, displacement records are not direct records obtained instrumentally but they are calculated by numerical integration of recorded acceleration data. Moreover; exponential curve fitting is employed to each test records to determine the damping ratio of the structure. Results prove that damping ratio of the structure is correlated with initial displacement applied to the structure. Moreover; using acceleration data recorded with instrumentation rather than displacement data calculated with numerical integration is more accurate.

[1] Assist. Prof. Dr., Sakarya University, Sakarya, muharrema@sakarya.edu.tr
[2] Assist. Prof. Dr., Sakarya University, Sakarya, serdarkuyuk@gmail.com
[3] Research Assist. MSc., Sakarya University, Sakarya, f.cemalyilmaz@gmail.com
[4] Assist. Prof. Dr., Sakarya University, Sakarya, elifd@sakarya.edu.tr
[5] Prof. Dr., Sakarya University, Sakarya, ecelebi@sakarya.edu.tr

INTRODUCTION

Damping property, a measure of energy dissipation in a vibrating system, is especially required in design stage of structures when dynamic response is considered. Since damping ratio cannot be directly derived from other structural properties; an experimental study is essential on completed structures of similar characteristics. Damping ratio calculated from other similar structure is not sufficient for direct use in new design but it is the only way so far.

There are basically three different test types that can be used to determine damping coefficient. One is ambient excitation in which the source of the vibration is wind, traffic or other environmental effects. Implementing the test results to determine the targeted value is some time out of control because of the uncontrolled timing and direction of the ambient effects. Since the amplitude of the sources is small, only linear behaviour of structures can be tested with ambient vibration. The smaller equipment needed to conduct the test makes this approach encouraging. However; a high density of measuring points is needed in ambient vibration test for more realistic models (Ivanovic et al., 2000).

A forced vibration test approach generally achieved by contra-rotating eccentric masses gives accurate results. This mechanical exciter creates a sinusoidal force in horizontal direction (Littler, 1995). It is possible to observe higher modes, with artificially created large amplitude by dynamic shaker which generally mounted on the top of the structure (Luco et al., 1988). But performing this test is more difficult than the well-known snap-back method.

In snap-back method, first an amount of initial displacement is imposed to the structure prior to vibration. Then, the structure is suddenly released from this initial displacement causing vibration. Once the structure released from its initial condition it is left to vibrate freely until the structure brought to rest by the effects of damping.

This paper presents damping ratio on the basis of analysis of test results obtained by applying snap-back approach. Amount of initial displacement is varied to discuss whether there is a correlation between damping coefficient and imposed initial displacement. Acceleration records were taken with a high quality accelerometer. Displacement of the bridge is not recorded directly but calculated by numerical integration. Both records are used to determine the damping coefficient to see the effect of using directly measured data and calculated data.

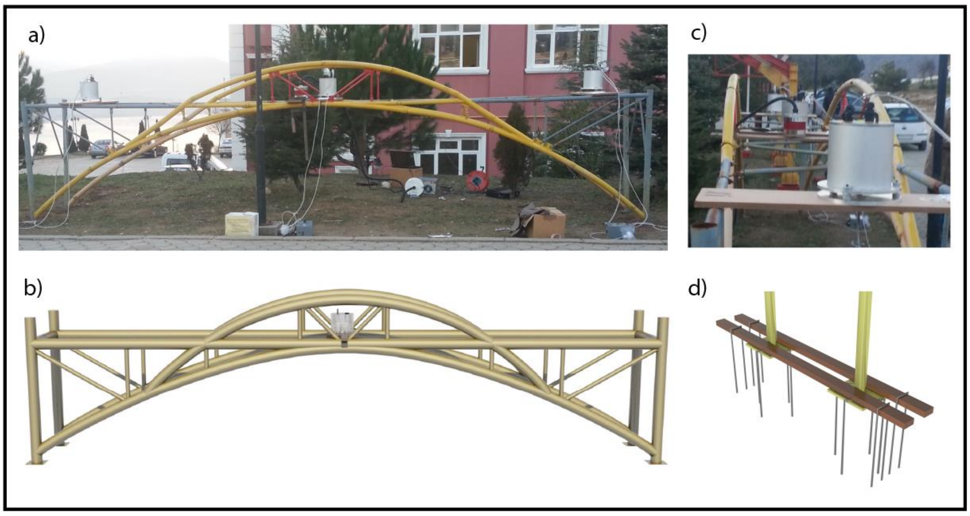

Figure 1. a) Experimental setup of scaled steel frame bridge b) Numerical model c) placement of accelerometer d) illustration of fixed support

