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FORCED VIBRATION SYSTEM IDENTIFICATION OF A SINGLE-SPAN BRIDGE UNDER VARIOUS DAMAGE STATES

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SUMMARY

Determining a structural system's physical characteristics through dynamic testing procedures is known as system identification and has been explored over the past two decades [Aktan, 1997, Liu and Yao, 1978]. Some of its fundamental principles, however, go back over three decades [Lin, 1985]. Liu and Yao note that prior to system identification most field tests were static tests and could not reveal many of the properties of a given structure [Liu and Yao, 1978]. Current research in the area of system identification is focusing on its capabilities and potential applications in the area of structural damage and integrity assessment.

The application of system identification as a non-destructive evaluation technique requires an initial system identification of a structure, the "before" snapshot, where the dynamic characteristics (natural frequencies, modes and damping) are determined for an undamaged structure. Then after a natural disaster (earthquake, flood, etc.) or a collision the structure undergoes a second system identification, the "after" snapshot. If the structure has been damaged, then the dynamic characteristics of the structure will have changed, primarily due to a change in structural stiffness and damping. These changes will be detected by the post-damage system identification, indicating the location and the degree to which structural damage has occurred.

The research outlined in this paper involved seven forced vibration tests on an isolated single span of a freeway overpass structure. The tests were performed in connection with a series of damage and repair states. For each damage/repair state of the structure, three horizontal natural frequencies and mode shapes were determined through forced vibration analysis. The results of the system identification of each state were then compared to determine the effects and location of the various states of damage and repair.

INTRODUCTION

In May of 1998 the Utah Department of Transportation and Wasatch Constructors made available for structural testing, previous to its demolition, a nine-span steel girder overpass on Interstate 15 (I-15) in Salt Lake City. This structure was subsequently demolished down to a single isolated span, which presented a simple specimen for verification of using system identification as a non-destructive evaluation technique.

The testing of this structure is of interest because of several issues. First, this bridge is field tested at full scale thereby eliminating many of the artificial boundary conditions that are introduced under laboratory testing. Second, this bridge was built in the early 1960's and, therefore, reflects a mature structure as the original or baseline structure. It is also extremely vulnerable to seismic damage and is severely deteriorated from the harsh environment. Third, the large number of condition states at which testing was performed produces a very valuable data set to evaluate the feasibility of utilizing vibration techniques for condition assessment and

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structural health monitoring. These various conditions were available because of the full scale destructive lateral load testing performed by Pantelides *et al*. [Pantelides, 1999].

BRIDGE DESCRIPTION

The test structure consists of a 21.5 meter long span that is supported on the ends by two bents that are at a 17.5 degree skew to the centerline of the bridge. The span consisted of a concrete slab that was 18.0 meters in width and 0.18 meters thick supported by eight steel girders spanning between the two reinforced concrete bents. At the south bent the steel girders were simply supported, resting on steel rocker bearings. At the north bent, the steel girders were also simply supported on steel rollers. The sizes of the columns and bent cap were 0.9 m × 0.9 m and 1.2 m × 0.9 m respectively. The illustration of this test span can be seen in Fig. 1.

Carbon fiber composites, used to retrofit the bridge, were wrapped around the periphery of the lower and upper parts of the columns and around the cap beam at the joints with the columns. Grade beams connected with tie rods were constructed at the pile cap level. These tie rods were also used to connect the pile caps positively to the foundation of the loading frame in order to facilitate the lateral load testing.

DAMAGE STATES

Forced vibration testing was performed on the simple span bridge structure seven different times between May 1998 and July 1998. Testing procedures and instrument placement were identical for all seven tests. The vibration testing was performed between each episode of damage or retrofit. The destructive lateral load testing and retrofit were performed and coordinated by researchers at the University of Utah under the direction of Dr. Chris P. Pantelides [Pantelides, 1999]. This damage was accomplished by pushing and pulling the structure in the transverse horizontal direction (E-W) with the load applied directly to the bent cap.

