

Enhancing an Upper Division Structural Dynamics Course Using K'nex Toys

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Using K'nex Toys in Architectural Engineering Programs

Abstract

For the past three years, students in ARCE 483 Seismic Analysis and Design in the Architectural Engineering program at Cal Poly San Luis Obispo have been designing experiments using K'nex toys. The resulting experiments have included the effects of fixity on natural frequency, flexible versus rigid performance, seismic activity on a bridge structure, soft story behavior in buildings, the effect of floor system stiffness on the deflection of a system, the effect of mass dampers on tall buildings, identification of building mode shapes, and even modeling a viscous damper using K'nex, sponges and jello. This paper will demonstrate that K'nex toys can be an inexpensive yet very effective classroom technology for creating physical models and demonstrations in even the most technical engineering courses.

Introduction

K'nex toys consist of various plastic rods and connectors cleverly-sized to allow the creation of a variety of truss-like structures. While the K'nex Corporation focuses on the K-12 market, there are a myriad of engineering applications that have been demonstrated and published at the university level.^{1,2,3} Many of these occur at the lower division level in freshman experience courses or introductory statics courses. Other applications have included constructing structural models for structural design and capstone courses. This paper takes this use of classroom technology even further by demonstrating how K'nex pieces can be used effectively in an upper-division, highly technical structural dynamics / seismic design course.

K'nex pieces consist of various rods and connectors as shown in Figure 1. The rods are ingeniously sized such that right triangles are naturally formed. While one size of rod forms the sides of a triangle, the next size up forms the hypotenuse. The pattern continues as the rods change colors and triangles get progressively larger. The connectors allow rods to be joined at 45 and 90 degree angles in various configurations. Some connectors can be combined to form three-dimensional joints. The connectors have holes in the center to allow free rotations at joints.

ARCE 483 Seismic Analysis and Design in the Architectural Engineering (ARCE) program at California Polytechnic State University in San Luis Obispo provides an introduction to dynamic response analysis of building structures with an emphasis on earthquake ground motion. It focuses on earthquake resistant design of buildings in accordance with building codes and is preceded by a pre-requisite course in structural dynamics which analyzes structures subjected to dynamic loads with single- and multi-degrees of freedom. Both are considered graduate-level courses even though they are taken at the undergraduate level. For the past three years, students in ARCE 483 have been designing experiments using K'nex product. It not only helps meet the ABET Criterion 3(d)⁴ requirement for students to design an experiment, but the students have fun and find some genuinely creative and useful ways to use the K'nex pieces as well. The

Architectural Engineering department has approximately 45,000 K'nex rods and connectors thanks to a generous donation from the K'nex Corporation. The types of experiments that have resulted in the ARCE 483 assignment include the effects of fixity on natural frequency, flexible versus rigid performance, seismic activity on a bridge structure, soft story behavior in buildings, the effect of floor system stiffness on the deflection of a system, the effect of mass dampers on tall buildings, identification of building mode shapes, and even modeling a viscous damper using K'nex, sponges and jello. This paper will demonstrate that K'nex toys can be an inexpensive yet very effective classroom technology for creating physical models and demonstrations in even the most technical engineering courses. The K'nex Corporation caters to the K-12 population in their educational efforts⁵, but there is also a viable market in the university engineering classroom.

