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Incorporating a shaking table into a basic course in earthquake-oriented structural engineering

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ABSTRACT: An understanding of structural behaviour during earthquakes is important for future engineers in order to provide the proper design of buildings and avoid damages. The College of Judea and Samaria in Ariel, Israel, offers a mandatory course in the design of seismic resistant structures, and correspondingly adapted related courses in engineering mechanics, structural dynamics and reinforced concrete structures. The geophysical conditions of Israel, located on the African-Syrian fault and the current seismic codes' requirements, are also considered in the teaching process. The laboratory facilities enable the demonstration of basic structural properties, ie stiffness, ductility, dynamic strength of concrete and steel, etc. Students can also investigate the response of structures to earthquakes using a laboratory shaking table, reproducing records of real seismic motions. Teaching according to the proposed programme yields deeper understanding of a structure's physical nature and modern design techniques in earthquake engineering, and helps students to get a better *feeling* of the building. In the final stage of the course, students design buildings considering the real seismic conditions of a building site. Students in their final diploma projects further use the knowledge received during the course.

EARTHQUAKE ENGINEERING EDUCATION IN SUPPORT OF NATIONAL EARTHQUAKE PREPAREDNESS

Israel lies along the Syrian-African Fault, one of the world's major fault lines. As a result, Israel has historically experienced multiple earthquakes, sometimes causing large-scale disasters. The last major earthquake in Israel occurred in 1927 and future events are expected. Due to the growing population density in the country, the consequences of such events could be catastrophic.

Since 1999, the course of *Seismic Structural Design* has been included into the educational programme at the College of Judea and Samaria in Ariel, Israel. Teaching was based on the facilities available at the dynamic laboratory. In 2001, a small-scale shaking table was later purchased. Simultaneously, the programmes of related courses have been adapted to meet the requirements of this course. At the current stage, the course includes lectures, practical exercises, laboratory works and a course project. Based on the knowledge obtained in the course, during the diploma project, students design structures according to a certain seismic zone.

This programme is expected to serve as a national (and international) model for integrating structural dynamics and earthquake engineering into the undergraduate curriculum.

COURSES ADAPTATION

Dynamic Part of Mechanics

One of the basic disciplines required for a proper understanding of structural design to earthquakes is the *Dynamic Part of Mechanics*. Tuition of this subject is oriented to provide a possibility for applying the obtained knowledge in further studying buildings' behaviour during earthquakes. With this aim, a tutor from the Department of Civil Engineering participates in teaching the laboratory part of the course. Additionally, the laboratory works in the frame of the course are realised in the laboratory for structural dynamics. It allows for the use of elements of structures in order to study their dynamic parameters.

In the laboratory works given in this course, the main emphasis is on learning the simple oscillation processes of progressive motion and rotation. Systems with the accumulation of elastic and gravitation energy are studied. These phenomena correspond accordingly to the behaviour of simple fixed-base structures and base-isolated ones during earthquake motions. One of the laboratory works is aimed at the study of rotational stiffness. In the test, instead of traditionally-used springs, torsion bars are involved that allow for the understanding of the torsion response of structures to earthquakes.

Structural Dynamics

The course of *Structural Dynamics* was also adapted for earthquake engineering applications. The teaching process was focused on the behaviour of real structural schemes subjected to ground motions (artificial vibrations and natural earthquake records). This allows the real damped response of structural elements and their ductility factor, required for seismic design, to be obtained. In order to reproduce the records of natural earthquakes, a small-scale shaking table is used (see Figure 1). This is also applied by members of the University Consortium on Instructional Shake Tables (UCIST).

Most of the laboratory works in this course are performed using models of framed structures instead of mass spring-damper systems. One of the aspects studied is the influence of the beam's rigidity on the equivalent structural stiffness. In seismic zones, buildings are always subjected to gravitation (static) loads.