The conditions at which the structure was tested are summarized in Table 1. A complete review of the tests can be seen in the paper by Muhammad *et al* [Muhammad, 1999].

Table 1. Damage/repair states for the seven forced vibration tests

Test(1)	***North bent (2)***	***South bent (3)***
1	Retrofitted with carbon fiber wraps; Rocker bearings were replaced with transverse rollers	Original condition
2	Unaltered since test 1	Laterally displaced until some yielding occurred in the top joints; minor cracking; concrete spalling
3	Unaltered since test 1	Retrofitted with epoxy injection into cracks; loose concrete was removed
4	Laterally displaced until significant yielding occurred in the top joints and the joint between column and pile cap; carbon fiber composite delaminated	Unaltered since test 3
5	Unaltered since test 4	Retrofitted with shotcreting and carbon fiber composite wrapping
6	Unaltered since test 4	Laterally displaced until significant yielding occurred and more extensive cracking in the top joints; carbon fiber composite delaminated; concrete was severely damaged underneath the composite wrap
7	Transverse rollers were replaced with rocker bearings that were welded into place	Unaltered since test 6

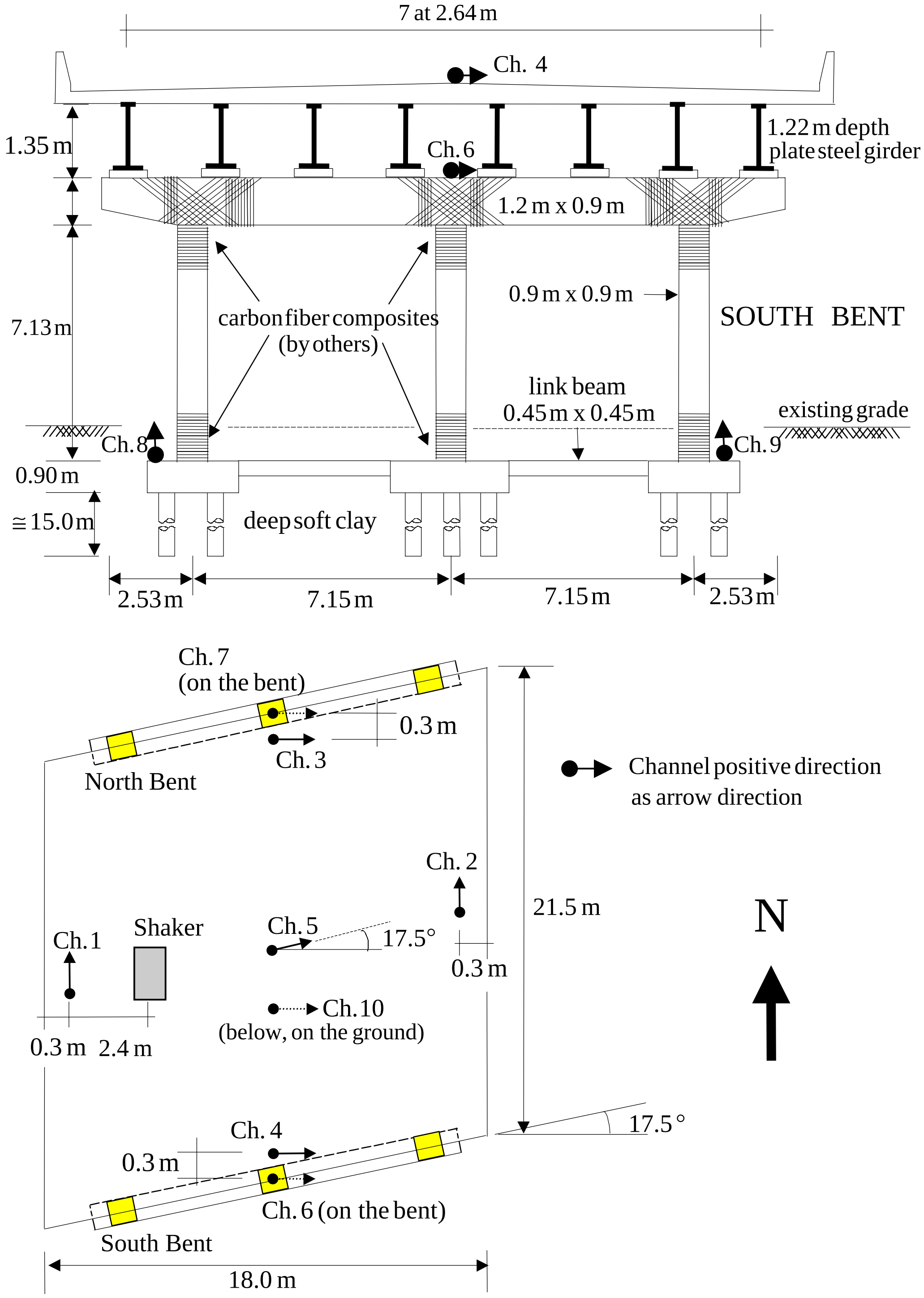

Figure 1. Bridge layout and instrumentation

EXPERIMENTAL PROCEDURES

An eccentric mass shaking machine capable of providing a sinusoidal force function in any horizontal direction provided the forcing. It was mounted at the same location during the two months of testing. The position of the shaker on the deck was chosen so that significant torsion could be induced in the bridge (Fig. 1). Frequency sweep forcing was applied in both the N-S and E-W directions at frequencies between 0.5 and 5.5 Hz at increments of 0.05 Hz.

Responses of the bridge were collected using an array of force-balanced accelerometers that were mounted on the structure. In Fig. 1 accelerometers are shown as channels 1 through 10. The dot and arrow direction of each symbol represents the position and the direction of each accelerometer, respectively. Accelerometers 1, 2, 3, and 4 were placed at the bridge mid-span along the