EXPERIMENTAL STUDY AND METHODS

Experiments are conducted on a scaled pedestrian bridge whose span and width is 6.84 m and 0.90 m, respectively (Figure 1-a-b). All the members are connected with bolts and the bridge is supported to soil with the boundary conditions shown in Figure 1d. Oscillations are recorded with high quality Capacitive Force Micromachined accelerometer, which has 32-bit high resolution and has 120 dB dynamic range, located at mid-span of the bridge (Figure 1-c). The transverse acceleration waveform with 100 sample per seconds extracted from sensor is converted to velocity, displacement and frequency spectrums after applying standard signal-processing techniques such as base line corrections and Butterworth band pass filtering. Frequency content of signals are derived by applying Fast Fourier Transform.

Free vibration decay is calculated for the test specimen excited with eight different initial displacement; 0.113 cm, 0.249 cm, 0.411 cm, 0.500 cm, 0.606 cm, 0.797 cm, 1.002 cm, 1.213 cm applied at the mid-span. Application of initial displacement is done by controlled human power. It is not given as impact force but rather, applied pulling and releasing the middle of bridge.

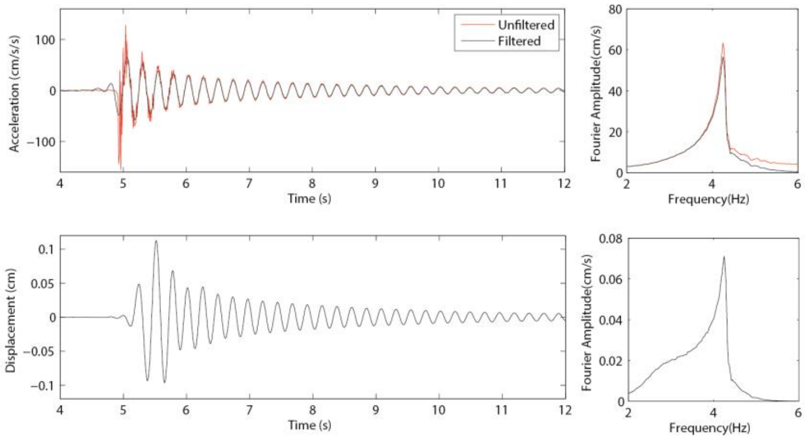

Figure 2. Unfiltered (Row) and Filtered data recorded for the test case with an initial displacement of 1 mm

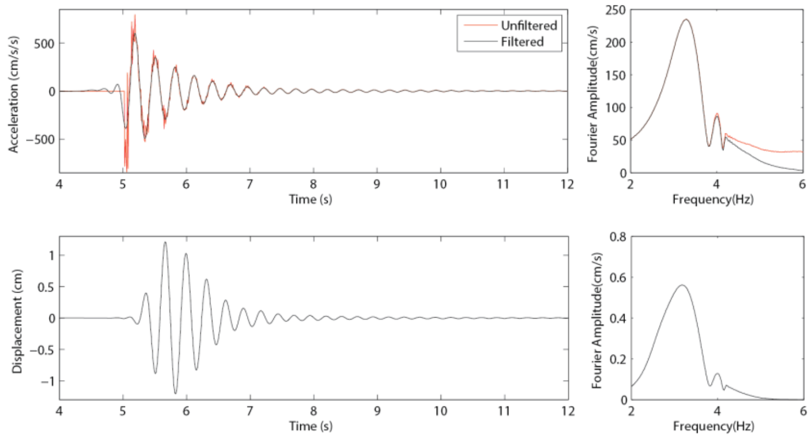

Figure 3. Unfiltered (Row) and Filtered data recorded for the test case with an initial displacement of 12 mm

Row data are first filtered to avoid noises by using our written Matlab code (Matlab, 2013). Unfiltered data and filtered data are plotted for two extreme cases, with minimum (Figure 2) and maximum (Figure 2) initial displacement. Noises are more evident at the beginning of the free vibration as expected. Also, Fast Fourier Transformation (FFT) is applied to see the frequency content of the structure. Fundemantal frequency of record show the natural frequency of the structure. It is easy to obtain this dynamic characteristic from the case with minimum initial displacement rather than the case with maximum initial displacement. For instance, natural frequency of 4 Hz is easily obtained by displacement and acceleration record when initial deflection of 1 mm is applied (Figure 2).

