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Application Development of Dynamic Plunking Technique as Non-destructive Test for Construction Material Quality Inspection

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Abstract: The study was conducted to investigate the effects of material defect and/or deterioration on the change of mechanical properties, such as Young's modulus E and stiffness k, for the selected materials using the dynamic plunking tests. The results of the tests showed that E decreases accordingly with respective to the defect condition of the specimens. In general, the test results clearly indicated that the dynamic plunking tests under development in the research can be of a feasible and useful tool as non-destructive technique for practical applications in construction material integrity verification.

Keywords: Dynamic test; non-destructive test; construction material.

1. Research background

Disastrous loss due to natural hazards in recent decades have been resulted from material deterioration or damage in structural components of infrastructures in many heavily populated, developed regions including Taiwan, where earthquake and tropical cyclone have imposed significant risk of losing lives and properties in the region. A proper and adequate maintenance program including regular structural integrity inspection is essential not only to ensure adequate operation safety but also to prolong the life span of the infrastructures in many natural hazard prone areas throughout the Taiwan region.

Non-destructive test (NDT) has been proven to be one of the most effective and commonly accepted techniques for routinely inspecting both the exterior and interior integrity of structural components of existing facilities in order to provide useful information for regular maintenance program, and for retrofitting when necessary. Timing inspecttion using NDT to reveal the current material quality and integrity of structural components is also necessary to avoid un-expected damage and severe material deterioration of the infrastructures in the event of natural or human hazardous activities.

The study was conducted to investigate the effects of material defect and/or deterioration on the reduction of mechanical properties such as stiffness k and Young's modulus E of the structural components using dynamic plunking test. A pulse impact was applied using a triggering hammer to induce a free vibration in elastic range of the tested structural component, from which the natural frequency f_n, damping ratio D, and stiffness k can be determined based on the theory of

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single degree
of freedom (SDOF) vibration. Furthermore, Young's modulus E can also be calculated for the tested structural components both intact (no defect) or with various defect/deterioration conditions.

In the study, a series of tests were designed and conducted on the modeled structural elements made of three selected materials: (1) 3000 psi standard concrete, (2) concrete with recycled aggregate, and (3) light-weight concrete. The tests were conducted on the specimens in the laboratory with the boundary condition of simple support based on which the stiffness k of the tested structural components and E of the structural material can be calculated as a function of length (span), weight and cross sectional dimension (width and height) of the specimens. For the purpose of comparison, the test specimens were prepared in both intact and two defective conditions resulting from surface crack or small void within the structural components. Results of the study was used to examine the feasibility and accuracy of using the elastic dynamic plunking technique as introduced for determination of material quality (Young's modulus E) in general material mechanics. In addition, the study was conducted to examine if the technique can be used as a promising tool for future application in non-destructive test for construction material quality inspection.

2. Theoretical background of elastic dynamic plunking technique

2.1. SDOF un-damped free vibration

In the study, the dynamic motion of the tested structural component was analyzed based on the concept of single degree of freedom (SDOF) in which the dynamic motion was mathematically described with respect to the center of gravity of the structural element as a rigid mass. In case that the energy loss between each vibration cycle is minimal or negligible, the system constitutes only the inertia force and elastic force that govern the nature of the dynamic motion of the system. This type of vibration, called "un-damped free vibration", is usually the simplest and ideal, however appropriate model for many dynamic analysis as shown in Figure 1 and Equation (1), as shown below:

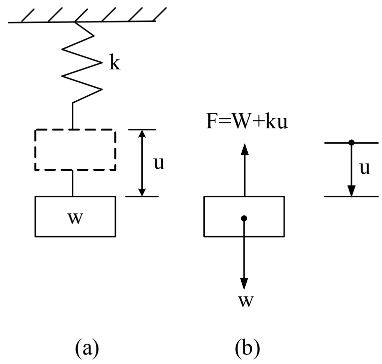

Figure1. SDOF un-damped free vibration

$$m\ddot{z} + kz = 0 \tag{1}$$

in which:
m: mass of the system,
k: stiffness of the system, and
z, and $\ddot{z}$: displacement and acceleration, respectively

It is well known the natural frequency f_n of the un-damped free vibration system can be expressed as the following:

$$f_n = \frac{W_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2}$$

in which
f_n: natural frequency (cycle/sec), and
w_n: natural frequency (radius/second)