perimeter of the deck, while accelerometer 5 was placed in the middle of the deck. Accelerometers 6 and 7 were placed on the south and north bents respectively. Accelerometers 8 and 9 were placed vertically on the east and west pile cap of the south bent respectively, to record the effects of uplift of the foundation. Accelerometer 10 was a free-field accelerometer that was placed on the ground under the structure.

In this study the three rigid body modes of the bridge deck are considered. Therefore only data from channels 1, 2, 3, 4, and 5 have been analyzed at this time.

Data was collected with a portable data acquisition system that utilizes a 16 bit external analog to digital card and was then fed to a desktop personal computer for storage using data acquisition software. Data processing was accomplished using digital signal processing software.

EXPERIMENTAL RESULTS

After performing a signal analysis of the experimental data, the relationships of displacement per unit force versus frequency and phase angle versus frequency for each test were determined. These plots can be seen in Figure 2. Using these plots, the natural frequencies and the corresponding mode shapes of each mode were determined.

The natural frequencies of the bridge for each test can be seen in Table 2. A decrease in natural frequencies occurs at tests 2, 4, 6, and 7 after the damage applied on one of the bents. On the other hand, a slight increase in natural frequency occurs at tests 3 and 5 after the retrofitting was performed on the South bent

TABLE 2. The natural frequencies and point of rotations from the experimental results

Structural variable (1)		Test 1 (2)	Test 2 (3)	Test 3 (4)	Test 4 (5)	Test 5 (6)	Test 6 (7)	Test 7 (8)
Natural Frequency	f_1 (Hz)	1.28	1.10	1.14	0.86	0.92	0.78	0.79
	f_2 (Hz)	2.18	1.55	1.65	1.20	1.30	1.10	1.15
	f_3 (Hz)	2.79	2.10	2.15	1.75	2.09	1.39	1.40
Point of Rotation	x_1 (m)	-632	-119	891	278	2556	584	-510
	y_1 (m)	1887	362	-2596	-991	-7396	-1811	1615
	x_2 (m)	25.9	-30.1	-38.7	18.4	15.7	192	232
	y_2 (m)	11.1	-11.2	-13.3	12.1	10.9	74.7	85.2
	x_3 (m)	-2.41	3.10	2.57	-4.85	-4.83	0.05	-0.18
	y_3 (m)	-0.28	1.22	1.68	-1.27	-0.05	0.51	-0.20