However, when an initial deflection of 12 mm is applied two fundamental frequencies obtained. Authors think that the first one is resulted from the impact effect of the larger initial deflection applied prior to free vibration. As its effect decays the natural frequency of 4 Hz is also obtainable from FFT.

Calculating Damping ratios of Bridge:

The equivalent damping ratio is calculated by using two different approaches to the well-known log-decrement equations. First approach uses the direct calculation with log-decrement equation and second method uses curve fitting to exponential envelope curve.

<u>Using Directly Log-Decrement Equations:</u>

The equivalent viscous damping ratio, (ξ) of the structure is calculated from the filtered damped free vibration record by using log-decrement equation given below (Chopra, 2012);

$$x = \frac{1}{2p} \ln \frac{u_i}{u_{i+1}} \tag{1}$$

where, u_i and u_{i+1} denotes two successive peak deflections. However, in most dynamic analysis experiments, deflections are not directly recorded, but they are obtained by calculating the numerical integrations of recorded accelerations. Thus, damping ratio can also be calculated by using two successive peak accelerations, $\ddot{u}_i$ and $\ddot{u}_{i+1}$;

$$x = \frac{1}{2p} \ln \frac{\ddot{u}_i}{\ddot{u}_{i+1}} \tag{2}$$

Instead of using two successive amplitudes, using two amplitudes several cycles apart is easy and suitable when decay of motion is slow. In that case, the log-decrement equations over *j* cycles can be expressed as;

$$x = \frac{1}{2pj} \ln \frac{u_i}{u_{i+j}} \quad or \quad x = \frac{1}{2pj} \ln \frac{\ddot{u}_i}{\ddot{u}_{i+j}} \tag{3}$$

Amplitudes of filtered damped free vibration record are determined for both acceleration and deflection record. Using Equation 1-2, damping ratio at each data point is calculated with these successive amplitudes and plotted next to each data record. Mean and median value of calculated damping ratio as well as result from Equation 3 is also included in the plot (Figure 3-4). Detailed result is given for two extreme case of initial condition of 1 mm and 12 mm in Figure 3 and Figure 4, respectively.

