ABSTRACT
This paper focuses on the correlation between frequency of a structure and degree of damage by testing a full-scale beam both statically and dynamically. To improve the quality of test data and reduce the effort for identifying the fundamental frequency of the beam, preloads are applied to the beam before conducting the dynamic tests. Test results have confirmed that the frequency of the beam itself depends on the load history while that of the beam plus sufficient preloads can be identified independently. This is because preloads can keep cracks open so that the cracked beam vibrates in a linear fashion.

INTRODUCTION
The dynamic Signature Test (DST) provides a viable tool to rapidly assess the condition of structures. It involves a series of vibration monitoring steps over the service life of a structure. The differences in two steps are caused by damage that a structure may have experienced during that time interval. Damage will soften the structure and thus modify its dynamic characteristics such as the frequency. The relationship between the degree of damage and the change in frequency is fundamental in order to diagnose any damage occurring in a structure.

DST has been applied by Yao et al. (1992) to diagnose damage occurring in a steel frame. The dynamic behavior and vibration monitoring of small-scale reinforced concrete (RC) beams was studied by Wang et al. (1998) using acoustic emission under ideal boundary conditions. Doebling et al. (1988) and Salawu (1997) reviewed the current development on the subject of vibration-based detection of structural damage and Mazurek et al. (1990) applied the techniques into bridge monitoring study.

This paper is aimed at calibrating the change in frequency with the degree of damage in RC structures. This calibration is accomplished by testing a 6.1-meter-long (20 ft.) RC beam both statically and dynamically. The concept of preloading the beam before dynamic tests is proposed to reduce the effort for frequency identification and improve the quality of test data. It is noted that
the RC beam tested represents a unit stripe of existing concrete slab bridge in the State of Missouri.

**TEST SETUP**

A 6.1-meter-long (20 ft.) concrete beam with a 38cm x 47cm (15" x 18-1/2") cross section is reinforced with two No.5 and two No.6 rebars at the bottom side only. The bars are made of Grades 50 and 80 steel, respectively. The compressive strength of the concrete is 39.8MPa (5770 psi).

The RC beam is simply supported on two steel structural shapes. The static and dynamic testing apparatus are set up as shown in Fig.1(a,b). For static tests, a point load is applied at midspan with a 30-ton hydraulic actuator installed between the RC beam and a reaction cross beam anchored to the strong floor with two threaded rods. For dynamic tests, a mechanical oscillator is fixed to the top surface of the beam at midspan to generate a harmonic force.

![Figure 1. Test Apparatus](image)

**TEST PLAN AND PROCEDURE**

The cracking and ultimate moments of the cross section are respectively equal to 53.3 kN.m (39.3 kip.ft) and 176.3 kN.m (130 kip.ft). Their corresponding point loads at midspan are $P_{cr}=36.6$ kN (8.22 kips) and $P_{u}=121.0$ kN (27.2 kips), respectively. According to the bridge of reference, the equivalent service load is approximately equal to $P_{ser}=40.5$ kN (9.1 kips).

Two factors are considered to determine the dynamic load for the beam test. One is to avoid any movement of the beam at its supports. The other is to consider the softening effect on frequency as cracks develop in the beam and the effect of a preload (mass), which amounts to 50% reduction in natural frequency. The first factor is taken into account by limiting the beam acceleration to less
than one g (gravitational acceleration). The second is implemented by estimating the lowest natural frequency of the cracked beam with preload. In compliance with the above two criteria, the magnitude of the dynamic load is determined to be $P_0 = 413$ N (92.9 lbs).

Two criteria are set to determine the maximum preload. One is to avoid any potential cracking of the tested beam as a result of preloading and dynamically loading since DST is not supposed to impose any additional cracks. The second is to limit the maximum preload within the equivalent point load at midspan due to service load of the existing concrete slab bridge. Based on these criteria, the maximum preload is estimated to be 19.8 kN (4.45 kips) provided that the damping ratio of the beam is assumed to be 1% at initiation of cracking. For the beam tested, the preload up to 11.9 kN (2.68 kips) was employed during dynamic tests, which represents about 50% of the weight of the RC beam. These loads were physically provided by firmly attaching steel plates on top of the beam as seen in Fig. 1(b).

