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Using a Small-scale Shake Table for Teaching Typical Problems of Structural Dynamics*

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A small-scale shake table is a very useful tool for studying structural models' dynamic behavior under real forces and for investigation of active and passive structural control systems' efficiency. Theoretical principles, forming a basis for numerical modeling of structural dynamic response, should be consistent with real behavior of structures. 'Hands-on' experiments demonstrate basic concepts in structural dynamics and provide undergraduate students with an opportunity to develop deep understanding of structural response to different dynamic loads. A shake table platform with programmable motion is used to create and apply real loads to structures. The load can be programmed as impulse or continuous, stochastic or prescribed in time and in magnitude. Changing the platform's position is used for creating dynamic loads acting in different directions, including a vertical one. The forces can be applied to an investigated structure by shake table acceleration and they can have a form proportional to the structural element's mass. Another possibility is to apply the loads directly to the structural elements.

Keywords: Structural dynamics; engineering education; shake table; laboratory tests

INTRODUCTION

EXPERIMENTAL METHODS FOR TESTING the dynamic behavior of structures are important for forming deep understanding by students of structural behavior under different types of dynamic loadings. It will yield proper understanding of modern methods, used in structural design for these dynamic loadings, as well as methods of protection of structures against disasters. Shake tables of various capacities are used for this reason all over the world [1]. However, using big shaking platforms is not always possible because of the high cost of the experiments. Hence small-scale laboratory shake tables have been implemented in the last few decades.

The University Consortium of Instructional Shake Table (UCIST) was formed in 1998 to enhance undergraduate and graduate education in earthquake engineering. Appropriate methodologies were developed using modern testing techniques and data logging procedures [2]. It was reported that using small-scale shake tables is very efficient in the course of structural dynamics.

According to [2], various types of dynamic loading, such as simple harmonic vibrations, sweep loads, records of real seismic excitations are applied on structural models and tested at the consortium universities. However, the possibility of using the shake table for testing structural models subjected to other types of dynamic loading is also important.

The Ariel University Center of Samaria started to use the shake table for educational and research purposes in 2001. A corresponding curriculum was developed in order to teach structural dynamics and seismic design of structures according to the concepts developed by the university consortium members [21]. It also allowed encouragement of undergraduate students' research activities that yielded further development of the approach implemented at the UCIST. However, following our experience of using the shake table, the standard package, supplied by the table manufacturer, is not enough and using original equipment may allow reproduction of other types of dynamic loading that are of high importance for understanding design methods of structures.

This research is aimed at developing laboratory testing procedures for structural models subjected to a wide variety of dynamic loadings. The problem is solved by analysis and classification of loadings, developing methods for their reproduction and creating real systems for testing structural models.

DYNAMIC LOADS CLASSIFICATION

We proposed to classify any loads acting on structures only according to their source as geophysical and man-made [3]. Classification of dynamic loadings used by the authors is addition-

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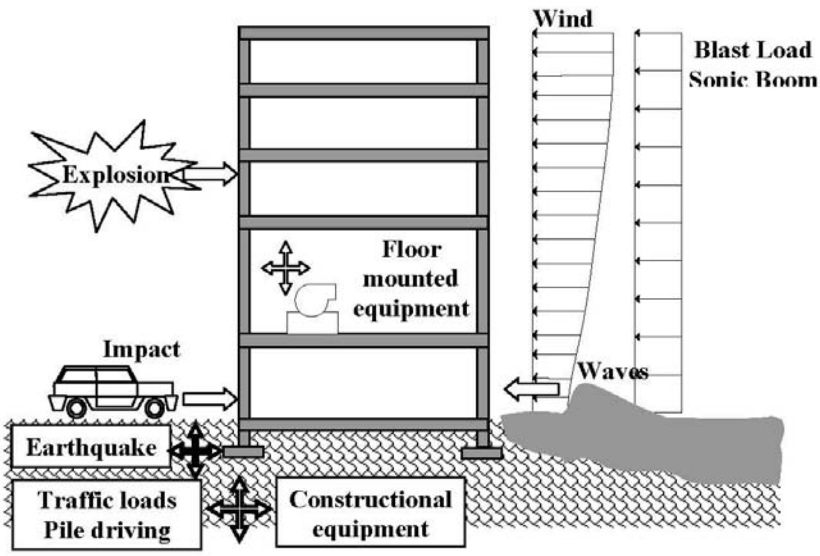


Fig. 1. Sources of dynamic loads acting on structures.

ally based on their realization methods by means of the shake table platform, i.e.: ground acceleration and directly applied loads. In the first case, the loads acting on the structure depend on its mass, whereas in the second they are independent.

Further classification is performed according to the direction of the dynamic loading's action—horizontal or vertical. According to the shake table programming features, the dynamic loadings can be divided into predictable and random, periodic and nonperiodic. Finally, by their nature, as in the classification of [3], the loads may be natural or man-made. Sources of some dynamic loads are presented in Figure 1. Figure 2 shows more detailed classification of the dynamic loadings according to the above-specified principles.

METHODS FOR IMPLEMENTATION OF VARIOUS DYNAMIC LOADINGS

For reproduction of dynamic loads a small-scale shake table manufactured by Quanser Consulting Inc. is used. The shake table consists of a 1Hp servo motor driving a lead screw. The main characteristics of the table, required for planning of experiments, carried out by the students, are shown in Table 1.

The shake table platform's displacements are transferred to the control system in the form of a vector, defining its positions with time intervals of 0.001 sec. If the external load is given in the form of a velocity record, it is integrated, and if it is a record of accelerations, it is double integrated.