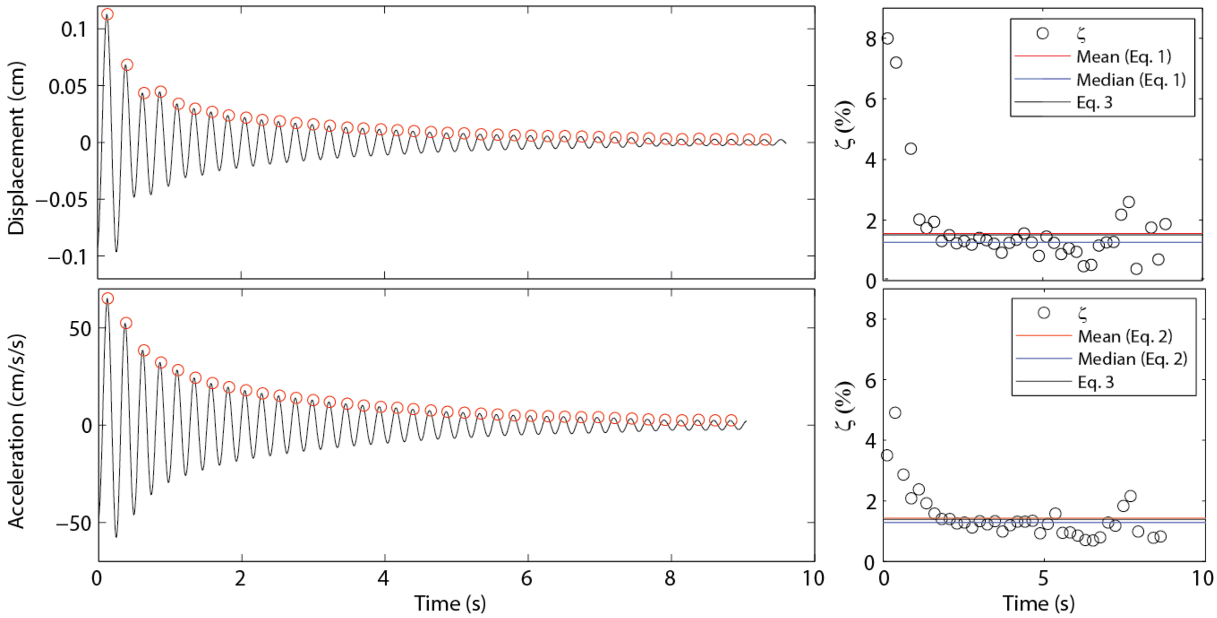

Figure 3. Determining ξ using equation 1, 2 and 3 for Experiment 1 (initial condition of 1 mm)

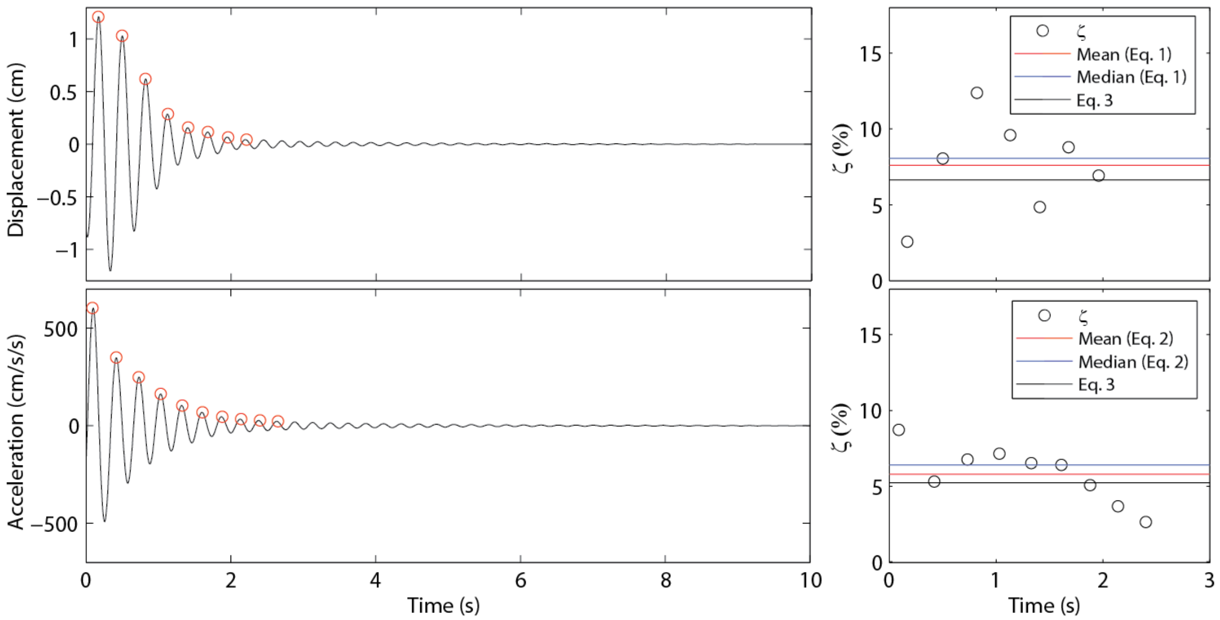

Figure 4. Determining ξ using equation 1, 2 and3 for Experiment 8 (initial condition of 12 mm)

<u>Using Exponential Envelope Curves:</u>

Displacement of a structure under ideally viscous damped condition, decay within an exponential envelope defined by Equation 4 (Chopra, 2012).

$$u(t) = \pm \rho e^{-\zeta \omega_n t} \tag{4}$$

where ρ is amplitude ω_n is angular frequency and t is time.

Ideally it is assumed that the peak displacement values are on points of this exponential curve. However, positions of peak displacements are near to these points on the exponential curve. But for most cases the divergence is negligible. Peak values of the data set are fitted with an exponential curve of the form $u(t) = ae^{-pt}$ in which $p = \omega_n \xi$. Since ω_n is known from FFT, ζ can be calculated from $p = \omega_n \xi$.