In most cases, Equation 2 is adequate for determining the 1st mode natural frequency which dominates the dynamic motion of a structural element made of the most commonly used construction materials such as concrete, rock, or steel. In the study, the natural frequency f_n of the tested specimens was obtained using the dynamic plunking technique provided the induced free vibration amplitude within the elastic range of the material the structural component was made of. Furthermore, the stiffness k of the structural component can be determined by rearranging Equation 2 as shown in Equation 3 below:

$$k = (2\pi f_n)^2 m = (2\pi f_n)^2 \frac{w}{g} \quad (3)$$

in which:
f_n: natural frequency (cycle/sec),
w: weight of the beam, and
g : acceleration of gravity

2.2. Stiffness k of the structural com ponent

As discussed earlier, the beam element with boundary condition of simple support is used in the study for modeled test as shown in Figure 2. It is well known that the static deflection at mid-point Δs , which is consistent with the 1st vibration mode of the beam subject to the elastic dynamic plunking test, and the corresponding stiffness k of the tested structural component can be derived based upon the basic theory in material mechanics. For a simply supported beam as shown in Figure 2, the static deflection due to a concentrated load at the mid-point and the corresponding stiffness k can be expressed in Equations 4 and 5 as the following:

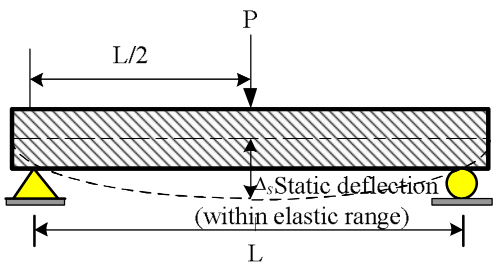

Figure 2. Static deflection at midpoint of simply supported beam

$$\Delta_s = \frac{P\ell^3}{48EI} \quad (4)$$

$$\text{then, } k = \frac{\Delta s}{p} = \frac{48EI}{\ell^3} \quad (5)$$

in which:
Δ_s : static deflection,
p : load,
L : span,
E: Young's modulus,
I : 2nd moment of inertia, and
k : stiffness of the beam.

It is anticipated that Equations 3 and 5 can be used as a basic theoretical concept for verifying material quality of structural component when the stiffness can be determined using the dynamic plunking technique. It should be noticed that the vibration amplitude and static deflection at mid-point are both within the elastic range of the material. This must be taken into account in conducting the dynamic plunking tests in order to obtain better test results. In the study, a series of plunking tests were designed and conducted on the simply supported structural components made of the 3 selected types of commonly used construction materials, in both no-defect and the designated defective conditions, first to determine natural frequency f_n and stiffness k, then to calculate the Young's modulus E of the tested material by combining Equations 3 and 5 as shown in Equation 6 below:

$$E = \frac{k\ell^3}{48I} = (2\pi f_n)^2 \frac{w}{g}\frac{\ell^3}{48I} \quad (6)$$

In should be pointed out that only about 55% of the element weight should be used in Equation 6 as a concentrated weight at the mid-point of the beam actually having its total weight uniformly distributed along the entire length of the beam

3. Laboratory testing program

3.1. Preparation of the specimens

In the study, 3 types of concrete discussed earlier (3000 psi standard concrete, concrete with recycled aggregate, and light-weight concrete) were used for preparing specimens for the dynamic plunking tests, of which the size and weight were shown in Table 1. It should be pointed out that no rebar were used in the specimens and the results of the tests only imply the mechanical characteristics of the concrete.