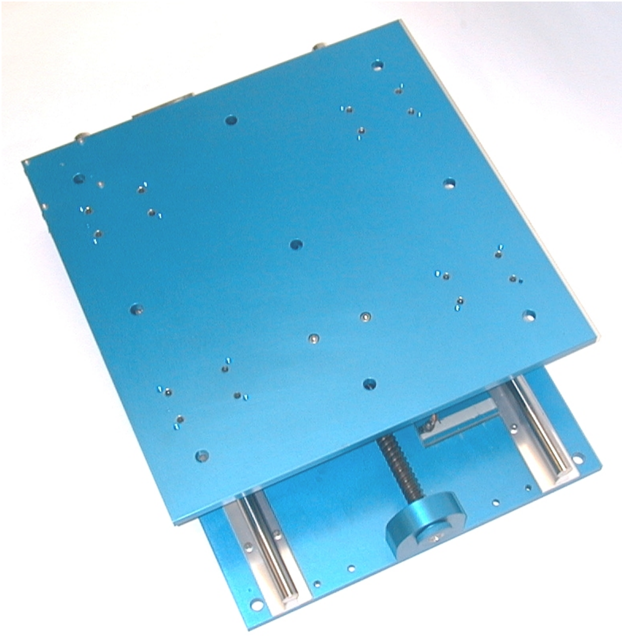

Figure 1: A small-scale shaking table used in the dynamic laboratory (general view).

In order to illustrate the influence of these loads on structural dynamic parameters, an effect of axial stresses in columns is included in the course curriculum.

Natural damping is one of the important structural dynamic properties; hence, this topic is studied intensively and forms a separate group of laboratory works. The natural damping of a framed model is obtained from a free vibration test by analysing the whole structural response record. An influence of the amplitudes on damping is studied. It is demonstrated that the damping increases according to the amplitude, which is important for the further understanding of buildings' behaviour during strong earthquakes.

Design of Seismic Resistant Structures

A series of new illustrative structural dynamics experiments were developed and integrated into the course curriculum. It extends the understanding and intuition of the undergraduate students enrolled regarding the dynamic nature of structures. It also provides them with experience in using modern engineering tools including sensors, dampers and other equipment for *hands-on* experiments.

A group of laboratory works deals with artificial damping. It includes models of structures with viscous, friction, passive and active tuned and semi-active magnetorheological dampers. The properties of these dampers are obtained and their influences on structural dynamic behaviour are demonstrated.

These tests allow for students' further understanding of the mechanism of supplemental damping and create a basis for the design of intelligent seismic resistant buildings. It also allows an effective seismic design of structures combining their own energy dissipation resources and artificial damping systems.

Other courses, such as *Pre-Stressed Concrete*, *Spatial Structures*, *Principles of Structural Design*, *Engineering Structures*, and *Foundation Analysis and Design* were also adapted to earthquake engineering aspects.

CHARACTERISTICS OF THE SHAKING TABLE

The basic component of the dynamic laboratory experiments is a typical small-scale shaking table shown in Figure 1. The shaking table is an effective unit applied in a wide variety of experiments for civil engineering structures. It is computer-controlled with a user-friendly interface and is reasonably priced for educational institutions with an interest in earthquake engineering. The main characteristics of the shaking table are given in Table 1. The shaking table software was improved by the researchers from the College in order to allow for a more exact reproduction of real earthquake records [1].

Table 1: Characteristics of the shaking table.

Specification	Value
Design payload	110 N
Peak acceleration	1 g
Operational frequency range	0 - 20 Hz
Peak velocity	50 cm/sec
Sliding table dimensions	45 x 45 cm
Stroke	15 cm
Weight of the shaking table	445 N

DESIGN OF SEISMIC RESISTANT STRUCTURES: SYLLABUS OF THE COURSE

Topics included in the course are elaborated on below.

Definition of an Earthquake

In this part, students learn about the source of the earthquake, its epicentre, the forms of waves and their distribution, the magnitude of the earthquake and available scales to measure the seismic energy. A review of the strongest earthquakes that have occurred recently and the rise in the price of buildings constructed in seismic zones are also discussed.

Vibrations of SDOF Structures under Earthquakes

This part is based on the preliminary knowledge obtained in the *Structural Dynamics* course. The difference is that instead of periodic excitations, real earthquake motions are introduced. The response of structures to impulse-type earthquakes is taught based on the non-damped and damped free vibrations theory. The forced vibrations of structures under real earthquakes are then studied.