RESULTS AND DISCUSSION

Log-decrement equations are used with filtered damped free vibration records, which are obtained from eight vibration tests. Mean and median values of damping ratio calculated by employing equation 1 and 2 using each two successive amplitude pair are presented in Figure 5. Damping ratio calculated by using two amplitudes, which are several cycles apart, is also included in Figure 5 for comparison purpose using Equation 3.

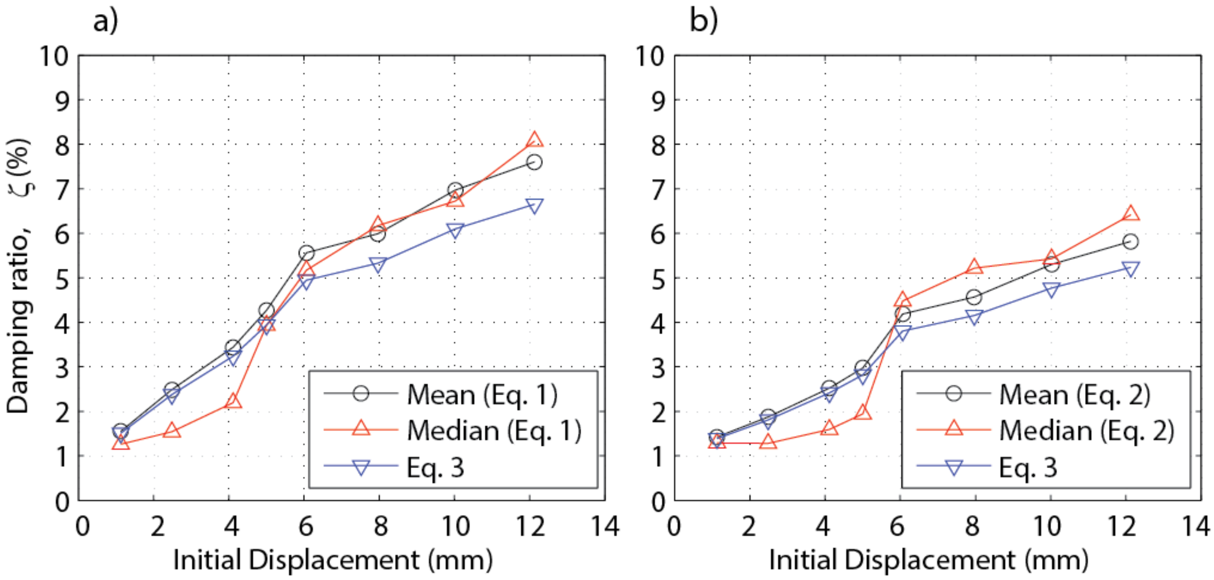

Figure 5. Damping ratio calculated with a) using displacement record, Equation 1 and 3 b) using acceleration record, Equation 2 and 3

Figure 5 clearly prove the correlation between the value of damping ratio and initial displacement applied prior to the free damped vibration. As the initial deflection increases the damping ratio is also increase. However, the tendency in the increase of the line is not as steep as the start point. In other words, the line tends to go to horizontal asymptotes. This more clear in Figure 5b, which is obtained from displacement record. One important finding is that using displacement record rather than acceleration changes damping ratio value. For instance damping ratio calculated by using displacement records is higher than that is found by using acceleration record. This difference is more evident for the test case with higher initial displacement.

Damping ratio calculated by equating $\zeta\omega_n$ to the amplitude of fitted curve of exponential form is presented in detail in Figure 6. Damping ratio value calculated with curve fitting method is tabulated with those obtained from Equation 1-3 in Table 1. For comparison purpose average of results obtained from Equation 1-3, and Equation 2-3 are plotted in Figure 7 with the results obtained from curve fitting method.