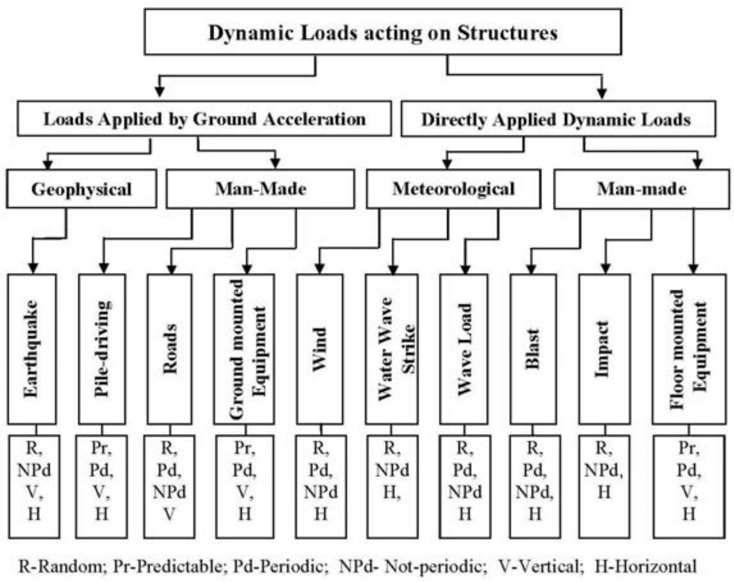


Fig. 2. Classification of loadings.

Table 1. Characteristics of the shake table

Parameter	Value
Table dimensions	460 × 460 mm
Maximum payload	15 kg
Operation bandwidth	0–20 Hz
Peak velocity	82.5 mm / sec
Maximum force	700 N
Peak acceleration	2.5 g
Stroke	150 mm

The shake table programming is realized using MATLAB or Simulink software. When programming using MATLAB the shake table platform displacement can be calculated using standard MATLAB functions or using a time history with 20 ms time intervals. When programming using Simulink standard commands are used the time intervals are 1 ms.

Testing structures, subjected to loads applied by ground acceleration, are carried out by locating the model on the movable platform of the shake table (Figure 16). In this case the platform reproduces the ground motion.

Structures, subjected to directly applied loads, are proposed for testing using a scheme originally developed for reproduction of dynamic loads (Figure 3). For this reason a model (position 1 in Figure 3) is fixed to a base, located near the shake table (position 2). An additional rigid device (position 3) is connected to the shake table's platform. Between the tested model and the device elastic elements (position 4) are connected.

The elastic elements are used for transforming the shake table displacement into loads, acting on the model. For linear elastic elements used in the experiments, the dynamic equilibrium equations can be written as follows:

$$[m]\{\ddot{x}\} = -[K]\{x\} + [K_S](u(t)\{1\} - \{x\}) \quad (1)$$

where $\{x\}$ is a vector of masses' displacements; u is the shake table displacements; {1} is a vector of ones, which dimensions correspond to {x}; [m] and [K] are the model's mass and stiffness matrices respectively; and $[K_S]$ is the elastic elements' stiffness matrix.

Eq. (1) can be rewritten in the following form:

$$[m]\{\ddot{x}\} + [K + K_S]\{x\} = [K_S]\, u(t)\{1\} \quad (2)$$

According to (2), a new model having equivalent stiffness $[K + K_S]$ and subjected to effective loading $\{P_{eff}(t)\} = [K_S]\, u(t)\,\{1\}$.

Stiffness of the elastic elements is obtained according to the total maximum load applied to the tested model and its distribution between the floors. A load, acting on a certain floor *i*,

$$P_{i,\max} = \alpha_i P_{\max} \quad (3)$$

where $P_{\max}$ is the total maximum load, obtained according to the model's strength and α_i is the load distribution coefficient, defined according to different loading's type (see Figure 2).

For example, for blast loading $\alpha_i = 1/n$, where n is the number of floors and with the water wave strike, wave load, impact and floor mounted equipment, the load acts at floor number j, $\alpha_i = 1$ for $i = j$, $\alpha_i = 0$ for $i \neq j$. For wind loading α_i is obtained according to the load, acting at a certain floor, taking into account the floor height relative to the base of the structure.

The elastic elements' stiffness can be obtained according to (4):

$$K_{S,ii} = P_{i,\max}/y_{i,\max} \quad (4)$$

where $y_{i,\max}$ is the displacement of floor number i in the tested model (Figure 3b) under the acting load $P_{i,\max}$. These displacements can be expressed as

$$y_{i,\max} = d - z_{i,\max} \quad (5)$$

Here $z_{i,\max}$ is the displacement of floor i in the designed structure (Figure 3a) and d is the maximum shake table displacement. A vector of floor displacements is as follows:

$$\{z_{\max}\} = [\delta]\{P_{i,\max}\} \quad (6)$$

where $[\delta]$ is the flexibility matrix for the model (Figure 3a).

As an example, a four-storey structure was selected. The floor diaphragms were rigid and there were four columns on each floor. The

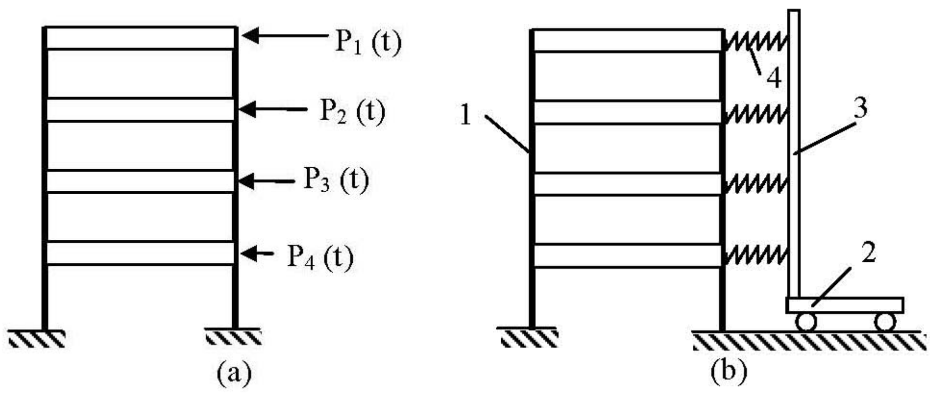


Fig. 3. Method for testing structural models under directly applied loads: design scheme, (b) test setup.