The Response Spectra

This topic is also an extension of the knowledge obtained in the *Structural Dynamics* course. Biot has introduced the standard spectra in seismic design [1]. This idea is used for teaching the design procedure for the equivalent static and modal dynamic analysis. The Standards provisions regarding various soil conditions are also involved [2][3]. The peak response of structures and the SRSS method are introduced.

General Principles of Structural Seismic Resistance

A definition of RC sections and structural ductility is given. The definition is based on the research performed recently by Iskhakov [4]. The students get the final analytical expression for plastic energy dissipation and ductility obtained in a closed form. Other problems, such as the influence of flexible and weak storeys, masses concentration and building irregularity, are also studied.

Earthquake Conditions and Parameters

The principal parameters of a building, soil and environment (ie peak ground acceleration, soil sections, building characteristics, dominant vibration period, ductility parameter and seismic design coefficient) are studied in this part. The storey shear force capacity and limitations in infill walls are also studied. The possible types of structural analysis under seismic excitation (equivalent static analysis and modal dynamic analysis) are introduced.

Principles of Equivalent Static Equivalent Analysis

First of all, a method for the calculation of the horizontal force acting on a building is given. Then the force distribution between the storeys is explained. For regular structures, this distribution is obtained using an original close analytical solution. A next step is the force distribution between the vertical rigid elements of the floor. Additionally, the torsion and P-Δ effects are studied. This part includes a full numerical example for an equivalent static analysis of a typical residential multi-storey building [5].

Principles of Modal Dynamic Analysis

Based on the preliminary knowledge from *Structural Dynamics* on the natural vibration modes of multi-storey structures, a method for the distribution of the design of horizontal forces is introduced. Students learn the interaction of the modes including the influence of torsion and second-order effects.

Geometrical Properties of Vertical and Horizontal Diaphragms

In order to develop engineering students' intuition and feeling of structural response to earthquakes, based on the knowledge obtained from engineering mechanics, the following parameters are studied:

- Second moment of walls section;
- Centres of masses, rigidity and gravitation of the floor diaphragm.

These parameters enable the student to obtain the distribution of horizontal forces between the rigid elements of a floor.

Design of Reinforced Concrete Frames

The constructive requirements for structural and non-structural elements are first given. The specific properties of concrete and reinforcing steel desired for the effective seismic design of structural elements are emphasised. Students learn about the design peculiarities of beams and columns in seismic zones. The increase of bending moments and shear forces due to seismic loads in flexible and weak floors is also considered.

Modern Methods Improving Structural Response to Earthquakes

The effect of base isolation for seismically excited structures is introduced. As an example, a friction pendulum and an electro-metric bearing system, incorporating lead core, neoprene layers connected to steel plates, are discussed. Students acquire the principal information about different passive artificial damping systems used in modern seismic applications. Combined systems that incorporate base isolation and supplemental dampers are also introduced. Finally, the effectiveness of the above-mentioned systems and their influence on structural seismic responses (peak accelerations and displacements) is demonstrated.

Exercises

Each of the topics mentioned above is accompanied by a practical exercise. After some of the topics, students should solve a homework based on the requirements of the Israel Seismic Code [3].

Exercise 1: Seismic Coefficient Cd

This exercise includes the calculation of the following parameters required to obtain the seismic coefficient:

- Soil influence S;
- Peak ground acceleration according to a given seismic zone Z;
- Seismic force reduction coefficient K (related to the ductility parameter μ);
- Coefficient of building's importance I.

The next step is determining the natural vibration period of the structure T. According to T, the spectral intensity coefficient Ra is obtained by three methods: analytical, using appropriate tables and from the graphs available in the Code 3.

Finally, the value of Cd is calculated and verified according to the requirements of the Code.

Exercise 2: Building's Spectral Acceleration Graph

For a given building site with the known above-mentioned parameters Z, S, K and I, and for the equivalent static analysis, the building's acceleration is obtained as follows:

$$a = \mathrm{Cd}\ Z\ g \qquad (1)$$

where g is the gravity acceleration.