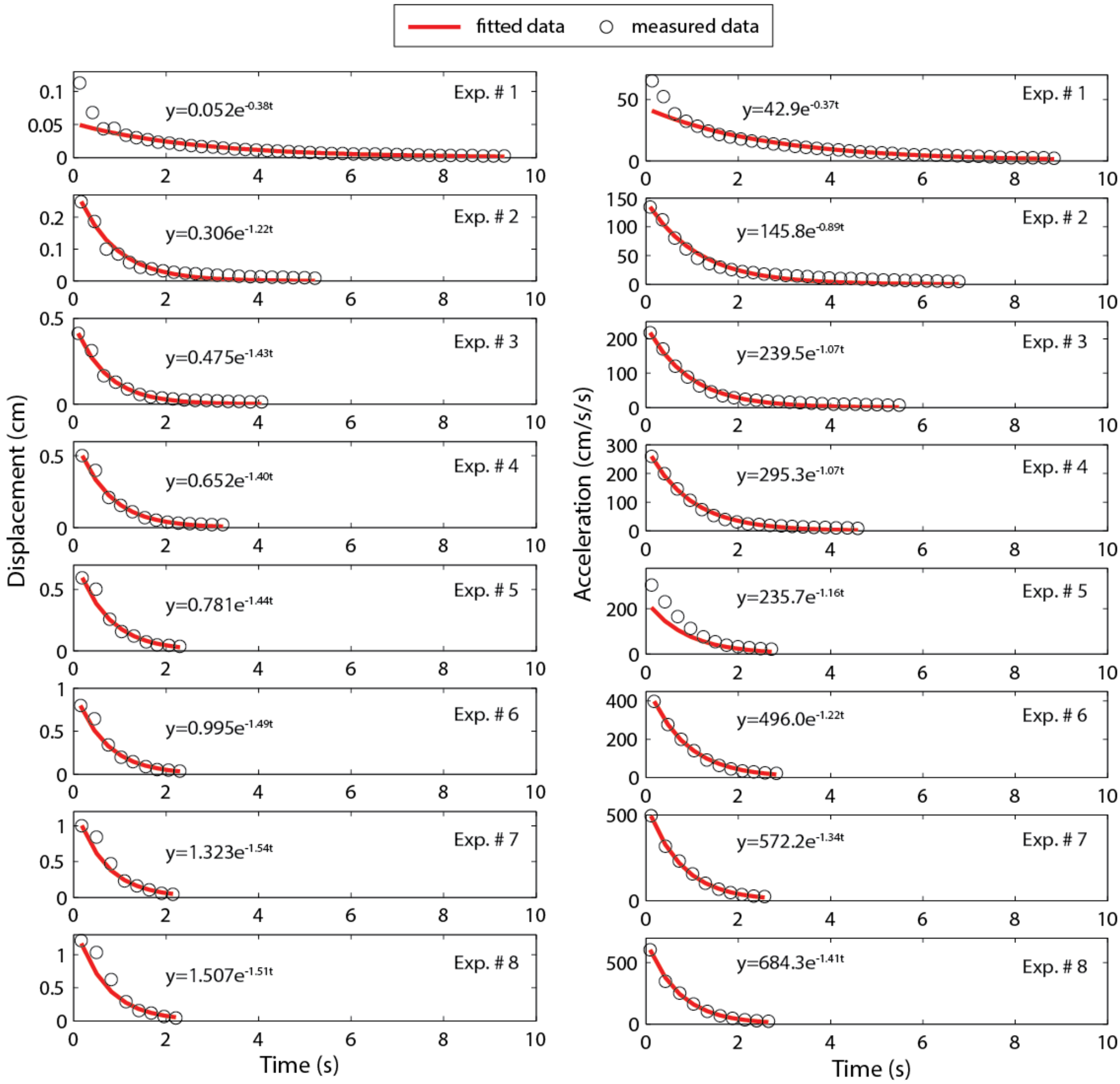

Figure 6 Fitting exponential curves to the displacement amplitudes in the decay range

Table 1. Damping values calculated for each test by employing Equation 1-3 and curve fitting method.

Exp. #	**Initial Disp. (mm)**	**Using Deflection Record**				**Using Acceleration Record**			
		Using Equation 1		Using Equation 3	Exp. Curve	Using Equation 2		Using Equation 3	Exp. Curve
		mean	median			mean	median		
1	1.0	0.015	0.013	0.015	0.014	0.014	0.013	0.014	0.014
2	2.5	0.025	0.015	0.024	0.046	0.019	0.013	0.018	0.033
3	4.0	0.034	0.022	0.032	0.053	0.025	0.016	0.024	0.040
4	5.0	0.043	0.039	0.039	0.052	0.030	0.019	0.028	0.040
5	6.0	0.056	0.052	0.049	0.054	0.042	0.045	0.038	0.043
6	8.0	0.060	0.062	0.053	0.056	0.046	0.052	0.042	0.046
7	10.0	0.070	0.067	0.061	0.058	0.053	0.054	0.048	0.050
8	12.0	0.076	0.081	0.067	0.056	0.058	0.064	0.052	0.053

Results indicate that there is a divergence between results obtained for initial displacement less than 6 mm. After this point, damping ratio calculated from both curve fitting and log-decrement equation agrees well. They both go to asymptote as expected. However, this is not the case when displacement records are used to determine the damping ratio. Differences between the damping ratio values with respect to reference values are tabulated in Table 2.

