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Dynamics of Structures

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Abstract

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It is rare nowadays that a whole year goes by without a major earthquake event wreaking havoc somewhere around the world. In some cases, like the 2005 Banda Ache earthquake in Indonesia, the damage involved large geographic areas and casualties in the six figures. In general, the number and intensity of earthquakes is not increasing, however, the vulnerability of the built environment is rising. With increasing unregulated urbanization around seismically active areas, such as the Circum-Pacific "belt of fire," sea rising in low-laying coastal area, and increasing concentrations of both energy production/distribution and digital/telecommunication network critical nodes in vulnerable areas, it is clear that earthquake-resistant design is key to future community resilience.

Designing structures to resist earthquake damage has progressed greatly in the last 50 years, primarily through work in Japan following the 1964 Niigata Earthquake, and in the United States following the 1971 San Fernando Valley Earthquake. The work has advanced along three parallel tracks: (a) **experimental work** aimed at developing improved construction techniques to minimize damage and loss of life; (b) **analytical studies** based on advanced geometrical and non-linear material models; and, (c) **synthesis of the results** in (a) and (b) into design code provisions that improve the ability of structures to resist unexpected loads.

Seismic testing in a laboratory setting is often difficult and expensive. Testing is primarily carried out using the following three techniques:

1. **Quasi-static testing** (QST), where parts of a structure are tested using slowly applied and equivalently predetermined lateral deformations with idealized boundary conditions. This technique is particularly useful to assess the effects of structural detailing on the toughness and deformation capacity of particular parts of structures.
2. **Pseudo-dynamic testing** (PSDT), where loads are also applied slowly, but the dynamic effects are taken into account by solving the equations of motion as the test progresses and by utilizing direct test feedbacks (primarily the instantaneous stiffness) to assess the actual stiffness and damping characteristics of the structure.
3. **Shake tables**, where scale models of complete structures are subjected to input motions using a hydraulically actuated base or foundation. Shake tables represent a more faithful testing technique, as the structure is not artificially restrained, the input is true ground motion, and the resulting forces are truly inertial ones, as one would expect in a real earthquake. However, the power requirements are enormous, and only a few shake tables capable of working at nearly full-scale exist around the world. Globally, there is only one large shake table capable of carrying out tests on full-scale structures, which is the shake table at the E-Defense facility in Japan, built in the aftermath of the 1985 Kobe earthquake.

In this experiment, we will utilize a small shake table and model structures to study the dynamic behavior characteristics of some structural models. It is these dynamic characteristics, principally the natural frequency and damping, as well as the quality of the structural detailing and construction, which make structures more or less vulnerable to earthquakes.

Transcript

1. Models

1. First construct several structures using very thin, strong, rectangular, T6011 aluminum beams, 1/32 in. in width and having different lengths. To build the first model, insert one single cantilever with length of 12 in. to a very rigid wood block. Place a mass of 0.25 lb. to the tip of the cantilever.
2. Similarly, build other model structures by attaching cantilevers with different lengths to the same rigid wood block. Attach a 0.25 lbs. mass to the tip of each cantilever.
3. Prepare two other specimens simulating simple frame structures with flexible columns and rigid floors. These can be built of thin steel plates and rigid acrylic floor diaphragms. One structure will be a one-story and the other will be two stories. The floor diaphragms will be instrumented with accelerometers.

2. Apparatus

For these demonstrations a small, table top, electrically actuated, single degree of freedom shake table will be used. The apparatus consists basically of a small metal table riding on two guiding rails that is displaced by an electric motor. The displacement is digitally controlled by a computer that can input periodic (sine waves) or random accelerations (preprogrammed earthquake ground acceleration time histories). All control is through proprietary software or MatLab and Si mulLink type software. The input forcing function can be checked by comparing it to the output of an accelerometer attached to the table.

3. Procedure

1. Carefully mount the model with various cantilevers to the shake table, using bolts attached to the model's base. Turn on the shake table and using the software, slowly increase the frequency until the maximum response of the structure is obtained for each cantilever. Note that each

cantilever enters resonance at a particular frequency. Record in a notebook the value of this frequency. Continue increasing the frequency until the displacements of all cantilevers reduce significantly.

2. Mount the one-story model structure to the shake table and repeat the procedure. Slowly sweep through frequencies until resonance is reached. Reset the software to run a typical ground acceleration time history (1940 El Centro) to show the random motions that occur during an earthquake.
3. Mount the two-story structure to the shake table and repeat the procedure. Note that two natural frequencies occur in this case.

Structural dynamics, or the analysis of structure's behavior when subjected to dynamic forces, is critical both for designing buildings able to resist earthquake and fatigue loads, and for providing occupant comfort in structures subjected to wind and other types of cyclic loads.

In order to develop resilient design strategies for our cities' infrastructures, we need to understand both the input, for example, the ground motion during seismic activity, and the output, or the structural response of the buildings. This issue can only be addressed through a combined analytical and experimental approach.

Seismic testing in a laboratory setting is carried out using shake tables, where scale models of complete structures are subjected to input motions using an electrically or hydraulically actuated base. This method represents a more faithful testing technique, as the structure is not artificially restrained, and the input is true ground motion.

This video will illustrate the principles of dynamic analysis by using a shake table and model structures to study the dynamic behavior characteristics of different structural models.

The usual self weight loads acting on a structure are quasi static because they change very slowly or not at all with time. In contrast, loads produced by hurricanes and blasts, for example, are extremely dynamic in nature.

During an earthquake, the ground moves with certain acceleration while the structure tends to stay still. As a consequence, the dynamic loads acting on a structure are inertial, and they depend on the mass, stiffness, and damping of the structure. To solve this problem analytically, we employ basic physics laws and simplified models of the actual structures.