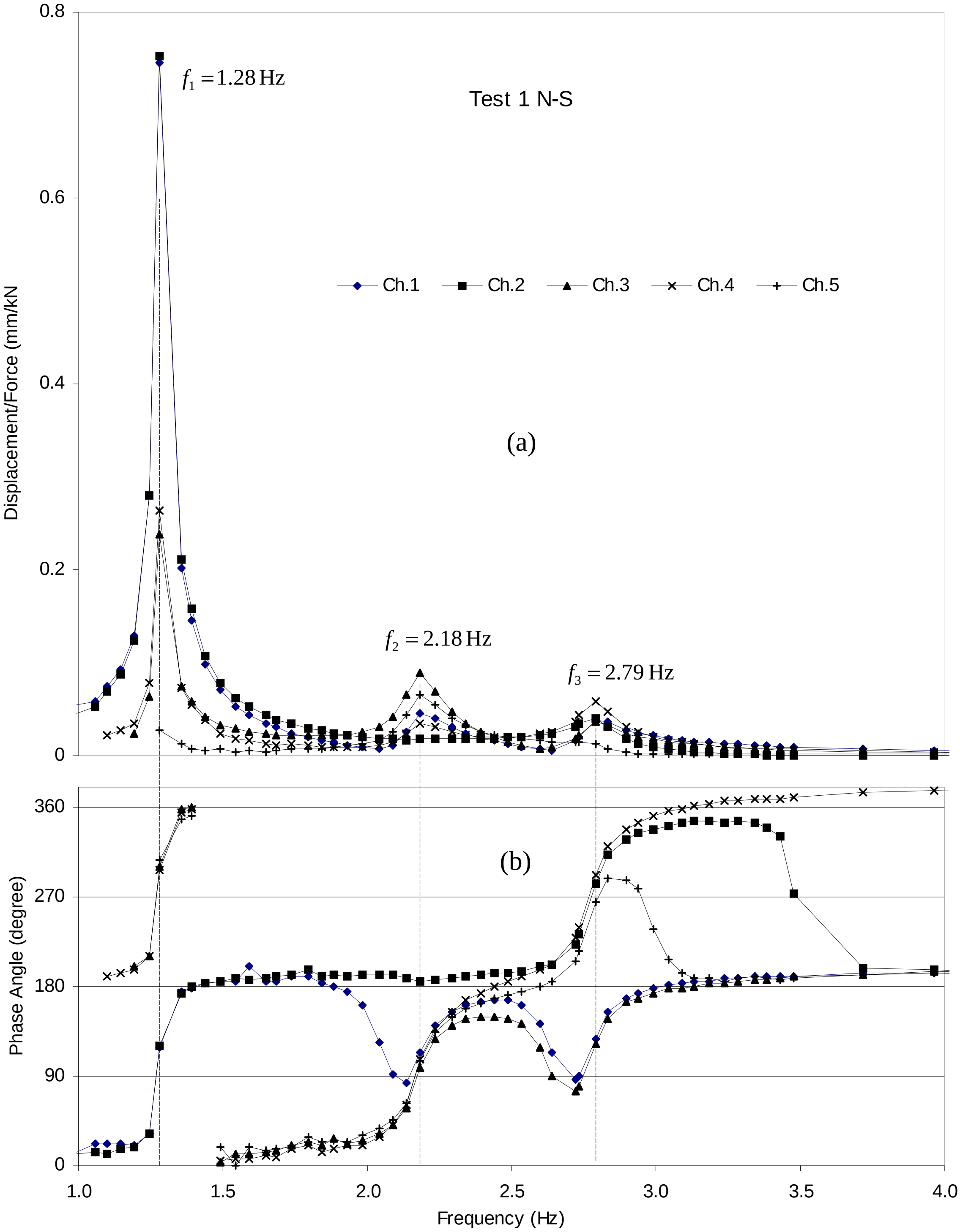

Figure 2. Displacement per Unit-Force and Phase Angle versus Frequency of Test 1 N-S Excitation

The mode shapes of the structure can be seen in Fig 3. For clarity, only the results of tests 1, 2, 4, and 6 are shown. As can be seen, mode 1 is predominantly longitudinal; mode 2 is predominantly transverse; and mode 3 is predominantly torsional.