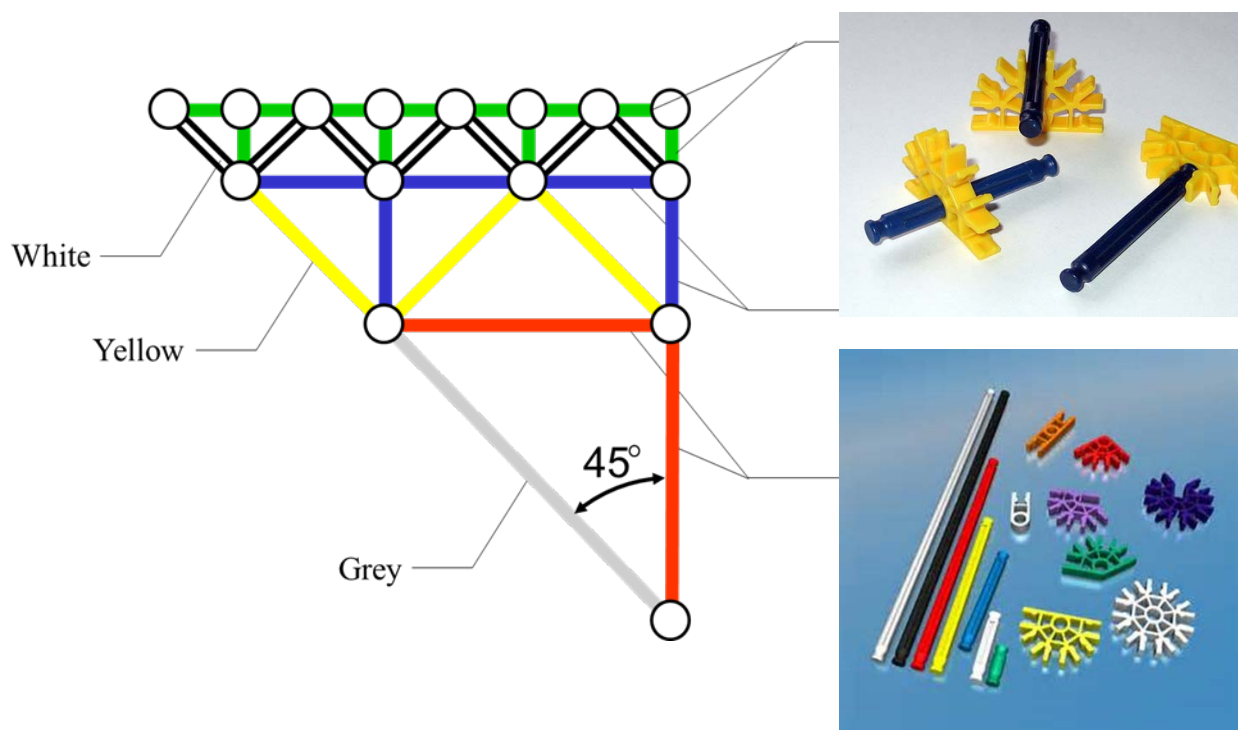


Figure 1: K'nex pieces consist of rods and connectors that allow a variety of structures to be created.

This paper is part of a larger effort to develop a consortium of schools that use K'nex product in the classroom. The consortium members will share ideas, communicate best practices, and encourage each other to improve engineering education and understanding through physical models.

Sample Experiments

The following are a sampling of the types of experiments created by the ARCE students completing this assignment. The purpose of describing some actual experiments in this paper is

two-fold. The first is to convince the reader that ARCE 483 is a technically rigorous masters-level course. Even though the students are using toys to create physical models, the technical concepts that they are attempting to explore are quite technically challenging. The second reason is that the design of experiments is a difficult outcome to meet for many civil engineering programs during an ABET accreditation visit⁶. Civil engineers typically do not design experiments so programs can struggle with this ABET 3(d) criterion. Hopefully the description of experiments will share ideas as to how this criterion can be met and benefit other programs.

Inverted Pyramid

The K'nex inverted pyramid couples the unique elegance of the pyramid shape with a free pin connection. By definition, the three-dimensional pin connection restrains translation of the structure in any direction, while allowing all degrees of rotation. The irregular shape of the structure allows for an experimentation with the different modes of a highly torsional structure.

The structure was predicted to fail at the single node between the base and the larger pyramid, where nine members converge, because the size and irregular shape of the structure would cause large deflections that would compromise the connection. The weight of the structure is 0.94 lbs, resulting in a mass of $0.0023 \text{ lb}/(\text{in}/\text{s}^2)$. Under its own weight, the structure deflected 3.38 inches, as can be seen in the image to the right in Figure 2. This testing of the structure revealed that the structure's stiffness was 0.27 lb/in. Following simple calculations, the natural period of the structure was determined to be 0.56 seconds. Testing of the inverted pyramid indicated three distinct modes of oscillation. As the structure entered its different modes, the stationary node