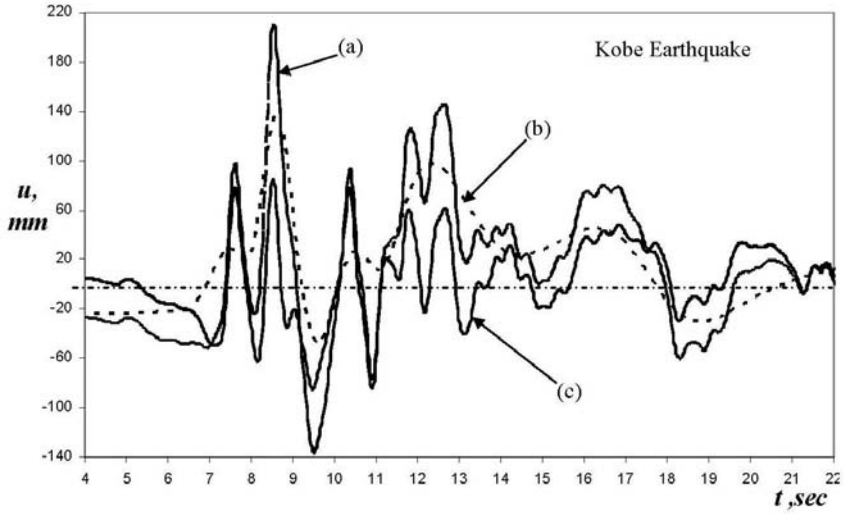


Fig. 4. Scaling procedure proposed by Agranovich et al. [4]: (a) ground displacement, (b) modifying function, (c) shake table platform displacement.

columns were equal for all floors; their length was 200 mm and sections were 20×1 mm. The flexibility matrix of the structure is

$$[\delta] = 0.49 \begin{bmatrix} 4 & 3 & 2 & 1 \\ 3 & 3 & 2 & 1 \\ 2 & 2 & 2 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \frac{mm}{N}$$

For testing the structure under blast loading it was considered that the maximum shake table displacement is 50 mm. This selection was made based on the technical characteristics of the shake table control system and the loading duration. The maximum load, acting on each floor was selected to be equal 5 N. This is the maximum load that can be applied to the structure without plastic deformations during its dynamic response.

The stiffness matrix of the elastic elements can be obtained using (4):

$$[K_S] = \begin{bmatrix} 0.195 & 0 & 0 & 0 \\ 0 & 0.178 & 0 & 0 \\ 0 & 0 & 0.152 & 0 \\ 0 & 0 & 0 & 0.124 \end{bmatrix} \frac{N}{mm}$$

The tested model has the following stiffness matrix:

$$[K + K_S] = \begin{bmatrix} 2.25 & 2.05 & 0 & 0 \\ 2.05 & 4.23 & 2.05 & 0 \\ 0 & 2.05 & 4.25 & 2.05 \\ 0 & 0 & 2.05 & 4.22 \end{bmatrix} \frac{N}{mm}$$

METHODS FOR REPRODUCTION OF VARIOUS LOAD TYPES USING SHAKE TABLE

Earthquake loading

Two orthogonal horizontal and the vertical

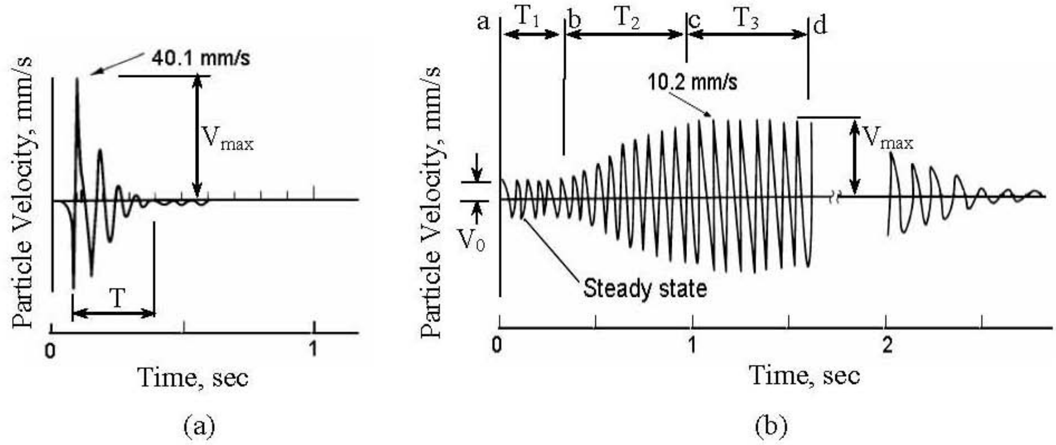


Fig. 5. Particle velocity time history generated by (a) an impact hammer, and (b) vibratory hammer (following [5]).

Fig. 6. Dynamic action on bridge-mounted sign support structures [10].

