AC 2009-739: TRANSLATING AN ENGINEERING RESEARCH PROJECT BASED ON IMPROVING BUILDINGS' RESISTANCE TO EARTHQUAKES INTO THE HIGH-SCHOOL CLASSROOM EXPERIENCE

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Translating an engineering research project based on improving buildings' resistance to earthquake into the high school classroom experience

Abstract

Earthquakes can cause damage and/or collapse of building structures. This phenomenon offers a real-life application of waves and resonance that teachers and students can discover while experimentally investigating retrofitting solutions for buildings subjected to earthquakes. In a NSF sponsored six-week summer Research Experiences for Teachers (RET) program, university faculty and high school teachers partnered to develop lessons based on engineering concepts. During this program, a team of three teachers researched under the guidance of a dedicated faculty and doctoral student ways to improve buildings' resistance to earthquakes. The goals were two fold. First, high school teachers learned the technology and analysis tools necessary to implement an engineering research project. Second, they extracted from their research experience, key concepts and ideas that could be translated into the high school classroom. In this paper, we first present a summary of the high school teachers' research results. Then we describe an outline of the lessons they developed and implemented and the evaluations conducted.

Introduction

The Research Experience for Teachers (RET) is a six week-program sponsored by the National Science Foundation (NSF). A group of twelve science and mathematics teachers were chosen to spend the summer working on current civil engineering research topics. During their summer, they learned about engineering, and developed skills necessary to implement a research project. They also collaborated with faculty and graduate students, acquiring a better understanding about which skills their students need to have. The group was divided into smaller groups of three teachers who worked on four different topics. This paper focuses on one group. The three teachers involved in the group investigated "buildings that resist earthquakes better." The goals of the collaboration were two fold. First, high school teachers immersed themselves in a research atmosphere, learning the technology, analysis tools and skills necessary to implement an engineering research project. Second, they extracted from their research experience key concepts and ideas that could be translated into the high school classroom. Third, they developed and implemented a lesson and evaluated its impact on student leaning. The paper describes their experience, the research project's main results, and their classroom implementation with the main results obtained from the students.

2. Research Experience for Teacher

The key concept of the program is to introduce teachers to a research project topic that they can use later in their classroom. Very often, students feel disconnected from the material presented to them. In order to engage students, using real life examples becomes an essential characteristic of lesson preparation. The teachers involved in the NSF sponsored program had the opportunity to discover several applications of the science and mathematics concepts that they teach to their students. Earthquakes and their effects on buildings offer an excellent platform to introduce the concepts of simple harmonic motion, natural frequency, stiffness, and resonance. Students encounter a lot of difficulty in understanding simple harmonic motion and the mathematics underlying this concept. They often treat it as a pure mathematics topic without any physical significance. By providing an illustration of these concepts, teachers can better engage students in the learning process.

During this experience, teachers had to set up a series of experiments choosing what to record, how to collect data using the appropriate sensors, and how to analyze the collected data. They also had to choose the best way to present those using graphs and tables in order to demonstrate laws of Physics. Teachers were introduced to Matlab and mathematics functions such as Fast Fourier Transform.

During the research project, the teachers first verified that building structures can be modeled as spring-mass systems. They investigated the characteristics of small-scale one-story steel-frame models by varying column lengths (L) and floor masses (M) using the stiffness test (see Figure 1 showing the one-story building model used, Figure 2 and 3 showing the stiffness test set-up, Figure 3Figure 4 showing the stiffness test results recorded, and Table 1 reporting all the stiffness test results). Varying column stiffness (k) by varying L and conducting free vibration tests, they found that k decreases when L increases. Additionally, the models' natural frequency (f_0) decreases when M or L increases[3] (see Figure 5 for the free-vibration test set-up used, Figure 6 showing the free vibration test results recorded, Figure 7 showing a peak amplitude graph used to compute the damping coefficient of the structure, and Table 2 showing the frequency and damping test results obtained). These results validated the spring-mass model[1]. Second, the study focused on the damaging effects of earthquake-induced resonance on buildings and ways to minimize such effects. Teachers selected and subjected a steel-frame model to forced vibration using a shake table (see Figure 8 showing the test set-up and the sensors used). The steel-frame model was subjected to various base motions simulated by the shake table over it was mounted and data for displacement, velocity, and acceleration of the top floor mass relative to the base was recorded. In particular, data was recorded when resonance occurred. The study was then repeated with frame models fitted with base isolators (BI) of different sizes. A BI decouples a building frame model from its foundation (base mass fixed to the shake table top in the frame model used in this study). The goal was to study the effects of BI on frame response due to earthquake induced vibrations. The results showed that BI initiates a shift (decrease) of the retrofitted model's f_0 and the smallest size BI gives the largest shift (see Figure 9 for the results obtained). Finally, teachers conducted free vibration tests on models fitted with and without viscous dampers (VD) with fluids of varying viscosity (η) to study the models' damping coefficient (c). Teachers determined that the incorporation of VD increased c, especially for higher viscosities.

3. Project-based lesson

In order to bring the skills and knowledge acquired from the research experience explained above, the teachers choose to introduce The Earthquake Retrofit Project. This project would provide the teachers with an opportunity to present a research-based project very similar to what they had experienced during their six-week RET program. They chose to use probes from Pasco[4] or Vernier[5] and the associated software Data Studio and Logger Pro. After introducing the concept of simple harmonic motion through classical models (pendulum and mass-spring simple harmonic motion), the teachers challenged their students to find ways to improve a K'NEX[6] structure's resistance to a simulated earthquake. The project discussed in the paper was developed around the 5E's of Learning (Engage, Explore, Explain, Elaborate and

Evaluate). The focus of this paper is the evaluation on student learning conducted for the project. In this project, students will use the engineering design process, data collection and their knowledge of simple harmonic motion and earthquakes to retrofit a single story structure to resist a low, medium and high frequency earthquake. The Earthquake Retrofit Project offers a platform for students to investigate the concept of simple harmonic motion and resonance in the context of a real-life situation: buildings subjected to ground motions caused by earthquakes[7].

a. *Goals of the project, Objectives and Ohio Standards*

The purpose of the project is to use the engineering design process to retrofit a K'NEX structure with common household materials to withstand the effects of a simulated earthquake better. The students' goal was to change the natural frequency of their structure so it would not match the natural frequency of the forced vibration. In real life, when the frequency of a building and an earthquake match, resonance occurs. The results of resonance are structural damage and loss of human life. Students may also want to create a building that can quickly damp, go back to its equilibrium position after being disturbed. Three different experimental tests were conducted in this student-centered project, the stiffness test, the free vibration test, and the forced vibration test. The students are able to model the essence of the physical system of a building under earthquake vibration, test and record its performance by collecting real-time test data to a computer using appropriately selected sensor devices. Finally, student will be able to represent the phenomenon graphically and mathematically using the laws of physics.

Using the Ohio Standards for Science, the teachers developed several objectives where students will be able to:

- Determine the natural frequency, period, and stiffness of a structure using data collection.
- Analyze the effect of an earthquake retrofit system (ERS) on stabilization (damping) of a structure.
- Utilize the engineering design process to make appropriate choices when designing ERS.
- Analyze data to determine the effectiveness of ERS.
- Explain how societal issues and considerations affect the use of ERS in the United States.
- Describe the movement of the structure using data tables, graphs and sketches.
- Derive linear equations that represent the motion of a structure.
- Represent free vibration and forced vibration curves as trigonometric functions and/or exponential functions.

The objectives are aligned with the Ohio Standards for Science for:

Physical Science

D. Apply principles of forces and motion to mathematically analyze, describe and predict the net effects on objects or systems.

Science and Technology

A. Predict how human choices today will determine the quality and quantity of life on Earth.

Scientific Inquiry

A. Make appropriate choices when designing and participating in scientific investigations by using cognitive and manipulative skills when collecting data and formulating conclusions from the data.

Scientific Ways of Knowing

C. Explain how societal issues and considerations affect the progress of science and technology.

b. Stiffness test

i. Setup

In order to measure the stiffness of the model, students used two probes from Pasco: Force Sensor and a Motion detector. One laptop with Data Studio from Pasco was used to dynamically record the force applied on the structure and the associated displacement, Δx. The model and test set-up are shown in Figure 10. The students completed this test both before and after their retrofits to see the effects.

ii. Examples of data analysis

The students choose to conduct at least three trials for the same model. A sample of the data reported in graphical form by the student is presented in Figure 11. From the graph obtained, using linear regression analysis they obtained the best linear fit and the slope of this line gave them the desired value of the stiffness, k. Table 3 presents the stiffness values reported by a student group. The test was repeated for different heights, in order for the students to understand the relation between column length and stiffness.

c. Free vibration test

i. Setup

The free vibration test requires only the motion detector with the laptop and Data Studio. The structure is pulled away from the motion detector and is then released. The motion detector transmits information about the position, velocity and acceleration versus the time. The sampling rate can be adjusted and was chosen to be 50 or 100 Hz. A photograph of the test set-up used is shown in Figure 12.

ii. Examples of data analysis

For the data analysis, the students used Data Studio from Pasco. The software allows to record data and to analyze it. An example of the kind of data obtained from the free vibration test is presented in Figure 13. From this data, students could extract the values of their structure's decreasing amplitude, and find its damping coefficient. An example of the summary of the data reported for the stiffness test and free vibration test by a student group is given in

.

d. Forced vibration test

i. Setup

The forced vibration was obtained by using a shake table, as shown in Figure 14. Students observed and record how varying the frequency of the shake table impacts the structure mounted on it.

ii. Examples of retrofit solution

The students looked for ways to change the natural frequency of their model or/and the damping rate. Methods that students employed during this project included cross-bracing, mass dampers, and slosh tanks. All of these methods were viable in changing the natural frequency and stiffness of their structures to help them resist an earthquake better. Figure 15 and give examples of student designs at two different high schools in which this project was implemented.

4. Assessments and Impact on students

In order to assess student learning of this engineering design project, a Lab Report Rubric and a Presentation Rubric is utilized, which are presented in Table 6 and 7). In one of the schools, the target population was composed of female students taking physics while the other school was co-ed. The project allowed this population to discover engineering and experience concepts that are related to civil engineering. The investigation did allow difficult concepts to be presented more attractively. Inquiry-based project presenting the effects of earthquakes on building was a platform used to present concepts of waves (the natural frequency and damping coefficient of the building) and resonance (effect of earthquake). They made the connection between the concept of waves and a real life application. The students understood the repercussion of this phenomenon on design of buildings done by structural civil engineers. Data collection, graphing and scientific process were reinforced in the set of activities. They also practiced these skills as self-learners. In addition, a project feedback for the project was collected, which confirmed that students learn better through a project-based lesson than a more traditional lesson.

Conclusions

The teachers involved in the RET program encountered several technical challenges and learned to overcome their technical difficulties. During this process, they succeeded to acquire skills that they were able to bring back to their students. The lesson that resulted from their summer experience reproduces, at a smaller scale, what they had experienced for six weeks during the RET Site. Following a 5E lesson plan, the teachers introduced the relation between building, earthquake and harmonic motion. The activity is designed for the students to initially try to find out the main parameters of small scale building models that impact its dynamic vibration characteristics and the impact they may have in causing some damage or even complete failure (or collapse) after an earthquake. Using the engineering design process, students develop preventive devices, such as base isolators or dampers, to mitigate the damage. They investigated the effects of these devices on the natural frequency and/or damping coefficient of the building. They also evaluated the performance of the building with these devices installed by mounting them on a shake table simulating earthquakes of different ground motion frequencies. The experimental investigation allowed students to grasp the concepts of waves, resonance and damping effects.

Acknowledgements

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- Mr. W. Henry Leach, Technical Professional of Physics, University of Cincinnati.

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7. The lesson plan is available on the following website http://www.eng.uc.edu/step/ret/

Table 1: Stiffness k as a function of column's length

L (cm)	k (lb/in.)	k (N/m)	kL^3 (lb in.^{2})
28.3	16.13	2831.7	22309.6
15.9	94.5	16586.4	23180.5
%error	1	1	
Comparison			**3.8%**

Table 2: Experimental frequency, theoretical frequency, and damping rate

Mass	M_1 = 3.52 kg	M_1 = 3.52 kg2	M_2 = 6.72 kg
Length	L_1 = 15.9 cm	L_2 = 28.3 cm	L_1 = 15.9 cm
f_0 (Hz)	10.1	4.42	7.42
$f_{o,theoretical}$	10.9	4.5	7.9
% error	7.3%	1.8%	6.1%
Damping rate	0.22	0.08	0.16

Table 3: Experimental data obtained by students for stiffness for the floor mass of 0.044 kg and height of 0.645 m

Building 2:

Mass: 0.044 kg
Height: 0.645 m

Trial	k
1	8
2	8.8
3	8.1

Table 4: Experimental data obtained by students for free vibration test for the mass floor of 0.0301 kg

Varying Height for mass m=0.0301kg:

	Height (cm)	Average K	K error	Average Damping	Damping Error	Average natural frequency
1	32	33.3	±0.45	3.07	±0.447	4.61
2	45.5	24.2	±0.33	1.61	±0.307	3.05
3	64	15.8	± 0.25	1.33	± 0.123	1.71

Table 5: Experimental data obtained by students for free vibration test for the height of 0.032m

Varying Mass for a height h=0.032m:

	Mass (g)	Average K	K error	Average Damping	Damping Error	Average natural frequency
1	30.1	33.3	±0.45	3.07	±0.447	4.61
2	50	30.0	±3.14	5.31	±3.14	3.54
3	84.2	36.7	± 0.16	2.52	±0.164	2.82

Table 6: Lab Report Rubric – Made using Rubistar

CATEGORY	4	3	2	1 or 0
Background Information	Researched information focused on earthquake dynamics, simple harmonic motion, the relationship between a building and spring and real-life earthquake retrofit systems are clearly and accurately discussed (1 page max)	Researched information focused on earthquake dynamics, simple harmonic motion, the relationship between a building and spring and real-life earthquake retrofit systems are discussed (1 page max). Minor errors exist.	Researched information focused on earthquake dynamics, simple harmonic motion, the relationship between a building and spring and real-life earthquake retrofit systems are discussed (1 page max). 1-2 topics are not discussed fully	Information is not clear or researched. Topics are not discussed clearly or fully.
Question/Purpose	The purpose of the lab or the question to be answered during the lab is clearly identified and stated.	The purpose of the lab or the question to be answered during the lab is identified, but is stated in a somewhat unclear manner.	The purpose of the lab or the question to be answered during the lab is partially identified, and is stated in a somewhat unclear manner.	The purpose of the lab or the question to be answered during the lab is erroneous or irrelevant.
Materials	All materials and setup used in the experiment are clearly and accurately described.	Almost all materials and the setup used in the experiment are clearly and accurately described.	Most of the materials and the setup used in the experiment are accurately described.	Many materials are described inaccurately OR are not described at all.
Procedures	Procedures are listed in clear steps. Each step is numbered and is a	Procedures are listed in a logical order, but steps are not numbered and/or are	Procedures are listed but are not in a logical order or are difficult	Procedures do not accurately list the steps of the

	complete sentence.	not in complete sentences.	to follow.	experiment.
Analysis	The relationship between the variables is discussed and trends/patterns logically analyzed. Predictions are made about what might happen if part of the lab were changed or how the experimental design could be changed.	The relationship between the variables is discussed and trends/patterns logically analyzed.	The relationship between the variables is discussed but no patterns, trends or predictions are made based on the data.	The relationship between the variables is not discussed.
Calculations	All calculations are shown and the results are correct and labeled appropriately.	Some calculations are shown and the results are correct and labeled appropriately.	Some calculations are shown and the results labeled appropriately.	No calculations are shown OR results are inaccurate or mislabeled.
Error Analysis	Experimental errors, their possible effects, and ways to reduce errors are discussed.	Experimental errors and their possible effects are discussed.	Experimental errors are mentioned.	There is no discussion of errors.
Conclusion	Conclusion describes the skills learned, the information learned and some future applications to real life situations.	Conclusion describes the information learned and a possible application to a real life situation.	Conclusion describes the information learned.	No conclusion is written.
Background Sources	Several reputable background sources were used and cited correctly. Material is translated into student's own words.	A few reputable background sources are used and cited correctly. Material is translated into student's own words.	A few background sources are used and cited correctly, but some are not reputable sources. Material is translated into student's own words.	Material is directly copied rather than put into students own words and/or background sources are cited incorrectly.
Engineering Design Process Notes	Clear, accurate, dated notes are taken regularly indicating use of the Engineering Design Process.	Dated, clear, accurate notes are taken occasionally indicating use of the Engineering Design Process.	Dated, notes are taken occasionally, but accuracy of notes might be questionable indicating use of the Engineering Design Process.	Notes rarely taken or of little use indicating use of the Engineering Design Process.
Scientific Concepts	Report illustrates an accurate and thorough understanding of scientific concepts underlying the lab.	Report illustrates an accurate understanding of most scientific concepts underlying the lab.	Report illustrates a limited understanding of scientific concepts underlying the lab.	Report illustrates inaccurate understanding of scientific concepts underlying the lab.
Components of the report	All required elements are present, in order and additional elements that add to the report (e.g., thoughtful comments, graphics) have been added.	All required elements are present and in order.	One required element is missing , but additional elements that add to the report (e.g., thoughtful comments, graphics) have been added.	Several required elements are missing and or out of order.
Participation	Used time well in lab and focused attention on the experiment.	Used time pretty well. Stayed focused on the experiment most of the time.	Did the lab but did not appear very interested. Focus was lost on several occasions.	Participation was minimal OR student was hostile about participating.
Retrofit Design Parameters	Follows all parameters established in experimental set-up	Follows all but 1 parameter established in the experimental set-up	N/A	Did not follow the established parameters

Table 7: Presentation Rubric – Made using Teach-nology

Criteria	Points			
	4	3	2	1
Organization	Student presents information in logical, interesting sequence which audience can follow.	Student presents information in logical sequence which audience can follow.	Audience has difficulty following presentation because student jumps around.	Audience cannot understand presentation because there is no sequence of information.
Content Knowledge	Student demonstrates full knowledge (more than required)with explanations and elaboration.	Student is at ease with content, but fails to elaborate.	Student is uncomfortable with information and is able to answer only rudimentary questions.	Student does not have grasp of information; student cannot answer questions about subject.
Visuals	Student used visuals to reinforce screen text and presentation.	Visuals related to text and presentation.	Student occasional used visuals that rarely support text and presentation.	Student used no visuals.
Mechanics	Presentation has no misspellings or grammatical errors.	Presentation has no more than two misspellings and/or grammatical errors.	Presentation had three misspellings and/or grammatical errors.	Student's presentation had four or more spelling errors and/or grammatical errors.
Delivery	Student used a clear voice and correct, precise pronunciation of terms.	Student's voice is clear. Student pronounces most words correctly.	Student incorrectly pronounces terms. Audience members have difficulty hearing presentation.	Student mumbles, incorrectly pronounces terms, and speaks too quietly for students in the back of class to hear.

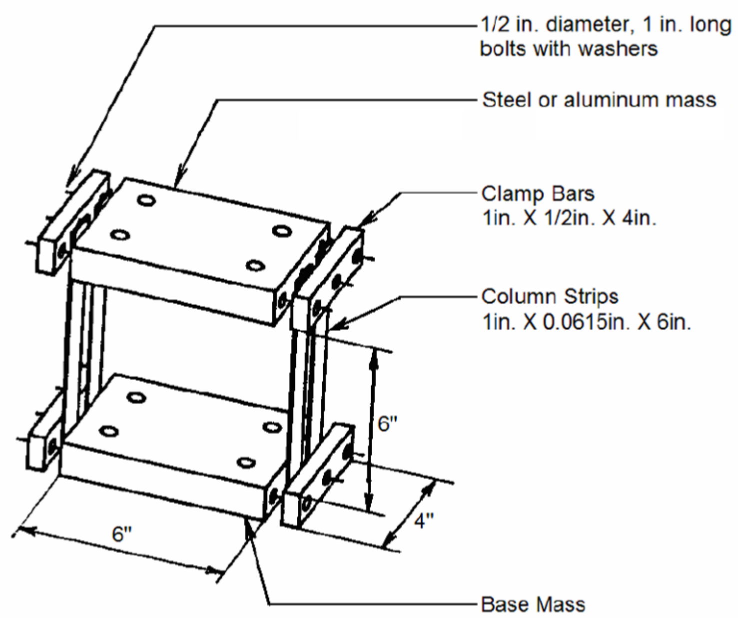


Figure 1: Schematic of small-scale single degree of freedom structure[2]

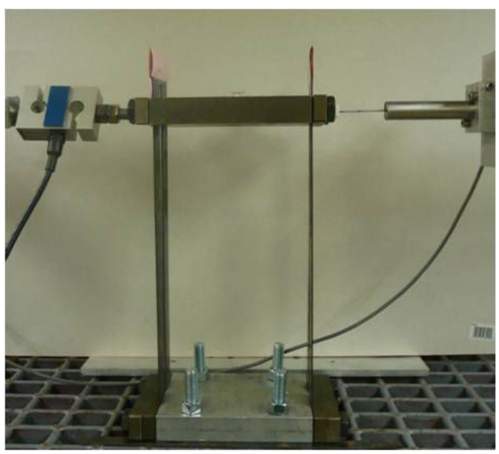


Figure 2: Stiffness experiment with Load Sensor (Left) and LVDT (Right)

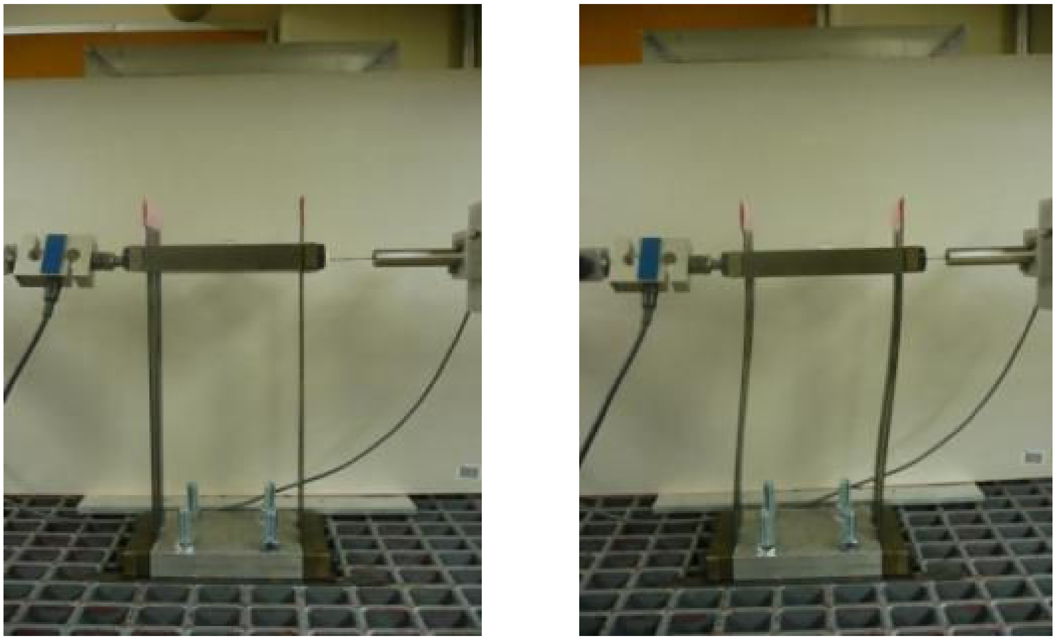


Figure 3: Stiffness test on structure prior to force and displacement (left), and with force and displacement (right)

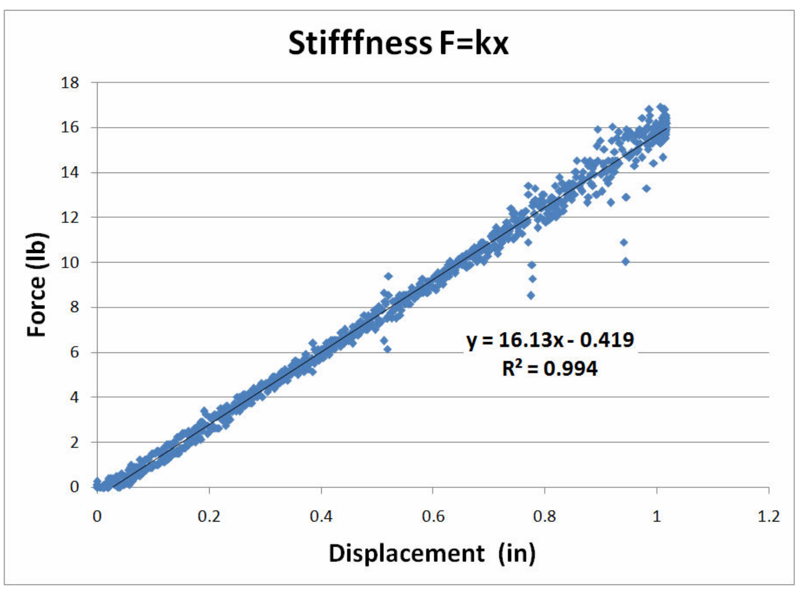


Figure 4: Stiffness is given by the slope of the force versus the displacement

Figure 5: Structure with additional mass clamped above floor and electromagnet (left) prior to free vibration test

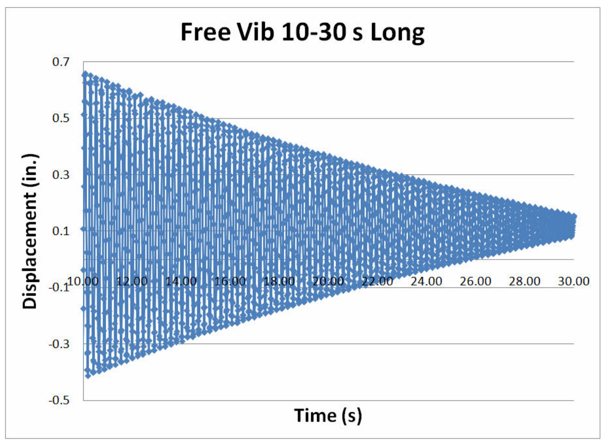


Figure 6: For model with M1 = 3.52 kg, L1 = 28.3 cm: free vibration data between 10 and 30 seconds

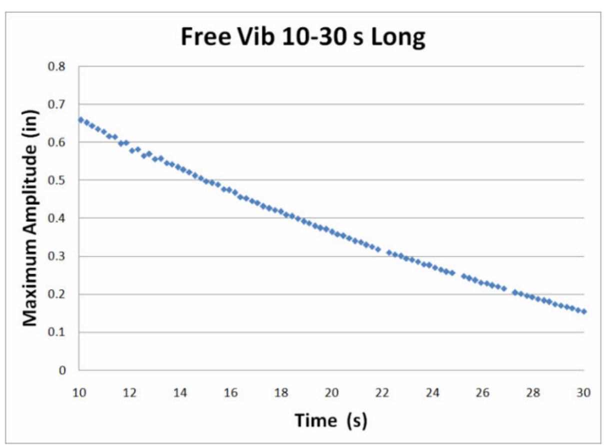


Figure 7: For model with M1 = 3.52 kg, L1 = 28.3 cm: maximum amplitude data showing the upper limit envelope e-pt

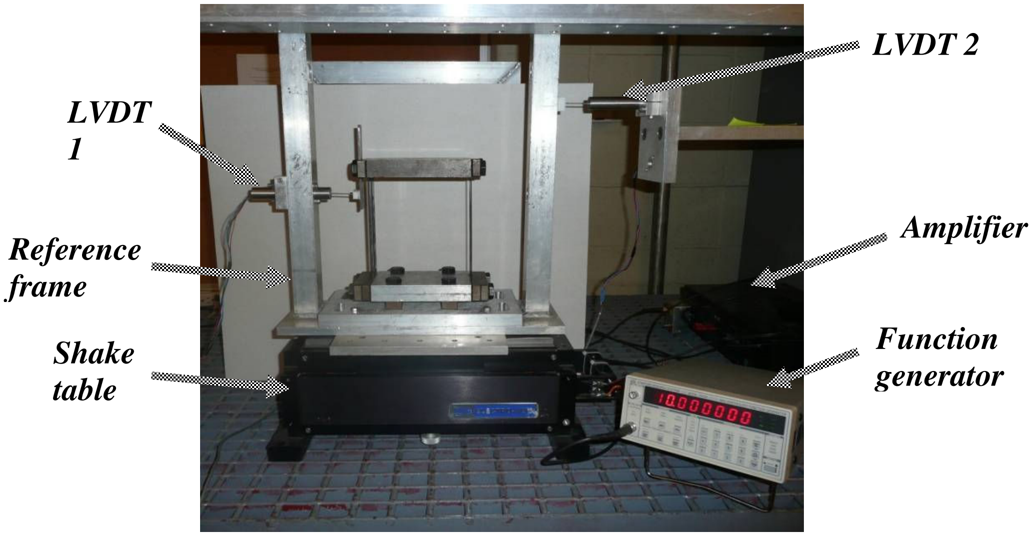
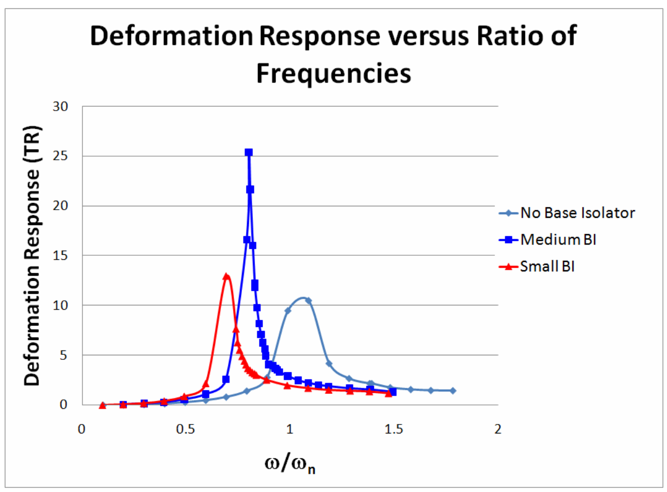


Figure 8: Structure bolted to shake table with function generator, amplifier, reference frame, and two LVDTs



$$TR = \frac{u_{\max}^{total}}{u_{ST}} = \left\{ \frac{1 + \left[2\zeta \left(\omega / \omega_n \right) \right]^2}{\left[1 - \left(\omega / \omega_n \right)^2 \right] + \left[2\zeta \left(\omega / \omega_n \right) \right]^2} \right\}^{1/2}$$

where TR = transmissibility, which is the ratio of the total maximum displacement of the structure to the maximum displacement of the shake table (ground), ω = angular velocity of the shake table, ωn = natural angular velocity of the structure and ζ = damping ratio.

Figure 9: Transmissibility versus Frequency Ratio when the structure is subjected to a harmonic excitation by the shake table

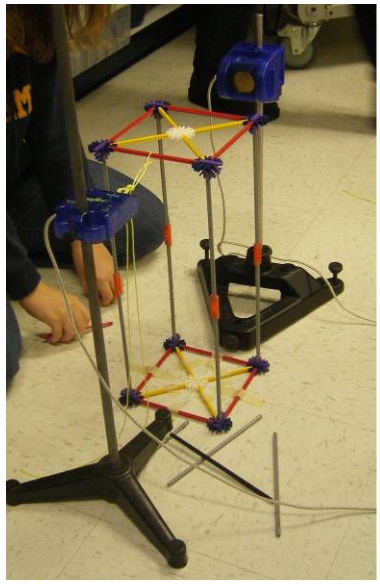


Figure 10: Experimental setup to measure the stiffness of the model: a force sensor and motion detector probes are connected to a laptop

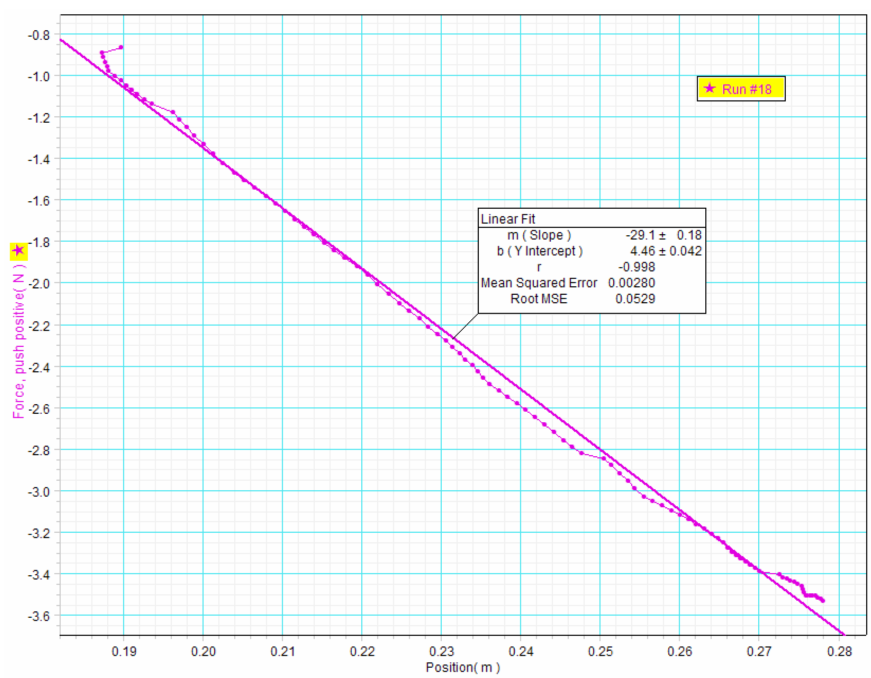


Figure 11: Force versus Position graph: the slope is the stiffness k

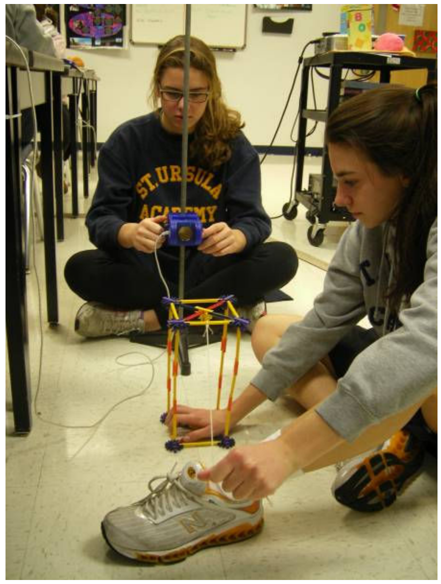


Figure 12: Setup for free vibration test: The model is pulled using a string and the motion detector records the displacement in function of the time

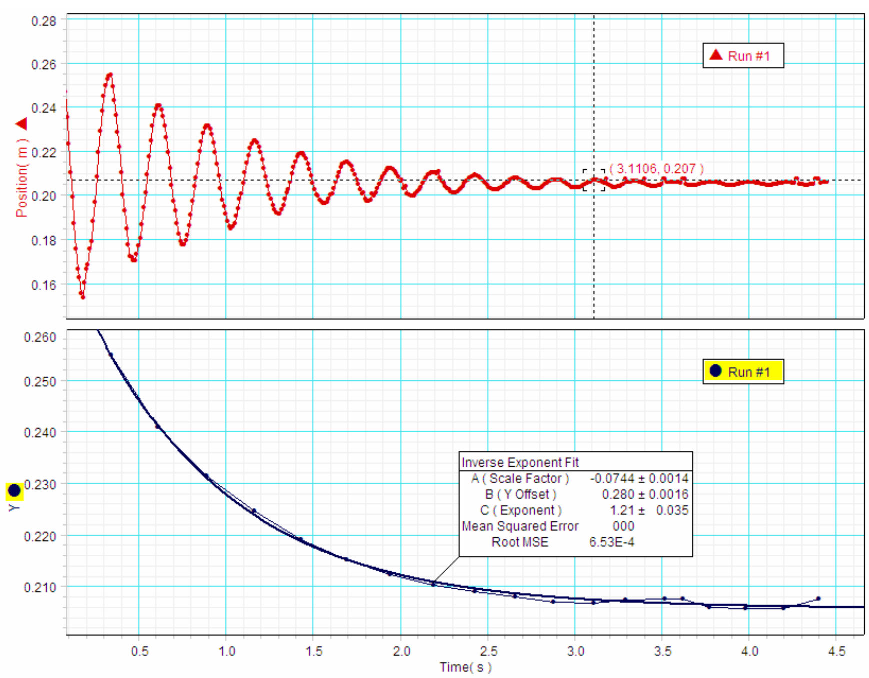


Figure 13: (a) Position versus time graph for free vibration test for building 1, and (b) maximum amplitude versus time and fit

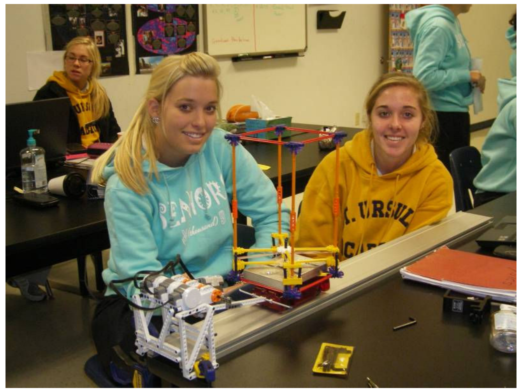


Figure 14: Shake table setup using Pascar and rail from Pasco: the Lego robot was modified to perform the external excitation and the retrofitting building is tested to observe the effect of the retrofit solution

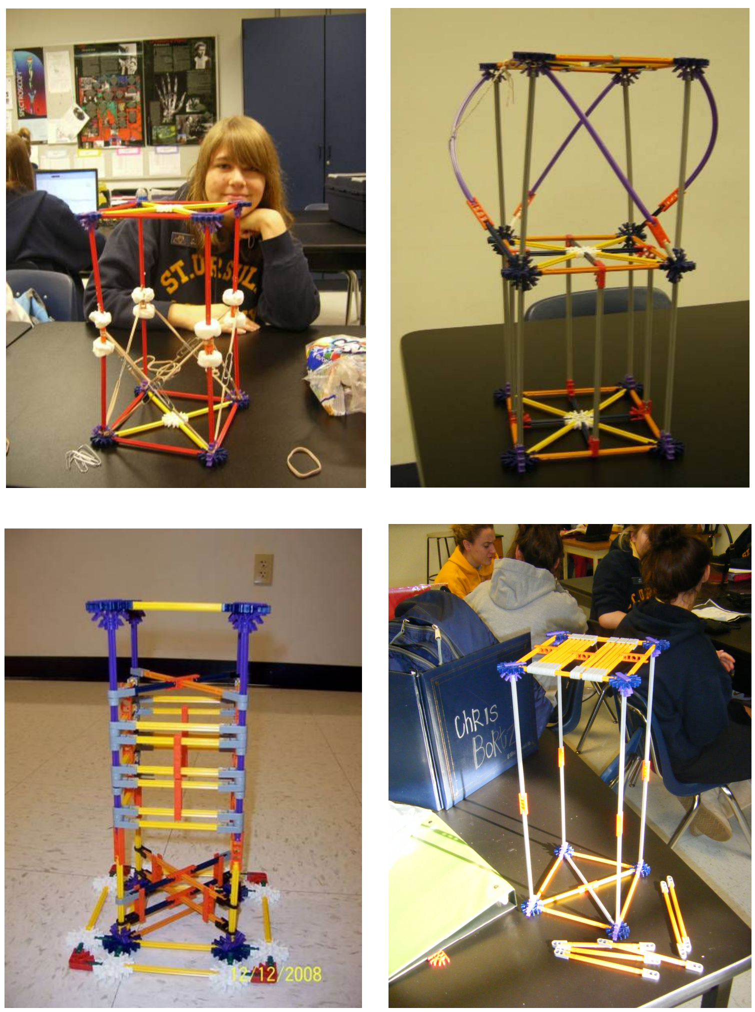


Figure 15: Four examples of retrofitting solutions: (1) model with flexible braces, (2) Model with flexible braces and dampers on columns, (3) model with mass dampers sliding on the first floor and(4) model reinforced with beams.

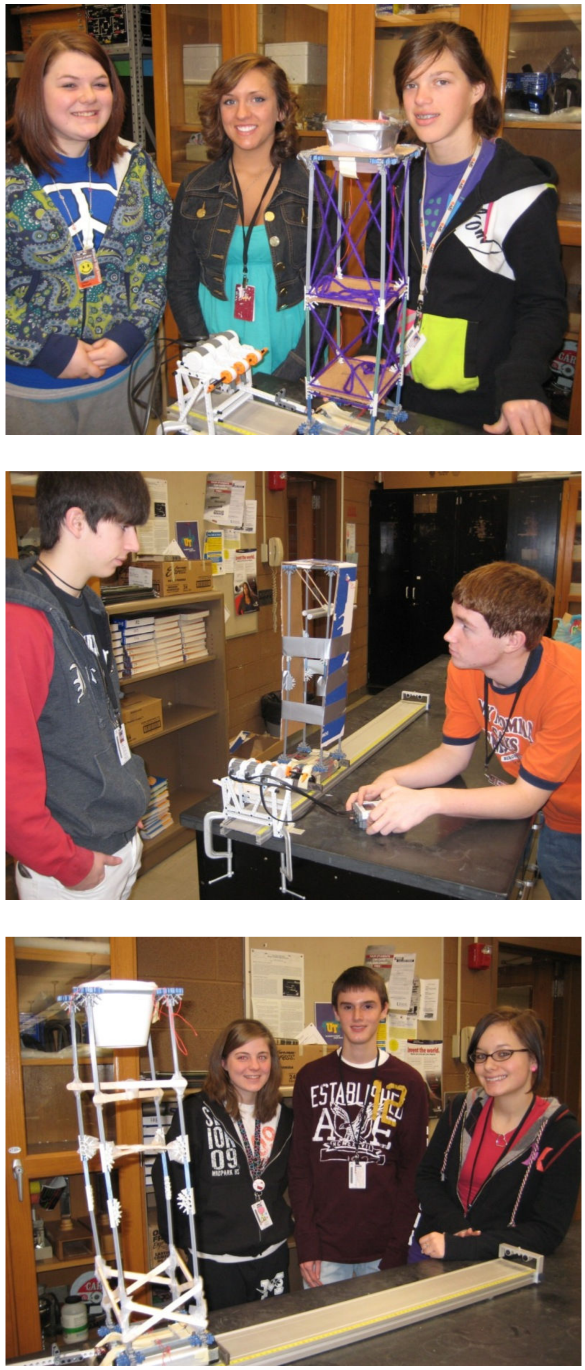


Figure 16: (1) Model with string bracing and a slosh tank w/ water, (2) model with cardboard bracing and a pendulum, and (3) model with Popsicle stick bracing and a slosh tank with pennies inside