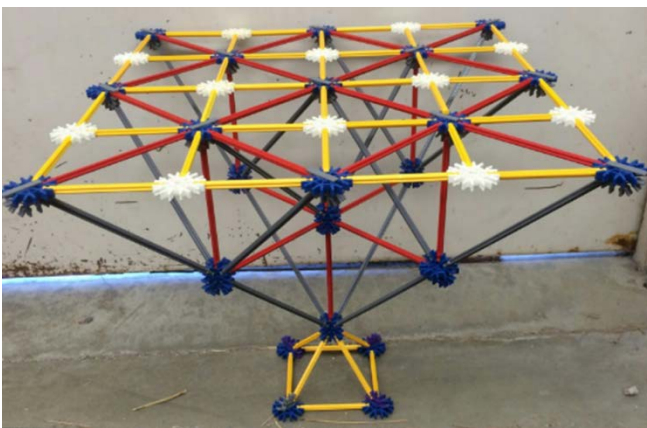
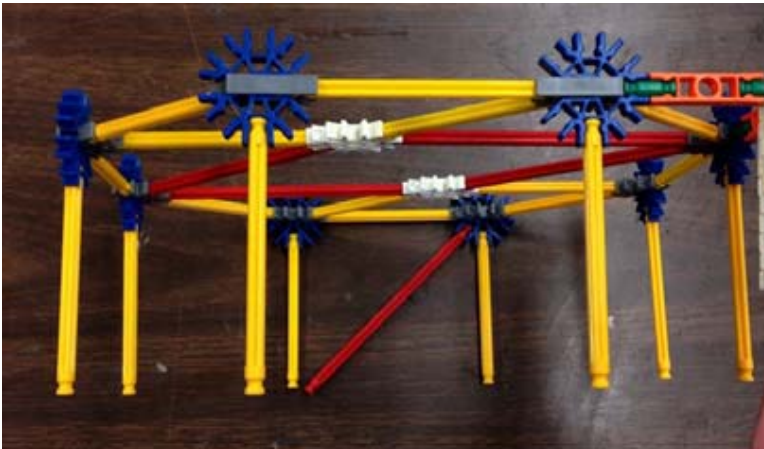


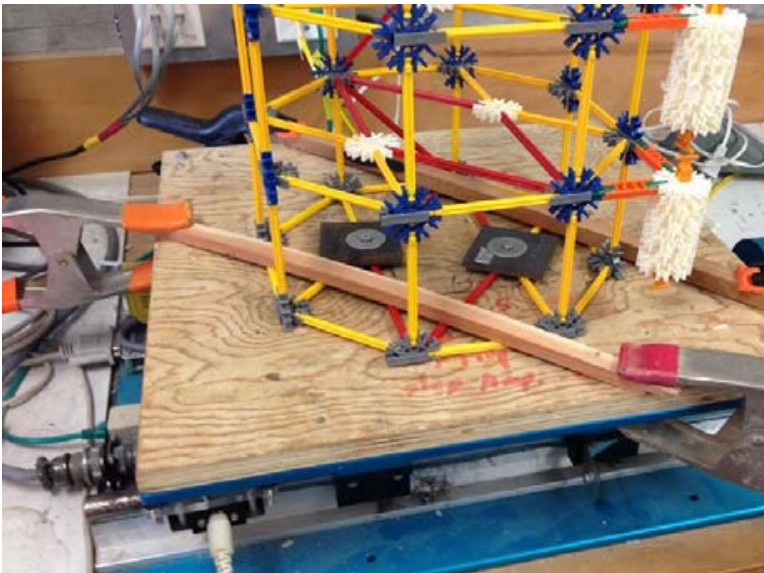
Figure 2: A pin connected inverted pyramid is examined for modes of oscillation

translated up the central spine of the structure. The first two modes of the structure consist of back and forth oscillation about either of the diagonal axes of the roof of the structure. The third mode performs a far more interesting oscillation. The entire pyramid rotates about the pin connection to the base. This mode clearly demonstrated the influence of the pin connection, restraining all directional translation and allowing rotation. The forces generated in the base are resisted through the tension/compression couples created in the axial members of the base. The diagonal members of the base are constantly transferring forces back and forth to each other to dissipate the energy generated from the rotation of the structure.

Torsional Displacement



Lateral braces and an offset mass were added to each floor



The model is connected to the shake table base.