For example, both a bridge and a frame with rigid beam can be simplified to a single degree of freedom system, consisting of an elastic cantilever with length L and mass m, stiffness k, and damping c. Alternatively, another model system can be represented by a mass attached to a spring of elastic constant k, as well as a dash pot with a damping coefficient c. These components can be combined in parallel and in series to model different structural configurations.

For our mass and spring model system, if the ground is moving the external force acting on this system is proportional with the ground acceleration. The other forces in the system are the elastic force in the spring, proportional to the displacement, as well as the reaction force in the dash pot, proportional to the velocity.

Using Newton's Second Law, we can write the equation of horizontal equilibrium of forces for this system. In the absence of external forces, and assuming the damping effects as negligible, this simplified equation has the following solution:

Here, wn is the undamped natural frequency of the system, and u0 is the initial displacement. If we add the effect of damping, the solution of the equation of motion is the following. Here the damped natural frequency of the system is expressed using the natural frequency and the damping coefficient.

The effective damping on the free oscillations of the system results in the decrease of the amplitude of vibrations with every cycle. Considering the displacements in two successive cycles, we can use the logarithmic decrement delta to calculate the damping constant zeta.

If the ground motion is taken as sinusoidal function, the solution for the equation of motion is given by the following function. Here phi is the phase lag, and R is the amplification response factor.

Let's plot this factor versus frequency ratio for different values of the damping coefficient zeta. For low values of damping, as the frequency of the forcing function approaches the natural frequency of the system, the response of the system becomes unstable, a phenomenon that is commonly referred to as resonance.

Now that you understand the theoretical concepts regarding the behavior of a linear elastic system to dynamic loads, let's investigate these concepts using a shake table.

First, construct several structures using very thin, strong, rectangular, T6011 aluminum beams, 1/32 of an inch in width, and having different lengths. To build the first model, insert one single cantilever with length of sixteen inches to a very rigid wood block. Place a mass of 0.25 lb on the tip of the cantilever.

Similarly, build three other model structures by attaching three cantilevers with lengths of 24, 32, and 36 inches to the same rigid wood block. Attach a 0.25 lb mass to the tip of each cantilever. Using thin steel plates and rigid acrylic floor diaphragms instrumented with accelerometers, prepare two other specimens simulating simple frame structures with flexible columns and rigid floors.

For these demonstrations, a table top electrically actuated shake table with a single degree of freedom will be used. A computer digitally controls the table displacement and generates periodic sine waves or random accelerations. The input forcing function can be checked by comparing it to the output of an accelerometer attached to the table.

First, carefully mount the four cantilever structures to the shake table using bolts attached to the model's base. Then turn on the shake table, and using the software, slowly increase the frequency, until the maximum response of the structure is obtained. Record in a notebook the value of this frequency. Continue increasing the frequency until the displacements of all the cantilevers reduce significantly.

Now, mount the one-story model structure to the shake table and repeat the procedure. Slowly sweep through frequencies until resonance is reached. Next, reset the software to run a typical ground acceleration time history to show the random motions that occur during an earthquake. Replace the one-story model on the shake table with the two story structure, and repeat the procedure. Note that two natural frequencies occur in this case. Record in a notebook the values of these frequencies.

Now let's perform the data analysis and discuss our results.

First, determine the frequency at which the maximum displacement occurred for each model. For the case of a cantilever beam the equivalent mass is given by the mass at the top, and the distributed mass of the beam. The stiffness k is the reciprocal of the deformation delta, caused at the top of the cantilever by a unit force, where L is the length of the beam and E is the modulus of elasticity.

Here, I is the moment of inertia that can be easily calculated if the width b and the thickness h of the beam are known. Place data in a table and then calculate the natural circular frequencies. With these values calculate the predicted periods of motion for the cantilever beams tested.

Next, look at the displacement versus time response recorded in this experiment, and determine from these plots the corresponding periods of motion of the cantilever beam. Add these measured periods to the table and compare them with the theoretical values.

The differences between the theory and experiment are due to several sources of errors. First, the beams are not rigidly attached to the wooden base, and the added flexibility at the base increases the period of the structure. Second, the damping was not accounted for in the calculations because damping is very difficult to measure and amplitude-dependent.

In this experiment we recorded the displacement versus time histories of the beam when the shake table was subjected to a varying sinusoidal deformation with an initial one inch amplitude. From these graphs, extract the maximum value for each frequency, and plot the magnitude of the displacement versus normalized frequency.

Now take a look at your plot. Initially there was not much response, as the energy input from the table motion does not excite the model. As the normalized frequency approaches one, there is a very significant increase in the response with the deformations becoming quite large. The maximum response has reached very close to one. As the normalized frequency increases beyond one, the dynamic response begins to die down. A large value of the normalized frequency corresponds to the situation where the load is applied very slowly with respect to the natural frequency of the cantilever and the deformation should become equal to that from a statically applied load.

Structural dynamics is widely used in the design and analysis of buildings, products, and equipment across many industries.

Designing structures resilient to earthquake damage has progressed greatly in the last 50 years. Nowadays the results from the experimental work, as well as from the analytical studies, are corroborated into design code provisions that improve the ability of structures to resist unexpected loads during a seismic event.

One easily observable dynamic response of a structure to wind loads is that of cantilevered traffic lights. As the wind flows over the structure, the wind regime is disturbed and vortices are generated through a phenomenon known as vortex shedding. These vortices induce forces perpendicular to the wind direction, resulting in a cyclic vertical displacement of the cantilevered arm, and as a consequence, potential fatigue damage of the structure.

You've just watched JoVE's Introduction to the Dynamics of Structures. You should now understand the theoretical principles governing the behavior of a structure subjected to dynamic loads. You should also know how to use a shake table to perform a dynamic analysis of a model structure.

Thanks for watching!