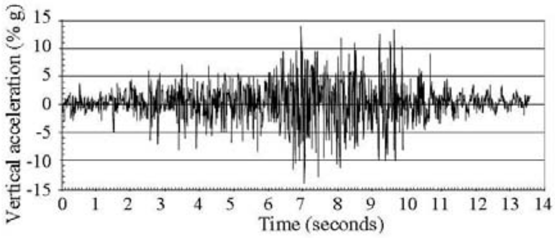


Fig. 7. Typical vertical acceleration trace of the support tower [10].

components of the ground motion, produced at a site by an earthquake, provide the characteristic of the shaking that should be reproduced by the platform. The problem is that the peak ground displacement that should be reproduced by the shake table is usually much bigger, compared to the platform stroke. Hence it is necessary to scale the signal.

A scaling procedure was recently developed at the Ariel University Center of Samaria and is used to control the shake table platform's displacements [4]. This procedure allows more exact reproduction of natural earthquake motions (Figure 4).

Pile driving

Traditionally, pile-driving vibrations are characterized by a peak particle velocity and its decay with distance from the pile. However, pile driving vibration characteristics can be accounted for by calculating the response spectra of the ground motions [5]. Figure 5 presents the ground velocity time histories generated by an impact hammer recorded at different distances from a pile driver.

The distinct impulse hammer pulses decay to zero between hammer blows, which occur at the rate of tens of times a minute. The dominant frequency of the impact motions is dependent on driving conditions and pile and hammer properties, but will range between 10 and 50 Hz for typical hammers.

Vibratory hammers produce ground motions at the hammer frequency which typically operates between 900 and 1400 rpm or 15 to 20 Hz. At run-up and shutdown of vibratory actions vibration amplitudes increase. More detailed description of this type of loadings is given in [5].

In order to reproduce the record, presented in Figure 5a, using the shaking table's displacement, the record can be approximated by the following expression:

$$V(t) = V_{\max} e^{-3t/T} \cos(2\pi f t) \qquad (7)$$

where V_{max} is the maximum velocity, T is the duration of the load and f is the loading's frequency. These values are obtained from the record (Figure 5a).

To reproduce the record, presented in Figure 5b, using the shaking table's displacement, the record can be approximated by the following expression:

$$V(t) = \varphi(t) \cos(2\pi f t) \qquad (8)$$

where $\varphi\,(t)$ can be found as follows: for part *ab* of Figure 5b $\varphi(t) = V_0$, for transfer part *bc* of Figure 5b:

$$\varphi(t) = V_{\max} - (V_{\max} - V_0)(1 + 5t/T_2)\, e^{-5t/T_2} \qquad (9)$$

and for part *cd* of Figure 5b $\varphi(t) = V_{\max}$. Parameters V_0 ,$V_{\max}$ and T_2 are selected according to Figure 5b.

Traffic loads

Dynamic traffic loads may yield vibrations in structures in both horizontal and vertical directions. An example of the second case is the action of car or pedestrian loads on bridges. This issue has been intensively investigated in the last decade [6–9]. An additional case is vibration response of Bridge-Mounted Sign Support Structures (Figure 6). There has been less research, however, on interactions between bridge vibrations and the dynamic response of such bridge mounted sign supports [10].

A typical vertical acceleration trace measured on the support tower is shown in Figure 7. As can be followed from the figure, the sign truss vibration takes place primarily at the natural vibration frequency, which is in the range between 5 and 10 Hz and belongs to the frequency interval that may be reproduced by the shake table (0—20 Hz). The loading can be reproduced by SIMULINK superposing two or more generators of harmonic vibration.

In order to simulate the dynamic load acting on the support towers by using the shake table, we propose to attach the table to the support structure so that the platform could move in a vertical direction (Figure 8a). This technique was also successfully applied in the laboratory for experimental investigation of seismic response of real relays used in electric transformer stations (Figure 8b). The truss in the tested model is replaced by a beam with three concentrated masses so that there is no change in the natural frequencies.

Equipment induced vibrations

According to [5], there are three main types of motion that may be caused by construction equipment (Figure 9):

(1) simple isolated impulse wave forms produced by dynamic soil compaction (wide dominant frequency range between 6 and 20 Hz);
(2) continuous waveforms produced by reciprocating machines such as vibratory rollers and vibroflotation equipment (dominant frequency range between 25 and 30 Hz);
(3) random semi-continuous impact motions produced by rolling (transportation) equipment (dominant frequency range between 10 and 20 Hz).

The shake table platform's velocity, corresponding to the record shown in Figure 9a, is programmed in Simulink using Eq. (7) and parameters according to Figure 9a. For reproducing the record shown in Figure 9b a Simulink triangular periodic signal is used. Finally, for record shown in Figure 9c, is programmed according to Eq. (8). In this case:

$$\varphi(t) = V_{\max}\left[1 - \frac{4}{T^2}(t - T/2)^2\right] \tag{10}$$

where $V_{\max}$ and T are parameters, selected according to Figure 9c.