After that, students calculate and draw the acceleration spectrum a(T) for buildings with a natural vibration period, T, ranging between 0.1 and 2.0 seconds.

Exercise 3: Total Seismic Force FH and Floor Seismic Force Fi

For a given regular multi-storey RC plane framed building with known storey heights, storey mass, full storey live load, live load reduction coefficient kq, and for a known seismic region, the following problems should be solved:

- Obtain the natural vibration period, storey weight, total design horizontal force and base shear force;
- Determine the floor seismic force for each floor neglecting the torsion effect;
- Identify what the torsion influence coefficient is for a given structural wall;
- Identify what the floor seismic forces are in the case when the torsion effect is considered by the above-mentioned coefficient.

Exercise 4: Equivalent Static Analysis

For a multi-storey building with known geometry, elements and materials properties, the following calculations should be performed:

- Total floor shear strengths in X and Y directions;
- Design dead load, live load, floor weight and total horizontal seismic force;
- The total seismic force distribution along the building's height;
- Floor torsion moments.

Exercise 5: Modal Dynamic Analysis

For the building given in the previous exercise, a modal dynamic analysis should be performed for the first three vibration modes.

Course Final Project

In the second half of the semester, when students are familiar with the basic seismic design concepts, they are given a task for a final course project entitled *Seismic Analysis of a Regular Multistory RC Plane Frame Building*. Students obtain a cross-section and a plane of a typical building floor, required structural details, frame ductility level and characteristic live load. The data, describing the seismic zone, seismic parameters (S, K and I), seismic load direction and reduction coefficient, are also supplied.

It is necessary to undertake the following:

- Check if the building is a regular one;
- Determine the natural vibration period, spectral intensity coefficient Ra and storey self-weight;
- Perform an equivalent static analysis of the building, including the determination of the total seismic force, roof level concentrated force, horizontal design forces at each floor, shear forces at each floor Vi, and floor shear capacity V_{cd}. The relations between Vi and V_{cd} for each floor and for two adjacent floors are also to be obtained. The last step is the calculation of the torsion coefficient, increasing the floor seismic forces;
- Analyse the given RC frame structure under the seismic forces, including the increase in seismic forces, determining the bending moments, shear forces, and axial forces diagrams and displacements in columns. One column and one beam-column connection should be designed.

Seismic Design Aspects in the Diploma Project

Over the last year, all students worked on their final diploma projects. The duration of the project was extended (from one to two semesters), mostly in order to include the seismic design part. It is assumed that the buildings designed by the students will be constructed in a seismic zone. Hence, the buildings constructive schemes have to correspond to the Code requirements for seismic zones.

The design process in the diploma project involves the case of a normal building design for seismic regions. It yields an understanding of the main concepts in structural seismic design, eg preferring regular structural systems, seismic isolation, using appropriate foundation types, etc.

The design of the beams, columns and connections, as well as rigid and infill walls, is performed according to the seismic code requirements. Students can use *STRAP* software for the seismic design process.

The examination board for the diploma project defence includes experts in seismic design.

CONCLUSIONS

The importance of the understanding of buildings' responses to earthquakes by future engineers yields certain changes in the undergraduate educational programme in civil engineering.

An obligatory course, *Design of Seismic Resistant Structures*, is given at the College of Judea and Samaria, and some other disciplines are adapted to satisfy it.

The laboratory facilities enable the demonstration of basic structural properties, eg stiffness, ductility, dynamic strength of concrete and steel, etc. Students can also investigate the responses of structures to earthquakes using a small shaking table to reproduce the records of real seismic motions.

The use of shaking table experiments enable the demonstration such important aspects like the influence of natural and artificial damping on the behaviour of structures subjected to earthquakes. It also allows for the demonstration of modern methods to reduce buildings' seismic responses.

Teaching according to the proposed programme yields a deeper understanding of a structure's physical nature and helps students to gain a better *feeling* of the building, making them more familiar with existing design techniques in earthquake engineering.

Finally, students design buildings by considering real seismic zone conditions. In their diploma projects, students apply the knowledge they acquired during the whole seismic engineering educational process at the College.

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