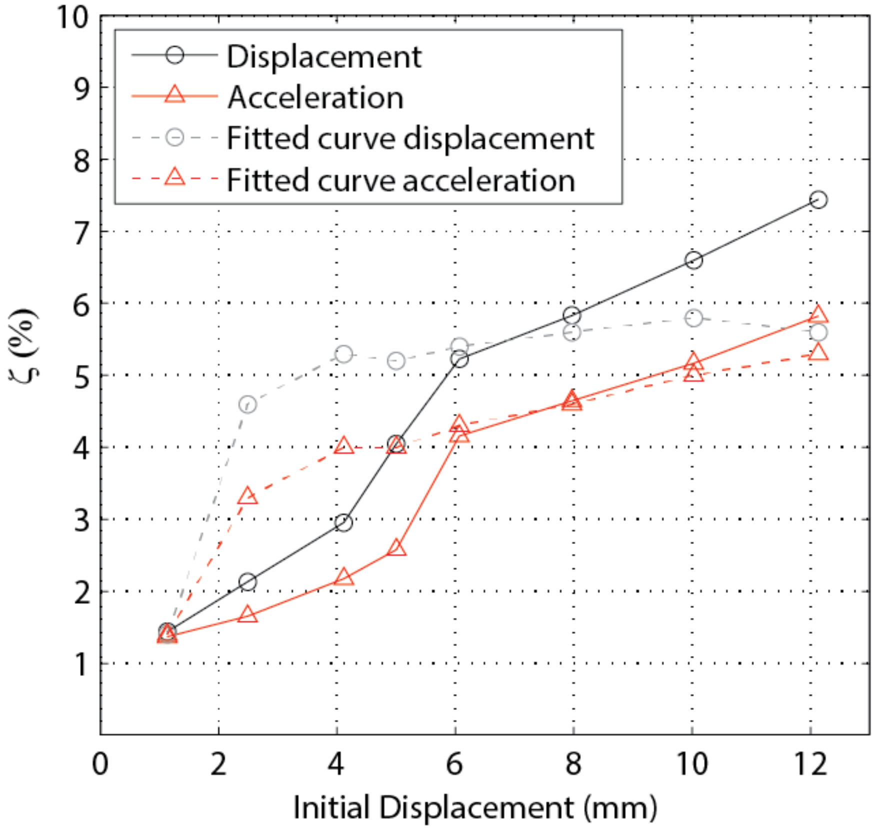

Figure 7. Comparison of results obtained from all approaches

Table 2. Damping values calculated for each test by employing Equation 1-3 and curve fitting method

Exp. #	**Initial Disp. (mm)**	**% difference between reference**		
		Displacement Record	Curve Fitting For Displacement Record	Curve Fitting For Acceleration Record
1	1.0	**5.0**	**2.3**	**2.3**
2	2.5	**22.6**	**64.1**	**49.9**
3	4.0	**26.4**	**59.0**	**45.6**
4	5.0	**36.3**	**50.4**	**35.5**
5	6.0	**20.5**	**23.0**	**3.3**
6	8.0	**20.3**	**17.0**	**-1.0**
7	10.0	**21.7**	**10.9**	**-3.3**
8	12.0	**21.8**	**-4.0**	**-9.9**

CONCLUSIONS

Damping ratio of a steel pedestrian bridge model is determined using free vibration decay tests with different excitation amplitudes created by introducing different amount of initial displacement. Log-decrement equations and exponential curve fitting methods are employed both on acceleration and displacement record obtained during the test. Results indicate that using acceleration records are more reliable since displacements are not directly recorded but numerically calculated from acceleration records. Also, different excitation amplitudes need to be introduced in free vibration decay test. In this study damping ratio of 1-7 % is calculated by using different initial excitation such as from 2 mm to 12 mm. Different amount of initial excitation must be introduced into the structure until asymptotic change in damping ratio is achieved.

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