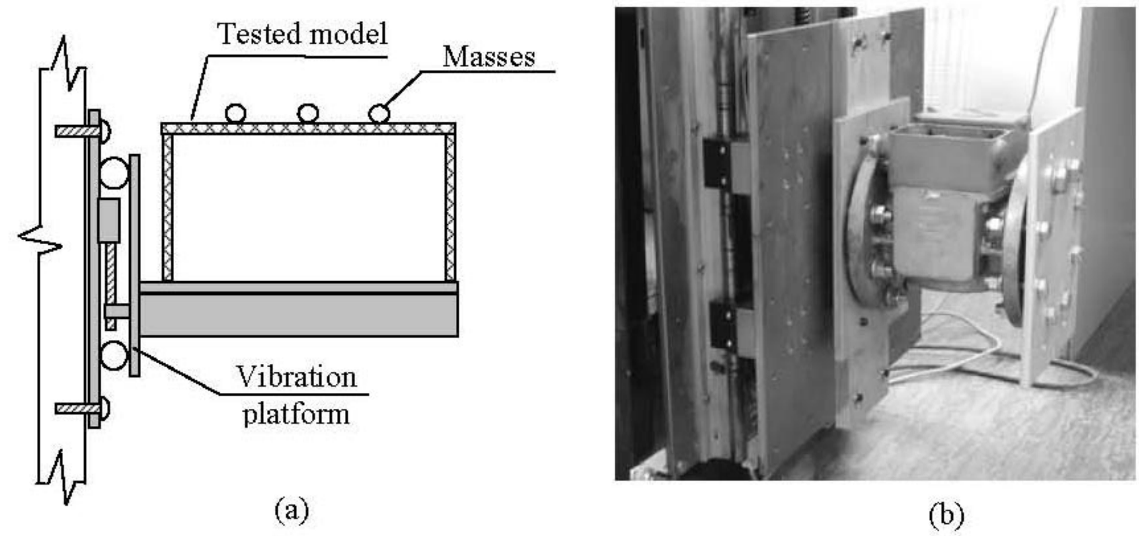


Fig. 8. (a) Using the shake table for applying vertical dynamic loads; (b) experimental investigation of seismic response of real electric transformer stations relay.

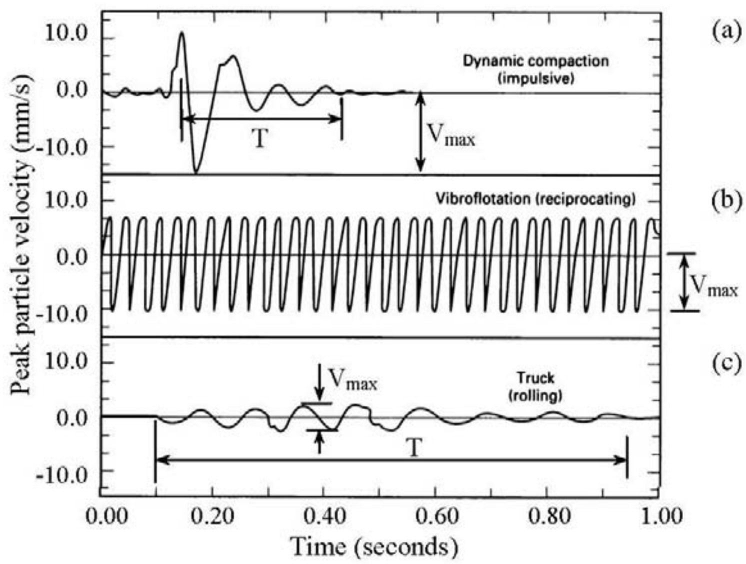


Fig. 9. Main types of motion that may be caused to structures by construction equipment, (a) simple isolated impulse, (b) continuous harmonic waveform, (c) random semi-continuous impact motions (following [5]).

Wind load

The wind velocity is not steady. It consists of a constant wind velocity (steady component) and a varying gust velocity (dynamic component). Therefore, structures deflect along the direction of the wind due to the mean wind pressure, and vibrate from this position due to gust buffeting [11]. The effect of the fluctuating wind force on the structure depends not only on the characteristics of the wind force, but also on the size, form and vibration characteristics of the structure.

A wind blowing on a slender prismatic or cylindrical structure creates vortexes intermittently on one side and then on the other side of the body. As a result, cyclic force is generated along the whole length of the body, whose direction is normal to the direction of the wind. By the SI 414 [12], the frequency of the vortex shedding and the cyclic force, generated by it, is calculated as follows:

$$n = S_t \frac{\bar{V}}{b} \tag{11}$$

where n is the frequency (in cycles per second) of the vortex shedding, S_t is the Strouhal number (for rectangular bodies and steel profiles should be 0.15), $\bar{V}$ is the mean hourly velocity (m/sec), and b is the projection of the structural width normal to the wind (m). Figure 10 shows fluctuations caused by wind turbulence (a) and vortex generation (b).

Generally, structural response under wind loads is obtained using wind tunnels [13], [14]. However, for educational purposes, in order to simulate the influence of wind loads, a shake table and additional springs with preliminary calculated stiffness coefficients may be used (Figure 11). The wind intensity depends on the height, hence the stiffness coefficients of the springs should be selected considering the load acting at each floor that may be obtained according to modern design codes for design of structures subjected to wind loads. The shake table platform's displacements are programmed in Simulink using a generator of harmonic motions.

Explosion, blast and sound boom

The events of 11 September 2001 have changed the design concepts of critical infrastructure. Impact and blast-resistant design has traditionally been considered only for essential governmental buildings, military structures and petrochemical facilities. Recently, increased attention has been given to bridges, which are crucial to the transportation infrastructure [15].

Much research has been conducted, and continued research efforts are being made, to improve the safety of infrastructure against natural hazards. Few research efforts have been made to mitigate the impact of manmade hazards, such as an explosion, on the civilian infrastructure that is most vulnerable to terrorist attacks [16].

When a blast occurs near a structure, a very high pressure is applied in a very short time. The structural response is significantly different from slower loadings, such as wind. If the structure is not able to absorb all of the blast energy elastically, then permanent deformations will occur, and could result in complete failure.

Any blast load can be defined using two parameters: the pressure of the blast and the impulse. When a blast occurs, a violent release of energy produces a high-intensity shock front that expands outward from the surface of the explosion. As this shock front, also called a blast wave, travels away from the source, it loses strength and velocity, and increases in duration. As the blast wave expands in the air, the front impinges on any structure within its path, resulting in a pressure force being applied to the structure.