To correlate the change in frequency with the degree of damage of the beam, static and dynamic tests were conducted in parallel. The beam was tested statically and dynamically in seven stages. At the end of the seventh stage, the beam was statically loaded to failure to determine its ultimate capacity. Each stage consists of two steps: 1) Slowly load and unload the beam at midspan once at the previous level of static load and twice at the current level; 2) Symmetrically attach to the beam at both sides of midspan as preload and apply a harmonic load at midspan with a mechanical oscillator.

Based on the cracking and ultimate loads, the static loads for seven stages of tests were determined as 35.6 kN (8 kips), 44.5 kN (10 kips), 62.3 kN (14 kips), 80.1 kN (18 kips), 97.9 kN (22 kips), 115.7 kN (26 kips), 124.6 kN (28 kips).

**TEST RESULTS AND ANALYSIS**

For simplicity of analysis, the degree of damage is represented by the static load to which a RC beam has been exposed. The load-displacement relation at midspan in seven stages and beyond is presented in Fig. 2. It can be observed that the beam starts cracking around the theoretical $P_{cr}$ and has the ultimate strength of 132 kN (29.7 kips), approximately 9% higher than the theoretical value.
The fundamental frequency of an elastic beam with a preload \( (P_p) \) at midspan can be derived by perturbation theory and expressed by

\[
f_p = f_0 \sqrt{1 + 2 \frac{P_p}{W}}
\]

where \( W \) represents the total weight of the beam; \( f_p \) and \( f_0 \) are the frequency of the beam with and without the preload, respectively. The frequency ratio between a beam with and without preload was calculated by Eq. (1) and compared in Fig. 3 with experimental results. It can be seen that the theoretical curve agrees very well with the experimental data and therefore it can be used to convert the frequency of a beam with preload, identified from resonance tests, into that of the beam alone regardless of the level of static loads. Figure 3 can be reproduced to show in Fig. 4, the frequency ratio of a loaded and an unloaded beam as a function of static loads. As one can see, the frequency ratio remains constant in the elastic range and decreases rapidly as the beam starts cracking. The unique relation between the frequency ratio and the static load makes it possible to quantify the degree of damage in a RC beam. This relation can be predicted using the linear model based on the cracked section properties. This part is not presented here due to the limited space.

One unique feature related to the nonlinear vibration of a cracked RC beam was observed during dynamic tests using harmonic loads. The amplitude of midspan deflection \( (D_{max}) \) after the 5th stage of static tests is presented in Fig. 5, in which four transfer functions are shown by decreasing and increasing the exciting frequency of harmonic loads. The characteristic frequencies at peak of the transfer functions vary significantly, implying the dependence of the frequency on loading history. While this phenomenon represents a typical nonlinear vibration problem, it was observed during testing that these frequencies will eventually converge to one after a long period of vibration. This may be caused by the loose debris in cracks that are crashed into small pieces after a while. The beam is then referred to as at resonance. This peculiar phenomenon in the context of linear vibration...
obviously increases the effort to identify the natural frequency and will contaminate the test data if not recognized.

The above phenomenon can be eliminated by introducing a sufficient preload on the beam before dynamic tests. Figure 6(a,b) show the transfer functions of midspan deflection of the beam without and with preload. It is clearly indicated that the resonance frequency can be easily identified from the tests with preload. This observation was confirmed during tests. In fact, it takes about 10% or less time to identify these frequency compared to those shown in Fig. (a).

CONCLUSIONS
The dynamic Signature Test has been demonstrated to be effective in detecting the overall damage in a RC structure. The degree of damage can be well correlated with the fundamental frequency of the structure. Based on this study, the following conclusions can be drawn:

1) The concept of applying preload in dynamic tests can improve the quality of test data and save tremendous time in the test. This is because the preload can keep cracks always open so that the beam vibrates linearly when subjected to dynamic loads.

2) The dynamic test under harmonic loads shows some unique features related to the nonlinear vibration of RC structures that cannot be detected by applying a wide-band input. The transfer functions obtained from this study is load-history dependent. This phenomenon may be attributable to the loose debris on crack surfaces and will be subject to further study.

3) The frequency of a RC beam can be determined from that of the beam plus a preload system that is directly identified from resonance tests. The theoretical relation between the frequencies is applicable regardless of the level of damage in structures.

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REFERENCES