The mode shapes of the rigid body deck can also be described in general as their motion about a certain point with certain radius to this point, namely point of rotation. This point is represented in this study by p_{ij}, in which i represents the mode, and j represents the test number. By geometry, perpendicular bisectors to the displacement lines will intersect at the point of rotation. Using this technique, by knowing the displacement of the rigid body of the deck, its point of rotation can be obtained. The points of rotation of modes 2 and 3 can be seen in Fig. 4.

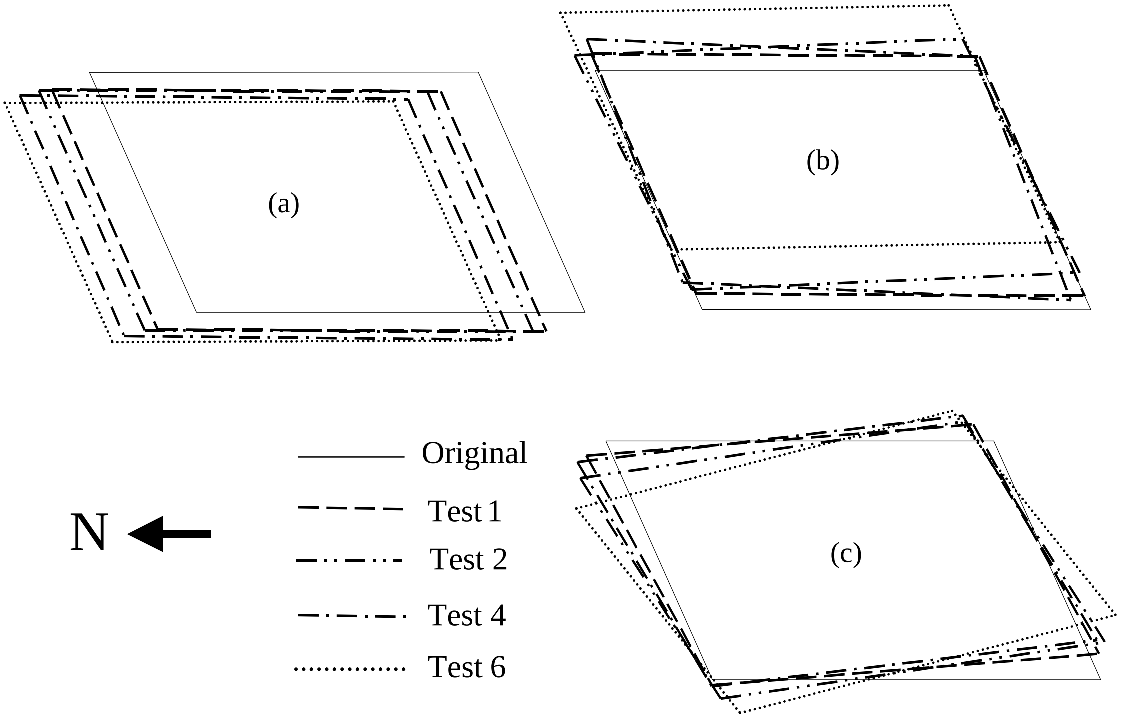

Figure 3. Mode shapes of tests 1, 2, 4 and 6; (a) mode 1; (b) mode 2; (c) mode 3

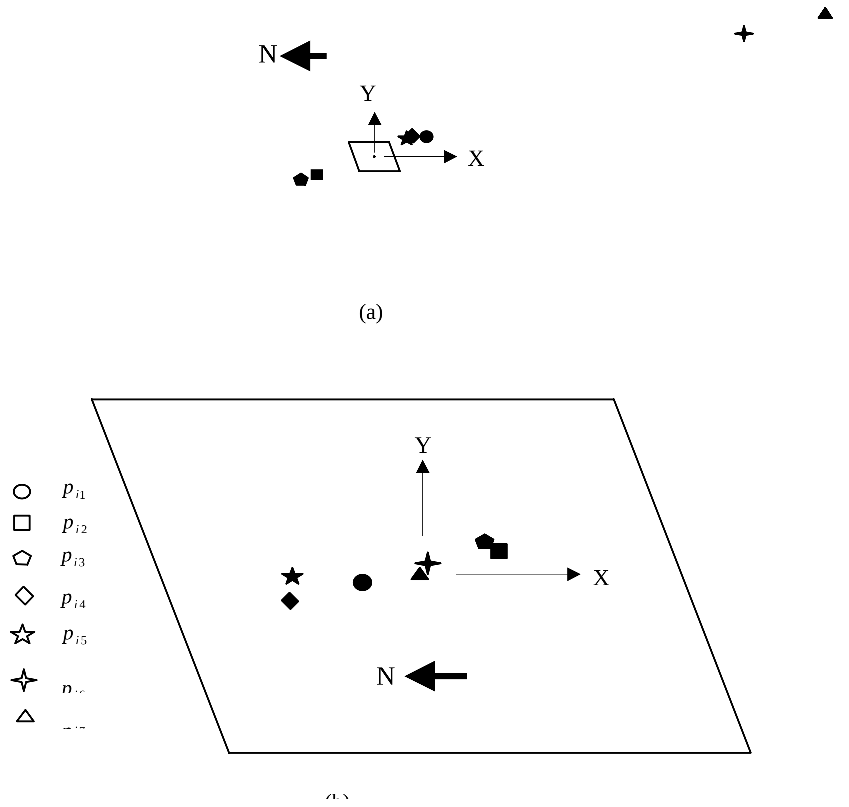

Figure 4. Point of rotation of rigid body; (a) mode 2; (b) mode 3

MODE SHAPES AND POINT OF ROTATION

Mode shape and points of rotation can give information about the damage by finding the displacement of each mode at each test. The difference can be used to indicate the location where damage/repair has occurred. The identification of damage is simpler in this study because there are only two bents that can be damaged.

Upon observation of the analysis results a relationship between the points of rotation and damage was discovered for the rigid body problem. The location of the point of rotation will indicate the amount of translation and rotation associated with a particular mode. The farther away the point of rotation moves away from the structure the more the ratio of translation versus rotation content increases. When a shift in the point of rotation for a particular mode occurs, it is an indication of a lopsided gain or loss of stiffness in the structure. In each case the shift can be examined to determine where the lopsided change has occurred.

There is currently detailed parameter modelling under way to help in interpreting the meaning of the points of rotation. This parameter modelling gives a greater understanding as to the relationship between the points of rotation and the location and degree of the gain/loss of stiffness.

CONCLUSION

This study has yielded several important conclusions and hence encourages further research to take place in using system identification as a non-destructive evaluation technique. The following conclusions were drawn on this research:

1. The changes of frequency at every state of tests related to the changes of stiffness due to damage or retrofit work on the structure.

2. The use of epoxy, shotcreting, and carbon fiber (in tests 3 and 5) slightly improved the stiffness of the damaged structure as indicated by slight increase in frequency.

3. The changes of frequencies and mode shapes (point of rotation) at each test are unique. Therefore, they can be used as a good indication in assessing the structural integrity from one state to the other state. The movement of point of rotation from one test to the other and the changes of the mode shapes can be used as indication to locate the damage or retrofit on the bent.

4. The forced vibration testing performed in this study could be used as a non-destructive evaluation test in assessing the structural integrity of the bridge.

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