The blast impulse is defined as the area under the load-time curve. Pressure acting on a structure over a short time period has a lower impulse than the same pressure applied over a long period of time. A highly impulsive loading consists of a relatively high pressure applied quickly, while a static loading consists of a pressure that slowly rises to its peak value applied over a long period of time. If the duration of a blast pressure applied to a structure is very short compared to the natural frequency of the structure, the load can be considered as pure impulse [17].

The form of the impulse, shown in Figure 12a, can be simplified as a triangular impulse [17]. Chock and Kapania [19] have created the blast profiles resulting from pressure waves that are created by sudden and violent release of energy in the explosive change, which causes a sharp rise in the pressure of the surrounding medium. A

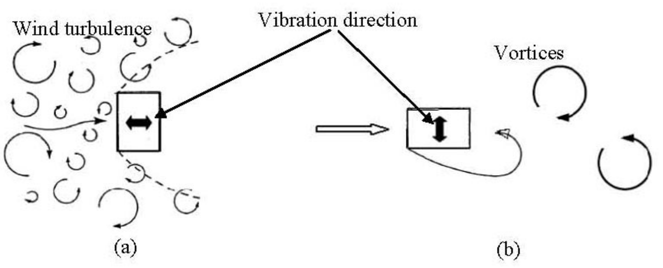


Fig. 10. Fluctuating air force caused by: (a) wind turbulence, and (b) vortex generation [11].

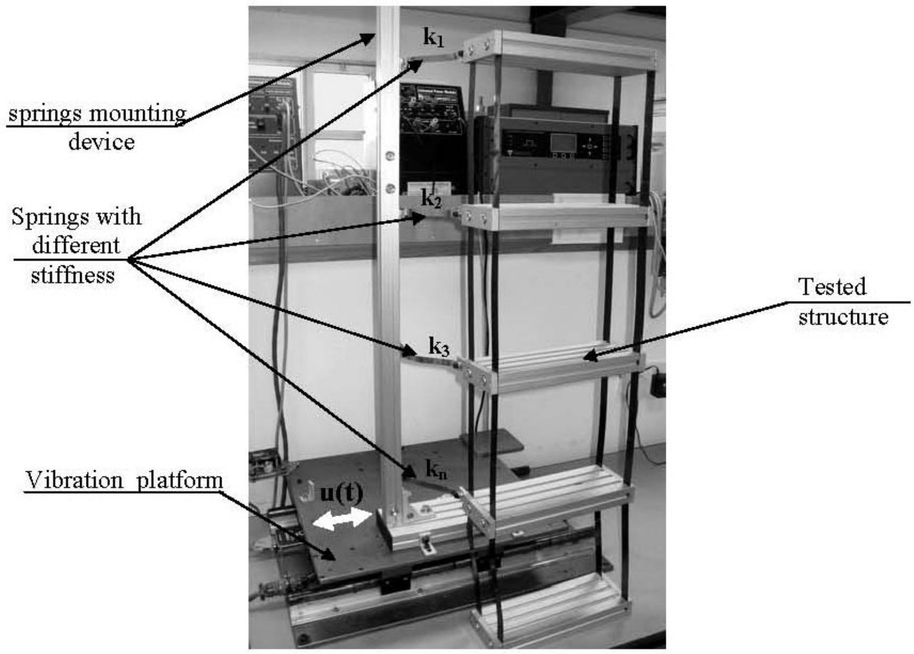


Fig. 11. Testing a structure subjected to a wind loads.

generic blast profile at a point is shown in Figure 12b. The pressure distribution is calculated according to the storey heights and model width and finally it is modeled by concentrated forces applied to the floor diaphragms.

Loadings, presented in Figures 12a and 12b, are programmed in Simulink using a function:

$$P(t) = P_{\max} e^{-2t/T} \cos(\pi t / T) \qquad (12)$$

where $P_{\max}$ and T are selected according to Figure 12. The loads acting on the floors are obtained according to the pressure multiplied by the structure's width and story height.

Air blast is the common description of air pressure waves generated by explosive detonation. Just as with ground vibration, these pressure waves can be described with time history where the amplitude is air pressure instead of particle velocity [5]. Time history of air blast from quarry shot is presented in Figure 13. The loading is programmed in Simulink according to (12) where P_{max} and T are selected according to Figure 13.

Sonic boom has higher intensity than air blast, but both have similar dominant frequencies. Typical air pressures caused by a sonic boom are shown in Figure 14. The shake table platform's displacements corresponding to this diagram are programmed in Simulink as a sequence of two

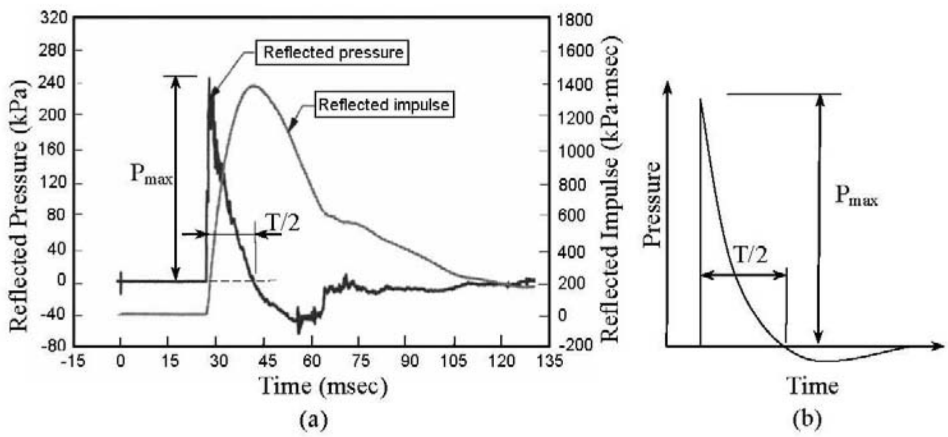


Fig. 12. (a) Reflected pressure and impulse wave forms measured of wall surface [18]; (b) A canonical blast pressure profile [19].

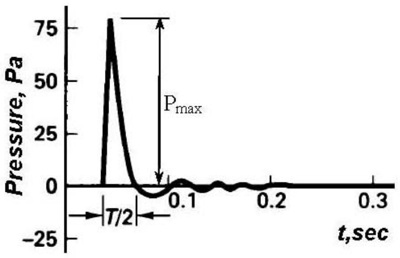


Fig. 13. Quarry air blast from blowout [5].

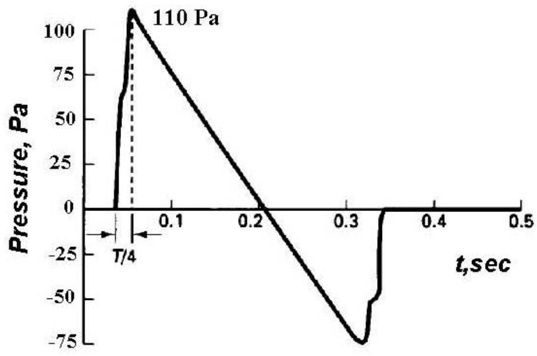


Fig. 14. Air overpressure due sonic boom [5].

triangular impulses with parameters according to Figure 14.

Impact loading

A basic model for impact loading consists of [20]:

- potentially colliding objects (vehicles, ships, airplanes) that have an intended course, which may be the centre line of a traffic lane, a shipping lane or an air corridor; the moving object will normally have some distance to this centre line;
- the occurrence of a human or mechanical failure that may lead to a deviation of the intended course;
- the course of the object after the initial failure, which depends on both object properties and environment;
- the mechanical impact between object and structure, where the kinetic energy of the colliding object is partly transferred into elastic-plastic deformation or fracture of the structural elements in both the building structure and the colliding object.

The collision force is a horizontal one; and just the force component perpendicular to the structural surface should be considered. The collision force for passenger cars affects the structure at about 0.5 m above the level of the driving surface; for trucks the collision force affects it at about 1.25 m above the level of the driving surface. The force application area is considered as 0.25 m (height) times 1.50 m (width).

The probability of a structure being hit by an airplane was usually taken as very small, but after the events of 11 September 2001, it was demonstrated that this type of loading can cause great

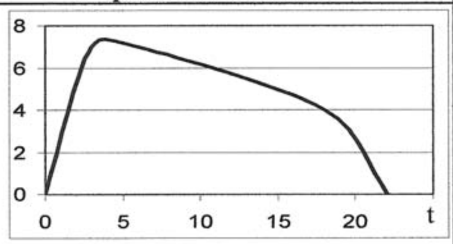
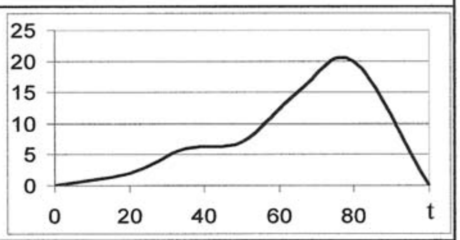
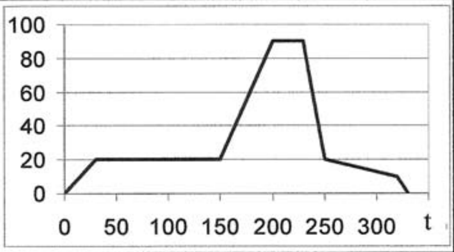
Type	t [msec]	F [MN]	Impact Characteristics
Cessna m=1.7 ton v=100 m/sec A=7 m^2	0 3 6 18 22	0 7 7 4 0	F 
Lear Jet 23A m=5.7 ton v=100 m/sec A=12 m^2	0 20 35 50 70 80 100	0 2 6 6 12 20 0	F 
Boeing 707 m=90 ton v=100 m/sec A=36 m^2	0 30 150 200 230 250 320 330	0 20 20 90 90 20 10 0	F 

Fig. 15. Impact characteristics for various aircrafts (perpendicular to immovable walls) (following [20]).

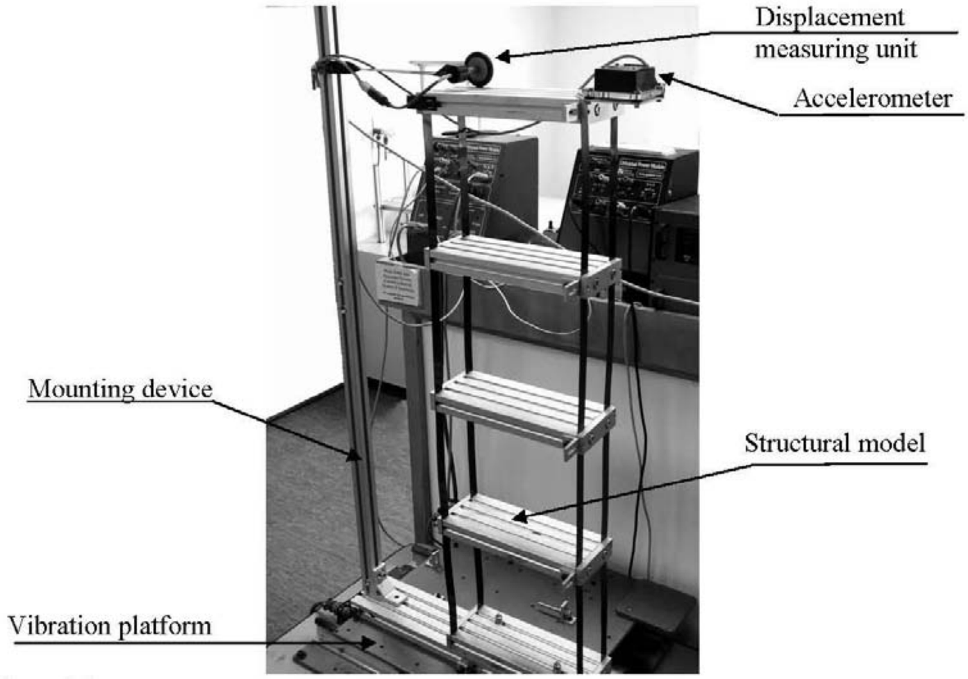


Fig. 16. Testing a structure subjected to a ground motion.