Table 1. Weight and dimension of the specimens

Material Type / Dimension / Specimen Type	Standard Concrete	Recycled Concrete	Light Concrete
	W×h ×L 6×9×40 (cm)	W×h ×L 6×9×40 (cm)	W×h ×L 6×9×40 (cm)
Intact	5.04 kg	5.0 kg	4.0 kg
Surface Crack	4.98 kg	5.0 kg	3.86 kg
Inside void	4.82 kg	4.9 kg	3.88 kg

Table 2. Function specification and frequency range of the electronic components

Sensor Number	Model	Serial#	Sensitivity	Range	Bias Level
N1	333B32	20859	102.4mv/g	0.5~3000Hz	0.2v
N2	333B42	20826	500mv/g	0.5~3000Hz	0.2v

3.2. Eectronics device for data collection/ process

In the study, the data procession system consists of two piezoelectric type acceleration sensors (333B32 and 333B42), along with a multiple channel data acquisition system. The dada acquisition system, which can be connected to a desktop or personal notebook computer, includes a mother board of E8491B signal output module and E1432A dynamic signal acquisition component to record and process the vibration of the specimens under dynamic plunking in velocity or acceleration. As summarized in Table 2 and shown in Figure 3, the electronic components used for the study are similar to those commonly used in structural non-destructive tests.

3.3. Description of the laboratory est

In the research, a total of 12 specimens with the specified defect conditions discussed earlier along with 6 specimens with no defect were prepared using the three selected construction materials. As shown in Figure 4, specimens with defect of surface crack were prepared by inserting pieces of paper at the bottom surface of the specimens while small polymeric beads, approximately 2-3mm in size, were mixed with the concrete aggregates to create voids inside the specimens.

For non-destructive tests on the repeatedly used specimens, at least six consecutive plinking tests were performed each to obtain the acceptable, sometimes average values of natural frequency and free decay vibration curve.

The test results were then used for analyzing the studied mechanical properties including Young's modulus E, stiffness k and damping ration D of the selected construction materials with respect to the designated defect condition.