The 14 story building is ready to shake

Figure 3: A largely unbraced tall building is examined for lateral torsion.

The purpose of this experiment was to build a K'nex structure to demonstrate seismic torsion with close to no lateral displacement, when activated on a shake table. The structure consists of four main components; a base floor, diaphragms, lateral bracing, and offset masses as shown in Figure 3. All 14 floors are identical and were constructed separately. The torsional displacement was best exhibited at high frequencies and relatively low amplitudes. The model was placed on the center of the shake table and connected to the shake table base. Two Y2"x1/2" pieces of wood of sufficient length to span through the diaphragm diagonally were clamped to the shake table. Under shaking conditions at various frequencies, the tower exhibited almost no horizontal displacement and twisted a significant amount.

Soft Story Buildings

Regular structures are well balanced in terms of mass, stiffness, strength, and ductility. A soft story irregularity is defined as a story lateral stiffness that is less than 70 percent of the story immediately above, or less than 80 percent of the average lateral stiffness of the three stories above. This experiment shows how a soft story irregularity would affect the performance of a building during an earthquake. A simple multistory structure is built using K'nex to model a multistory, soft story building and its behavior. As shown in Figure 4, the first story is laterally braced in the direction of ground motion; the main section of the second story is built to be a soft story by having no braces to reduce the stiffness; and the third story lacks lateral braces but is stiffer because of the floor diaphragm. Also the floor height is smaller than the height of the second floor which its increases the stiffness.

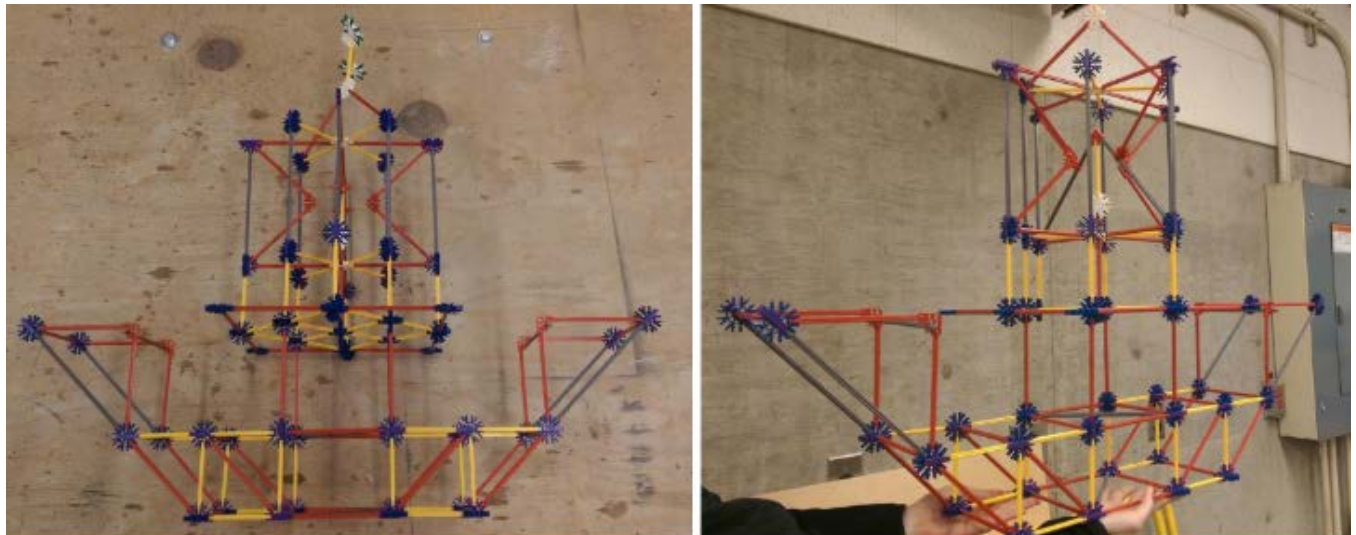


Figure 4: A structure built with an intentional soft story in the second floor.

The stiffness calculations for the individual floors indicated that the second floor has a stiffness extreme soft story irregularity (i.e., less than 60 percent of the story immediately above). The students predicted a huge second-story drift compared to the other levels above it. