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Stiffness Estimates Using Portable Deflectometers

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ABSTRACT

The use of falling-weight deflectometers (FWD) and portable falling-weight deflectometers (PFWD) is nowadays common for field characterization of pavement system layers. In particular, the application of portable deflectometers in quality assurance of newly constructed granular base has become more widespread. Typically, these devices are used for an in-situ assessment of the Young's modulus of the base layer. The traditional back-calculation uses an elastostatic half-space framework to relate Young's modulus of the pavement foundation to the stiffness estimates obtained from force and velocity measurements. The data interpretation method that is customarily used for stiffness estimation uses peak values of the force and displacement records in lieu of their static counterparts. This study deals with the performance of a particular device, PRIMA 100, which is examined via the newly developed Beam Verification Tester (BVT) of known static stiffness. It is shown that the conventional, peak-based method of back-analysis produces incorrect estimates of the static stiffness of the BVT. An alternative, spectral-based data interpretation method is proposed. This method, based on: (i) concept and measurement of the frequency response function, and (ii) a single-degree-of-freedom mechanical model, is employed to extract the true static stiffness from PRIMA 100 measurements. The results show a good agreement between the true static stiffness of the BVT and its PFWD estimates stemming from the modified approach. The BVT apparatus can therefore be used to assess the performance of the sensors and data interpretation of PRIMA 100-type deflectometers.

INTRODUCTION

Deflectometer-type devices are dynamic non-destructive testing tools commonly utilized in field characterization of pavement systems. These devices impart an impact or vibratory load to the road surface, with the applied force and the induced pavement surface motion being simultaneously monitored. The property directly estimated from the experimental force and surface deflection records is often the static stiffness of the loading plate-pavement system, with the pavement Young's moduli resulting a posteriori from the elastostatic data interpretation. A well-known example of such devices is the Falling Weight Deflectometer (FWD). Indeed, the backcalculation of the elastic properties of pavement layers on the basis of FWD measurements is a well-recognized procedure in pavement integrity assessment (cf. Lytton (*1*)).

Among the various testing devices used for non-destructive in-situ assessment of pavement layers, portable deflectometer-type devices, such as the GEOGAUGE, PRIMA 100, and LOADMAN, have recently become the focus of increasing interest. Similar to the full-scale deflectometer tools, they incorporate the dynamic force and velocity measurements. They evaluate the elastic stiffness of the loading plate-base or subgrade system, often referred to as the "soil stiffness", and provide the user with an estimate of the equivalent-homogeneous Young's modulus of the granular base and subgrade layers, usually modeled for the purpose of back-analysis as a homogeneous elastic half-space.

In the context of non-destructive field characterization of paving materials, most publications dealing with the performance of deflectometer-type devices make use of field results from competing devices. It is well known, however, that the modulus estimates obtained in the field are strongly dependent on the level of stress applied to the soil (cf. Hardin and Drnevich (*2*)), and therefore on the particular device being used. For example, one can refer to the comparative studies of Chen et al. (*3*), Siekmeier et al. (*4*), Mc Kane (*5*), Van Gurp et al. (*6*), and Fleming et al. (*7*) as an illustration of the discrepancy between stiffness estimates stemming from various deflectometer tools. Unfortunately, the in-situ elastic properties of soils and granular materials are generally unknown; as a result, the correctness of stiffness estimates associated with a given device is difficult to evaluate in the field.

This paper presents an assessment of the reliability of the stiffness estimates obtained using PFWD tools. Three issues are addressed: (i) design of a laboratory tool to verify the stiffness estimates stemming from a given portable device, (ii) scrutiny of the traditional backcalculation procedure for stiffness estimates, and (iii) investigation of an alternative stiffness estimation method. One particular PFWD tool, PRIMA 100, is chosen as an example in this study. More details on this research can be found in (*8*).

PRIMA 100

The Device

The PRIMA 100 device was obtained from the Danish company Carl Bro Pavement Consultants. The device is composed of three main parts (Figure 1a): (i) base with loading plate, sensors and associated electronics, (ii) falling weight (10 kg sliding hammer), and (iii) upper frame (sensor housing, rubber buffers, and guidance rod). The base incorporates two sensors: a load cell, and a geophone (velocity transducer). Both sensors are connected to an electronic box comprising the data acquisition and filtering systems. The loading plate is circular with a 10 cm diameter. Additional rings can be attached to it to obtain loading plates of 20 and 30 cm diameter, to accommodate different soil types and contact pressure.

During testing with PRIMA 100, the load is applied to the road surface via the circular plate. The resulting force and velocity time histories are measured above and below the center of the plate, respectively. The corresponding displacement time history is automatically obtained by means of integration (internal to the device) of the velocity record. PRIMA 100 is connected to a computer equipped with software for recording, data interpretation, and visualization. The output includes respective time histories and peak values of the applied load f(t) and ensuing deflection x(t), as well as an estimated value of the soil Young's modulus E. A typical plot of the force and deflection time histories data generated by PRIMA 100 is presented in Figure 2a. The plot corresponds to a test performed on the laboratory concrete floor, but its key characteristics are comparable to those obtained from a field test. These are: (i) the peak value of the deflection signal lags behind the respective force peak, and (ii) the general trend of the displacement signal shows amplitude decay after the peak of the first oscillation. The time lag between the peak values is due to the effects of inertia. The deflection signal decay is mostly due to the effects of radiation damping (i.e. geometric spreading) in the medium below.

Data Interpretation

In the interpretation of PFWD measurements (including those obtained from PRIMA 100), it is generally assumed that the pavement foundation can be simulated as a half-space that is elastic, homogeneous, and isotropic. The material of the half-space (base or subgrade) is characterized by the Poisson's ratio ν and Young's modulus E; the latter should be regarded as an equivalent-homogeneous modulus if the pavement system consists of several layers. For the load applied over a circular area of radius a, the following relationship can be derived from the well-known Boussinesq point-load solution (cf. Craig (*9*))

$$E = 2k_s \frac{1-\nu^2}{\eta a} \tag{1}$$

In Equation 1, η is the shape factor dependent upon the stress distribution applied ($\eta = \pi$ when the stresses are uniform, the case of so-called "flexible loading" plate, and $\eta = 4$ when the stresses result from imposed uniform displacements, the case of rigid loading plate), and k_s is the ratio of the applied resultant force f and induced resulting vertical displacement x at the center of the circular loading area

$$k_s = \frac{\text{f}}{x} \tag{2}$$

Owing to the fact that Equations 1 and 2 assume *static* loading, k_s is often called the static stiffness of the loading plate/half-space system. It is evident that the elastostatic analysis provides a closed-form solution for the Young's modulus of the half-space in terms of the static stiffness k_s and Poisson's ratio v.

When applying dynamic load, both force f and displacement x are functions of time. The temporal spectra of these quantities are usually disregarded, and the common practice in FWD testing (Lytton (*1*)) is to estimate the static stiffness of the loading plate-soil system from the peak values of the load and displacement time histories according to

$$k_{peak} = \frac{\text{f}_{peak}}{x_{peak}} \tag{3}$$

LABORATORY TESTS

Beam Verification Tester

To examine the performance of PRIMA 100, a laboratory device named the Beam Verification Tester (BVT) was developed at the University of Minnesota for the Minnesota Department of Transportation (*8*). The underlying concept of the BVT test is to simulate a linear support system of known and adjustable stiffness, which can be dynamically loaded by the PRIMA 100 device. The support system should respond in a well-understood fashion to both static and dynamic loads, and can be instrumented to provide accurate load and displacement data. Finally, the device should occupy a limited space, be movable, and be accommodated in a laboratory setting easily. These requirements are met by a simply supported steel beam with variable span.

The BVT, schematically shown in Figure 3a, resembles a four-point bending test. Its components are: (i) a 93 cm long, and 10.16 cm x 1.59 cm (4" x 5/8") in cross section, steel "verification" beam resting on two cylindrical supports, (ii) a support I beam, attached to a heavy I steel beam (rigid foundation), and (iii) a rigid receptacle for the PRIMA 100 device (with 10 cm loading plate), resting on two cylindrical supports. During testing, the base of PRIMA 100 and the verification beam experience the same rigid body motion. Adjustable clamps are used to ensure firm contact between various elements during impact testing.

Slots are machined on the top of the support beam to allow for five different beam spans, ranging from 30 cm to 70 cm. However, only the 50 cm, 60 cm, and 70 cm spans were used in this investigation. Auxiliary dampers can be attached to the ends of the verification beam, Figure 3b, to provide additional damping to the BVT.

Experimental values of the static stiffness k_s of the verification beam were obtained from a series of static load-deflection tests performed with an MTS load frame. Table 1 reports the experimental stiffness values, obtained from the experimental force vs. displacement curves using a linear least-square fitting. These results were corroborated by measurements using strain gages attached to the verification beam, whose readings were analyzed following the four-point bending test theory. For the selected beam spans, the value of k_s ranges from 1.06 to 3.08 MN/m, which is not too far below the realistic range of in-situ base and subgrade stiffnesses; 6 MN/m to 24 MN/m with the loading plate of 10 cm to 30 cm diameter resting on typical construction soils.

Testing the BTV with the whole PRIMA 100 device attached, and dropping the 10 kg mass over the heights up to 1 m, produced the load pulse of about 15 ms, with its peak value up to several kN. However, due to low mass of the verification beam, this dynamic load produced unacceptable "ringing" of the whole tester. Reducing the drop height eliminated somewhat the ringing: dropping the 10 kg mass over the height of 10 cm induced the load pulse with its peak value reaching approximately 1 kN. Consistent results without the parasitic ringing were obtained with the upper frame and guiding rod of PRIMA 100 removed, and the load applied by a small rubber hammer directly to the top of the load cell. Using this configuration, referred to as modified (Figure 1b), the period of the load pulse ranges approximately between 4 and 10 ms, with peak values significantly below 1 kN.

Owing to the low amplitude of the rubber hammer impact force and the resulting full linearity of the tester response, the modified configuration was selected for most of the verification tests. It should be emphasized that by removing the upper frame of PRIMA 100 no structural or sensory integrity of the device was violated, and the software recorded accurate results.

Verification Tests

Typical force and deflection records obtained from PRIMA 100 software during a BVT test with modified configuration are presented in Figure 2b. As in the case of Figure 2a, the displacement signal in Figure 2b lags behind the force signal signifying the inertial effects. However, the displacement signal in Figure 2b does not die out at the end of the available acquisition window of 60 ms. This difference in the displacement time history durations is primarily due to the fact that the beam has very little damping, while testing concrete floor shows much higher (intrinsic and radiation) damping characteristics. Even though the modified configuration was preferable, tests also were conducted with the original PRIMA 100 configuration and 10 cm drop height.

In the BVT verification tests, peak stiffness k_{peak} was computed from Equation (3), using peak force and displacement values displayed by PRIMA 100 software. Next, k_{peak} values were compared to k_s

values, the true verification beam stiffness, for each beam span tested. The average results from several series of tests, shown in Table 1, indicate a significant discrepancy between the true static stiffness of the beam and the peak estimates. The two sets of measurements involving the original and modified PRIMA 100 configurations give different results for k_{peak}, but neither one is in a good agreement with the true value of BVT stiffness, k_s. The ratio k_{peak}/k_s ranges between 0.72 and 3.21, which corresponds to k_s estimation error ranging from 30% to 220%. It is also seen that for shorter beam spans k_s is underestimated, whereas it is overestimated for longer spans.

Two possible reasons can contribute to the observed misfit: inaccurate PRIMA 100 sensors, and inconsistency of the peak-method of stiffness calculation. Sensitivity and output of both PRIMA 100 sensors were checked: (i) the load cell under static dead loads, and (ii) the geophone during impact testing, by comparison of its time history with those obtained from additional sensors (accelerometers and geophone) attached to the BVT. A good agreement between the output of PRIMA 100 sensors and verification tests testify to the quality of the sensors. The geophone verification tests also proved the correctness of the velocity integration algorithm for displacements calculation embedded in PRIMA 100 software. Since inaccuracy of PRIMA 100 sensors must be ruled out, the stiffness prediction error is attributed to the peak-based data interpretation method. In fact, this method is nowadays recognized (e.g. Roesset (*10*); Guzina and Osburn (*11*)) as a possible cause for the inconsistency of FWD field results.

ALTERNATIVE METHOD FOR STIFFNESS ESTIMATION

Theoretical Background

As mentioned earlier, the peak method of static stiffness evaluation disregards the transient nature of the load and displacement histories recorded on the BVT that responds as an inertial system to impact loads. When considering inertial systems, it is convenient to analyze their response in the frequency domain rather than in the time domain. This change of domain can be accomplished by means of either the continuous, or discrete (DFT), Fourier transform of time domain data, with appropriate algorithms such as the Fast Fourier Transform algorithm (FFT) readily available in numerical modules. The frequency-domain, or spectral analysis of force and displacement data was used, for example, by Briaud and Lepert (*12*) in their study of foundation system, and by Guzina and Osburn (*11*), for the back-analysis of multi-layered pavement systems.

The, spectral analysis of transient data for a linear system makes use of a frequency response function (FRF) defined as the ratio between the Fourier transform $\Psi(f)$ of the output $\psi(t)$, and the Fourier transform $\Theta(f)$ of the input $\theta(t)$, i.e.

$$\text{FRF}(f) = \frac{\Psi(f)}{\Theta(f)} \tag{4}$$

where $f = \omega/2\pi$ is the linear frequency and ω is the angular frequency.

In the following, we consider two particular FRFs, namely, the dynamic stiffness $K(f)$ and mobility $M(f)$ defined by

$$K(f) = \frac{F(f)}{X(f)} \tag{5}$$

$$M(f) = \frac{\dot{X}(f)}{F(f)} \tag{6}$$

where $F(f)$, $X(f)$ and $\dot{X}(f)$ are the respective Fourier transforms of the force f(t), the displacement x(t), and the velocity $\dot{x}(t)$.

One should note that the static stiffness of a linear system corresponds to the magnitude of the dynamic stiffness $K(f)$ at zero frequency, $f = 0$. This implies that for evaluating k_s, the distribution of $K(f)$ at low range of frequencies should be known from experiments. However, due to inherent limitations, geophones do not give reliable measurements in the low frequency range. As a guideline, the output of a common geophone with a natural frequency of the order of 5 Hertz should not be taken into account for frequencies below 10 – 20 Hz. As a result, the $K(f)$ value at zero frequency cannot be estimated directly from the motion measurements. To overcome this problem, one must extrapolate experimental data to zero frequency. As data extrapolation may be inaccurate, a suitable theoretical model of the system considered is needed as a guide for the extrapolation.

A model that has found a wide application in analyzing the dynamic response of linear systems is the Single Degree of Freedom (SDOF) mechanical system containing three elements: stiffness k, mass m, and damping coefficient c, as shown in Figure 4. The differential equation governing the dynamic response of a SDOF system is

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = \mathrm{f}(t) \tag{7}$$

where $\ddot{x}(t)$ denotes the acceleration. In simulating the BVT response to PRIMA 100 loading as that of a SDOF system, it is assumed that the SDOF constant k corresponds to the static stiffness of the beam k_s. Similarly, the mass m comprises the mass of the PRIMA 100 device and receptacle, plus the mass of all other components located between the verification beam and the point where the load is measured. The coefficient c accounts for the internal and contact friction in the BVT.

Dynamic stiffness function $K(f)$ and mobility $M(f)$ of the SDOF system are readily obtained from the equation of motion, Equation 7, using Fourier transforms and their properties. They are given by the following complex-valued functions

$$K(f) = k\,[(1 - \beta^2) + 2\,i\,\xi\,\beta]$$ (8)

$$M(f) = \frac{1}{k}\,\frac{2i\pi\,f}{(1 - \beta^2) + 2\,i\,\xi\,\beta}$$ (9)

where

$$\beta = \frac{f}{f_n}$$ (10)

is the tuning ratio,

$$\xi = \frac{c}{4\pi\,m\,f_n}$$ (11)

is the damping ratio, and

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$ (12)

is the undamped natural frequency.

One may note that the real part of Equation 8

$$\mathrm{Re}\{K(f)\} = k\,(1 - \beta^2)$$ (13)

does not depend on damping, is represented by a parabola, and can easily be used to extract the $k_s = k$ value at $f = 0$ of the Fourier-transformed experimental data. Alternatively, the data can be fitted to the $K(f)$ and $M(f)$ spectral distributions, Equations 8 and 9. However, because the mobility function is related *directly* to the measured force and velocity, this function rather than the dynamic stiffness is preferable for curve fitting.

Validation Tests

Tests were conducted on the BVT to validate the spectral method of static stiffness estimation via the mobility function $M(f)$. As the correctness of the Fourier Transform data depends critically on capturing the entire time records of transient signals, the PRIMA 100 data acquisition system with a 60 ms window was

replaced by a SigLab spectral analyzer that allowed for recording the signals up to 3.2 s. It was verified experimentally that both the force and velocity signals died out over this period.

To reduce the effects of experimental noise and variability, a spectral average technique was used. As demonstrated by Bendat and Piersol (13), the spectral average technique is very efficient in minimizing the errors. More recently, Guzina and Osburn (*11*) applied this technique to obtain reliable FRFs pertaining to the FWD data. In the spectral average technique, the mobility function is estimated from

$$M(f) = \frac{G_{f\dot{x}}(f)}{G_{ff}(f)} \tag{14}$$

where $G_{f\dot{x}}(f)$ is the one-sided cross-spectral density function of the force and velocity records, and $G_{ff}(f)$ is the one-sided auto-spectral density function of the force record. When dealing with N_T ($n = 1, 2, \dots N_T$) discrete digital records of length N each, the one-sided spectral density function are given by

$$G_{f\dot{x}}(f_j) = \frac{1}{N_T} \sum_{n=1}^{N_T} [F(f_j)^*]_n [\dot{X}(f_j)]_n \tag{15}$$

$$G_{ff}(f_j) = \frac{1}{N_T} \sum_{n=1}^{N_T} [F(f_j)^*]_n [F(f_j)]_n \tag{16}$$

where f_j is the discrete (sampling) frequency. In Equations 15 and 16, $[F(f_j)^*]_n$ and $[\dot{X}(f_j)^*]_n$ denote the complex conjugate of the averaged discrete Fourier transforms (DFTs) of the force and velocity records

$$[F(f_j)]_n = \Delta t \sum_{q=0}^{N-1} [f(t_q)]_n e^{-2\pi i t_q f_j}, \; j = 0,1,2...N-1 \tag{17}$$

$$[\dot{X}(f_j)]_n = \Delta t \sum_{q=0}^{N-1} [\dot{x}(t_q)]_n e^{-2\pi i t_q f_j}, \; j = 0,1,2...N-1 \tag{18}$$

where $t_q = q\,\Delta t$ and Δt is the sampling period. The spectral averaging approach also allows for assessing the quality of the measurements and validity of the linearity assumption via the coherence function

$$\gamma^2(f) = \frac{|G_{f\dot{x}}(f)|^2}{G_{ff}(f)G_{\dot{x}\dot{x}}(f)} \tag{19}$$

where $G_{\dot{x}\dot{x}}(f)$ is the one-sided auto-spectral density of the velocity record, i.e.

$$G_{\dot{x}\dot{x}}(f_j) = \frac{1}{N_T}\sum_{n=1}^{N_T}[\dot{X}(f_j)^*]_n[\dot{X}(f_j)]_n \qquad (20)$$

The coherence function assumes values in the range from $\gamma^2(f)=0$ if no correlation exists between the input and output, to $\gamma^2(f)=1$ when the system is perfectly linear and noise-free are the measurements. The SigLab spectral analyzer has built-in FFT and spectral density functions computation.

An in-house Matlab code was used to fit the theoretical $M(f)$ curve of the SDOF system, Equation 9, to the experimental mobility data, Equation 14. The fitting process followed a Matlab built-in optimization method, which uses the simplex search method of Nelder and Mead (*14*), and the least-square minimization of differences between measurements and trial SDOF mobility function.

Validation tests with the modified PRIMA 100 device were conducted for 50, 60, and 70 cm spans of the BVT. The mobility function $M(f)$ was estimated as a spectral average of a series of ten measurements, together with the coherence function $\gamma^2(f)$. It was found that for frequencies higher than 150/200 Hz, the measurements were associated with a significant decrease of the coherence function, which indicates that the beam response was non-linear, noisy, and with stray vibrations. Accordingly, with $\gamma^2(f)>0.95$ taken as a threshold, the acceptable frequency range for data interpretation was found to be 10 - 150 Hz. Also, as the coherence function decreased in the vicinity of the fundamental natural frequency of the beam ($f_n \approx 50$ Hz), experimental points near f_n were excluded from the fitting process.

Figure 5 shows an example of the real and imaginary parts of the SDOF mobility curves fitted to the experimental data for the 60 cm span. It can be seen that the SDOF analog matches the experimental data well. From this fitting process, the parameters of the equivalent SDOF system, i.e., stiffness k, damping coefficient c, and mass m were estimated. The mobility function-obtained values of the BVT static stiffness $k_m = k$ are given in Table 1. The results show that the method proposed yields the true static stiffness of the beam k_s with less than 2% error. It also was found that the repeatability of the results was within 5%.

On the basis of the fitted SDOF parameters, the curve corresponding to the real part of the dynamic stiffness $K(f)$ of the SDOF system, Equation 13, was extrapolated as shown in Figure 6. It is evident, that the stiffness $k_s = 1.70$ MN/m at $f = 0$ is in close agreement with the true value, $k_s=1.71$ MN/m, value listed in Table 1.

SUMMARY AND CONCLUSIONS

A laboratory tool for assessing the performance of the sensors and the data interpretation method in portable deflectometer devices used for quality control in pavement construction was developed for a particular device, PRIMA 100. This tool, termed the Beam Verification Tester (BVT), revolves around a

simply supported beam assembly with known and adjustable static stiffness. The approach adopted for the PRIMA 100 device is based on comparing the known stiffness of the BVT and that obtained from the PRIMA 100 software. Original and modified configurations of PRIMA 100 were tested. It was demonstrated that the data interpretation method embedded in PRIMA 100, which is based upon the peak force and displacement values, produces significant systematic error in BVT static stiffness estimation; the error may exceed 100%. The reason for this error is the neglect of inertial effects induced by the impact loading.

An alternative data interpretation procedure was proposed. The new procedure is based on the spectral analysis of frequency domain data in term of the experimental mobility function. The corresponding numerical algorithm makes use of the SDOF inertial analog, and discrete spectral density functions. The results of validation tests show that the alternative procedure yields stiffness estimates with less then 2 % error.

The key conclusions stemming from this investigation are:

1. The BVT, a mechanical analog of PFWD support with known stiffness, offers a rational and rigorous basis for routine verification of the performance of PFWD devices such as PRIMA 100. The portable BVT is appropriate for testing at low load values; a larger device would allow for testing at higher loads.

2. Static data interpretation schemes embedded in the PFWD devices may be erroneous and compromise the effectiveness and the reliability of such tools. Spectral analyses offer means for enhanced data interpretation.

3. The analysis presented in this study is limited to data interpretation schemes that are suitable for an idealized load/support system (PRIMA 100/BVT), which allowed for the use of a SDOF analog. Similar analyses should be performed for supports close to or simulating the actual multilayer pavement systems, with appropriate half-space models.

4. Field testing combined with the spectral analyses, in tandem with BVT-type testing, seems to offer the most promising way for verification of measurements and back-analyses of pavement system properties stemming from PFWD devices.

AKNOWLEDGEMENT

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TABLE 1 BVT stiffness

Beam span	[cm]	50	60	70
True BVT stiffness	k_s [MN/m]	3.08	1.71	1.06
Original PRIMA 100 configuration	k_{peak} [MN/m]	0.91	1.23	1.39
Peak method	k_{peak}/k_s	0.30	0.72	1.31
Modified PRIMA 100configuration	k_{peak} [MN/m]	2.17	2.67	3.4
Peak method	k_{peak}/k_s	0.70	1.56	3.21
Modified PRIMA 100 configuration	k_m [MN/m]	3.09	1.71	1.07
Alternative method	k_m/k_s	1.00	1.00	1.01

a)

b)

FIGURE 1 PRIMA 100 device: a) original configuration; b) modified configuration.

a)

b)
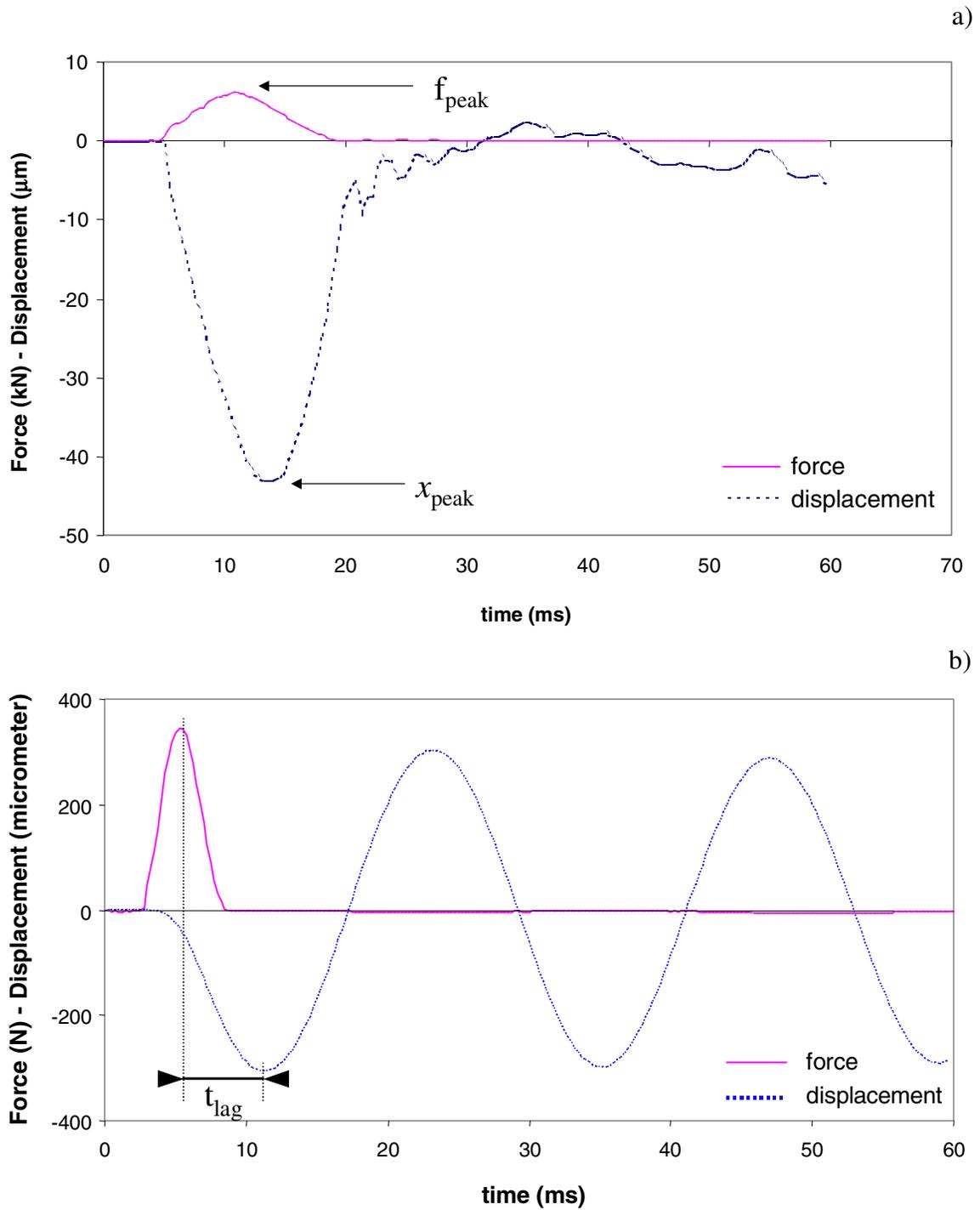
FIGURE 2 Plot of PRIMA 100 software output: a) original PRIMA configuration
(concrete floor); b) modified PRIMA configuration (BVT with 70 cm span).

a)
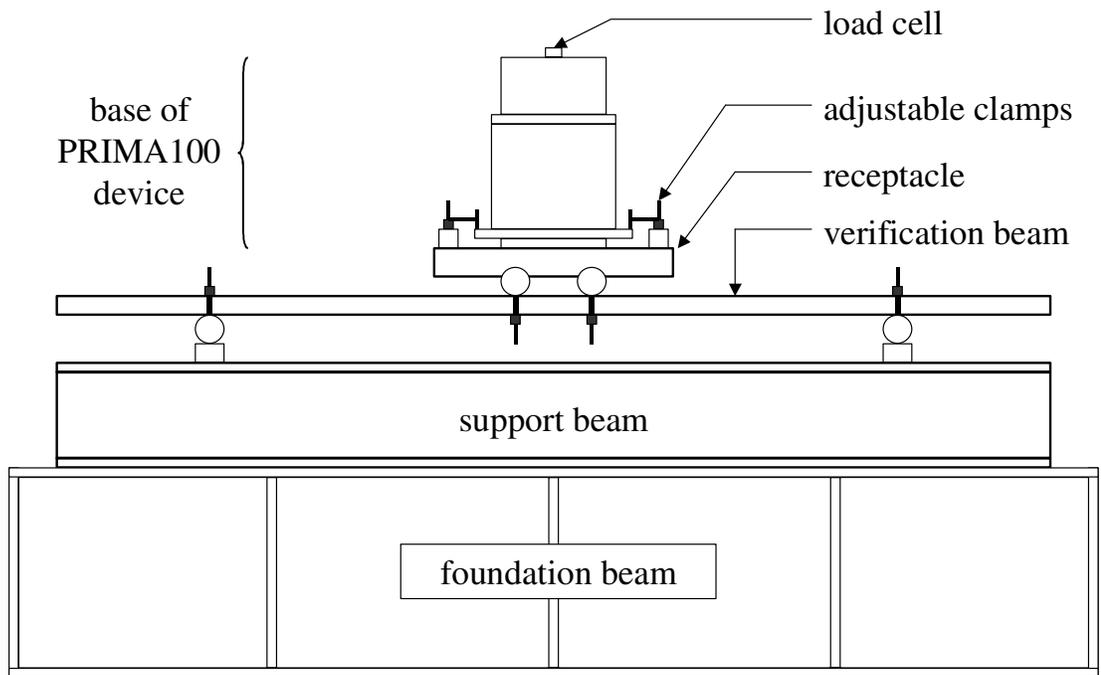
b)

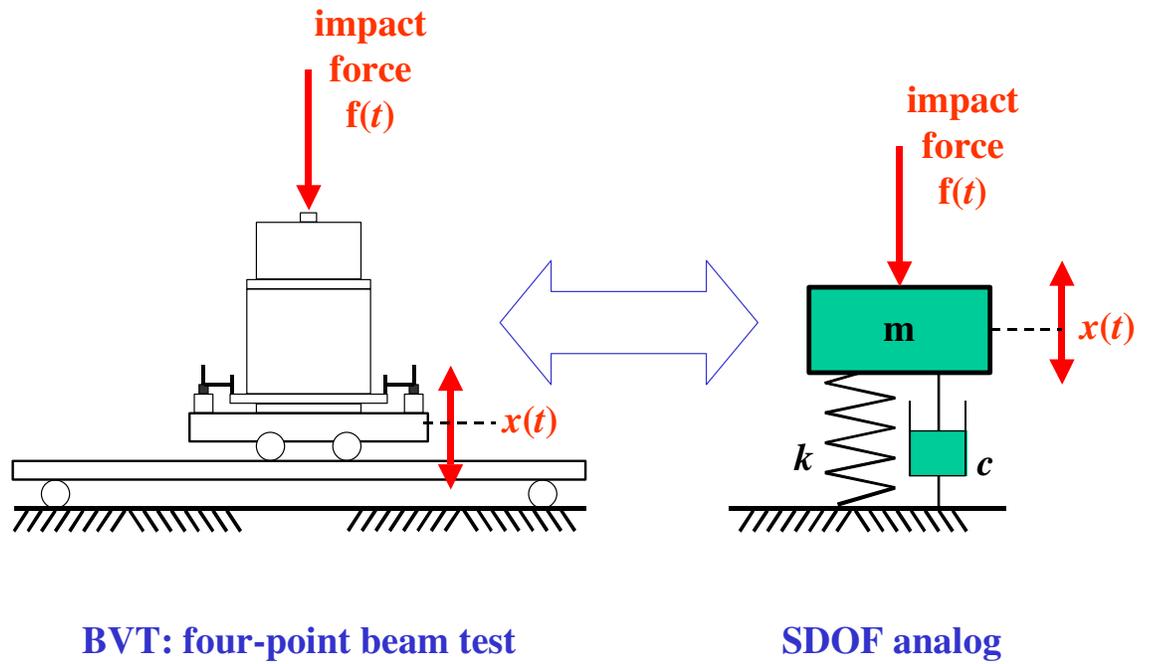FIGURE 3 Beam Verification Tester (BVT): a) schematics; b) photograph.
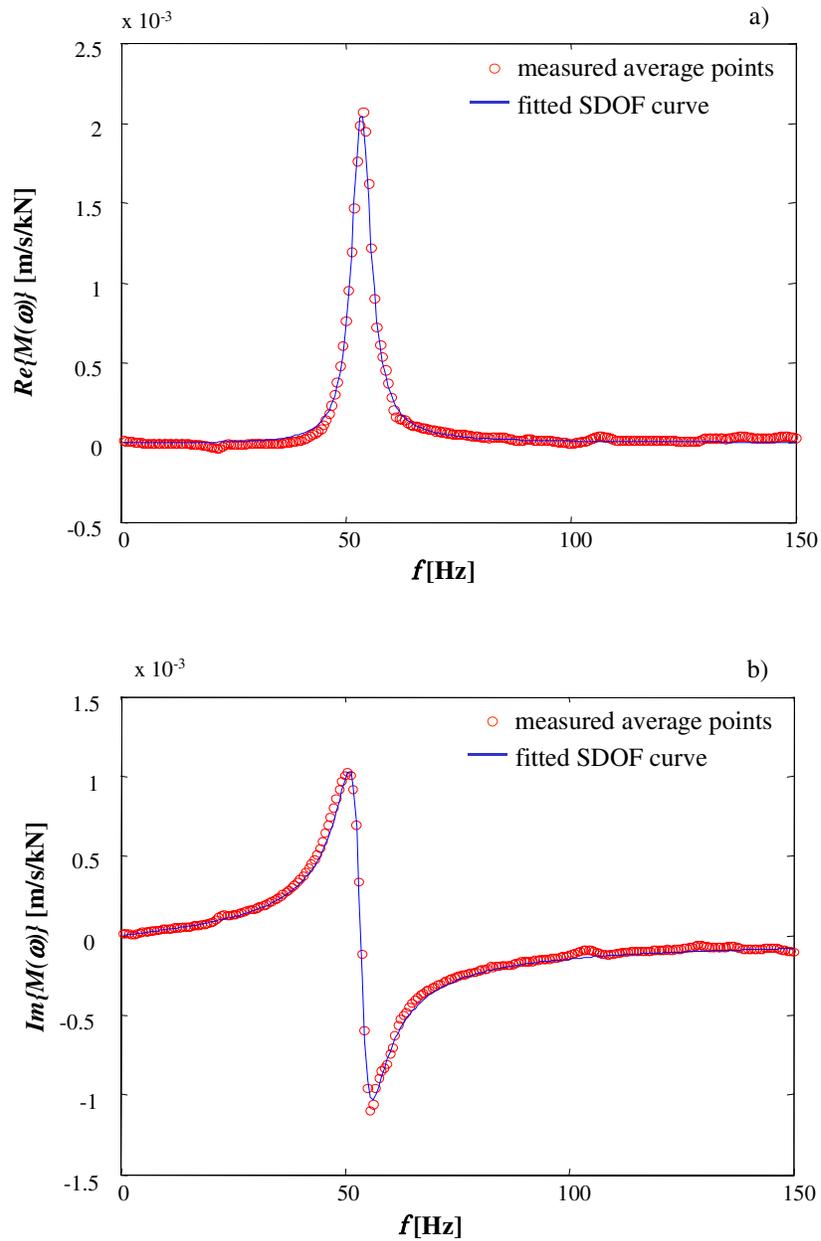
FIGURE 4 SDOF analog for the BVT.

FIGURE 5 Real and imaginary parts of the mobility
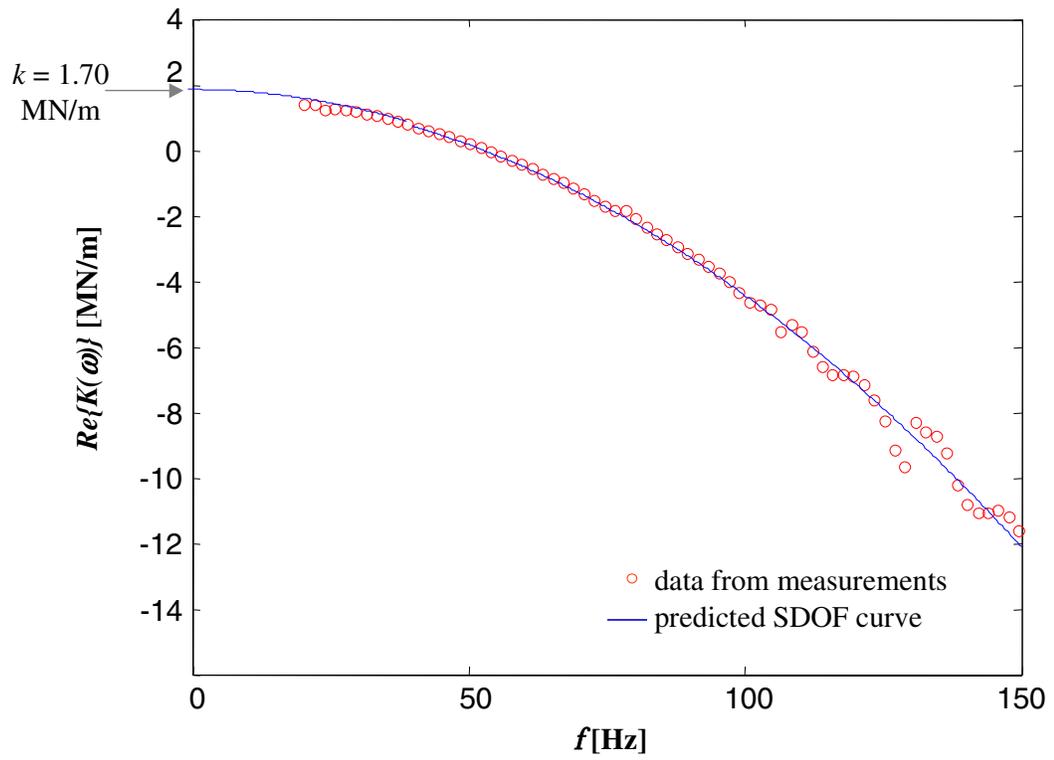function for the BVT with 60 cm span.

FIGURE 6 Real part of the dynamic stiffness function for
the BVT with 60 cm span.