Figure 3. VXI multiple chanel data acquisition system

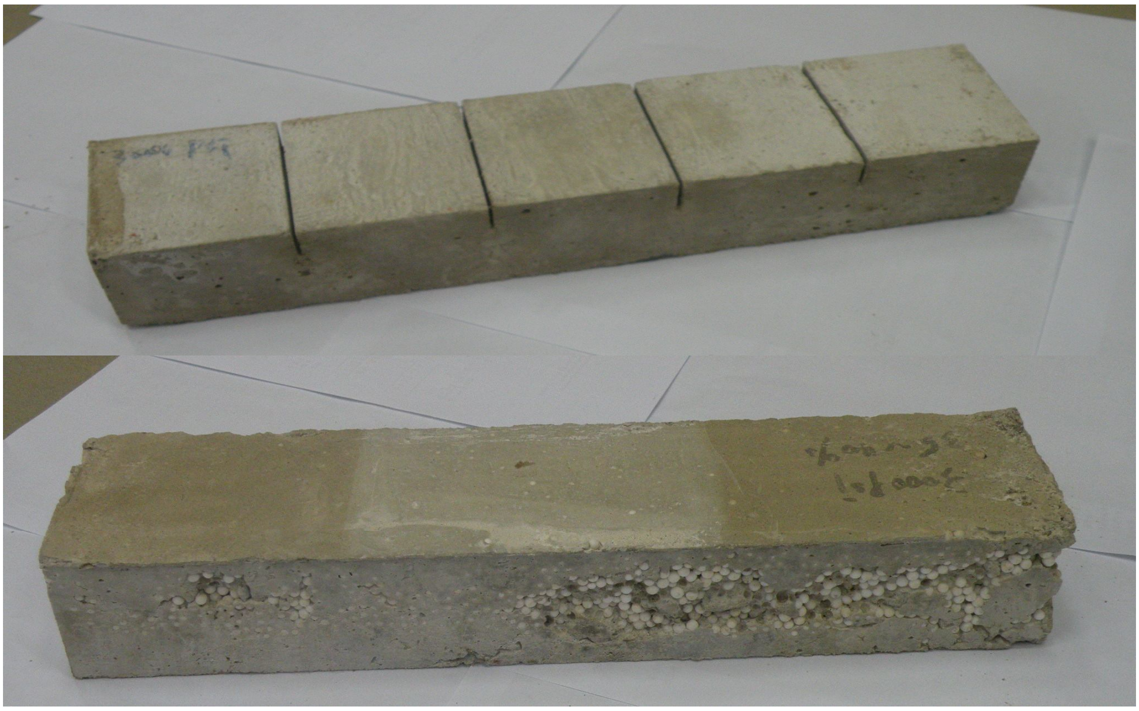

Figure 4. Concrete specimens with defects used for the dynamic plunking test

4. Analysis and Discussion of the Test Results

In the study, the natural frequency of 1st mode free vibration at the mid-point of the tested simple-support beam was determined from the tests for the three selected materials and with the designated defective conditions. First, the results of the tests revealed that the damping ratio D were in the range of about 3.9-6.3% (average 4.6%), 6.1-9.4% (average 7.5%), and 3.3-11.4% (average 8.4%) for the standard, recycled and light concrete, respectively. Generally speaking, the results suggest that the damping ratio D of the concrete may be in the range of 5-10% which is relatively lower than commonly used in practice on the level of 15-20%, both implying that the difference between natural frequency and damped frequency were minimal and negligible. The test results showed no consistent trend of change in damping ratio with respect to the defect level of tested structural specimens.

However, the results of the tests revealed that clear and significant decrease in stiffness k and Young's modulus E, calculated using Equations 3 and 6, due to the specific defect conditions discussed earlier. As shown in Table 3, the Young's modulus of the tested beam specimen with surface crack defect were 47-65% of the intact material, which is significantly less than that of inside void defect at 62-84%. In general, the study results also indicated that defect due to surface crack may result in more decay in modulus E and stiffness k than due to inside void. This is reasonable because surface cracks of the tested beam may propagate and elongate during vibration, which even more severely when the cracks are on the tensile side of the beam.

In addition, for the purpose of comparison and verification, Young's modulus E of the three concrete materials used for the intact specimen were compared respectively with the standard values revealed in previous studies. As shown in Table 4, the values of E obtained from the test results are within the reasonable range of recognized values with a deviation of less than 10% for standard and light concrete, while the concrete with recycled aggregate has a higher deviation of 27%, which may be due to the in-consistent quality of the aggregates used for preparing the test specimens.

5. Conclusions

Based on the results of the tests, the conclusions of the study can be addressed as follows:

a) The defect/deterioration of construction materials due to surface crack or inside void, in terms of decreasing Young's modulus, can be evaluated by examining the natural frequency of free vibration of the structural component at certain vibration mode and boundary condition.

b) Based on the results of the tests discussed in the study, when at the same level of defection, surface crack may lead to more decrease in Young's modulus E than due to inside void in structural component, which are about 50-60% and 60-80%, respectively.

c) Results of the tests revealed that the damping ratio was generally in the range of about 5-10% for the three selected concrete materials used in the study, which are smaller than the anticipated for concrete on the level of about 15-20% in practice. The difference may due to the scale effects of the model tests for the structural components used in the study and further investigation is needed when damping ration D is a critical factor in applications.

d) The study results indicated that the dynamic plunking tests discussed in the study can be of a feasible and useful technique as non-destructive test in material quality verification for both intact and defective structural components. However, theoretical approach and laboratory procedure including the data collection/process system should be improved by further study before any applications in practice can be anticipated.

Table 3. Test results of simple-support beam specimen

Detect Type	Natural Frequency $f_n(H_Z)$	Stiffness k (10^4 kg/cm)	Young's Modulus E (10^5 kg/cm^2)	$\frac{E\ defect}{E\ intact}$ (%)	Damping Ratio D
Standard Concrete					
Intact	600.00	3.6	2.3	100.0%	3.9%
Crack	417.39	1.7	1.1	47.8%	3.8%
Void	564.71	3.0	2.0	84.9%	6.3%
Recycled Concrete					
Intact	533.33	2.8	1.8	100.0%	9.4%
Crack	431.46	1.8	1.2	65.2%	7.3%
Void	504.83	2.5	1.6	87.5%	7.3%
Light Concrete					
Intact	581.67	2.7	1.7	100.0%	10.8%
Crack	408.51	1.3	0.8	47.7%	11.4%
Void	468.29	1.7	1.1	62.2%	3.3%

Table 4. Comparison of modulus E values

Material Type	Plunking test E calculated 1×10^5 (kg/cm^2)	Standard Concrete E (Average) 1×10^5 (kg/cm^2)	Deviation
1.Standard Concrete	2.3	1.4~2.8 (2.1)	+9.5%
2. Recycled Concrete	1.8	0.94~1.9 (1.42)	+27%
3. Light Weight Concrete	1.7	1.0~2.4 (1.7)	0%

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