damage. Hence, it should be considered in structural design. Following [20], it is recommended that different types of aircraft (civil, military, etc.) should be analyzed. The form of the impact can be reproduced with a high enough accuracy by 5 ms and 20 ms time intervals for Cessna aircrafts and other planes (as shown in Figure 15).

The shake table platform's displacements are programmed in Simulink as a set of linear functions corresponging to appropriate parts of the given diagram.

MEASUREMENTS, DATA LOGGING AND SIGNAL PROCESSING

For each experiment, carried out by the students, the following data are measured:

- absolute acceleration of the shake table platform and its displacement relative to the fixed base;
- absolute floors' accelerations and their displacements relative to the shake table's platform.

The test setup and measuring equipment layout is shown in Figure 16.

For data logging and transforming an analog signal into a digital one a Multilog data logger with six input canals is used. The signal transfer velocity is 2047 signals per second. For signal processing DB-Lab software is used. It has wide possibilities for experimental data analysis and convenient graphics. Additionally EXCEL and MATLAB software is used for advanced data analysis.

IMPLEMENTATION OF DEVELOPED TOOLS IN UNDERGRADUATE COURSES

The above tests have been incorporated in structural dynamics, which is an obligatory course in a structural engineering undergraduate program. Each experiment is carried out by the students and it includes the following stages:

- preliminary stage;
- experiment planning;
- carrying out the experiment;
- analysis of the experimental results.

The preliminary stage includes learning the process, shake table control system, measuring equipment and data logging system. This is carried out by the tutor at the beginning of the laboratory work. Later, the students select a model that will be tested (Figure 17), assemble it from standard elements and calculate the static and dynamic characteristics of the model (flexibility and stiffness matrices, matrix of masses, natural frequency).

Planning the experiment includes calculation of maximum shake table platform displacement, considering the technical characteristics given in Table 1. Then, the stiffness of the additional elastic elements (springs) is obtained. Later the students and tutor select the parameters that should be measured in the test and the required equipment for these measurements.

Carrying out the experiment includes the model identification by obtaining its stiffness matrix, natural frequencies and modal damping experimentally. It also includes observation of dynamic beha-

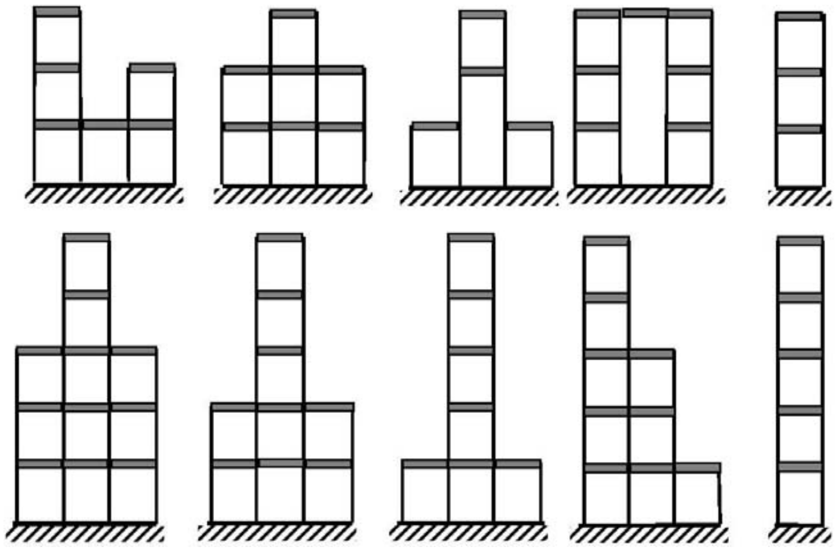


Fig. 17. Selected examples of tested structural models.

vior under the applied load, measuring and recording the dynamic response. The experiments are carried out by the students in small groups (three students in each group), and the data obtained are further analyzed by each student individually.

Analysis of the experimental results includes modeling of the dynamic response according to the tested model's parameters, comparing the experimental results with the theoretical ones and error estimation.

CONCLUSIONS

Small-scale shake tables are effective tools for modeling structural dynamic response to various excitations. Laboratory work, based on this facility, demonstrates basic concepts in structural dynamics and gives students an opportunity to develop deep understanding of structural response to different dynamic loads. A classification of these loads, based on their reproduction by the shake table, was given and corresponding laboratory work was included in the course curriculum.

Two methods for realization of dynamic loadings were defined: ground motions and directly applied forces. For the first type of loading the tested structure is located on the shake table platform, which reproduces the ground acceleration. For the second type, a new method for realizing loads, using originally designed connecting elements, was proposed. The authors have developed the idea of the method and design approach. A numerical example for application of the method was given.

Mathematical models for programming real dynamic loads were proposed and implemented using MATLAB and Simulink facilities. Originally developed routines allow implementation of required algorithms for shake table platform displacement making possible reproduction of corresponding real dynamic loadings.

The results of this study and the proposed methodology can be recommended for using at other universities for teaching structural dynamics. It can be also useful for research purposes in order to simulate structural response to different types of dynamic loadings.

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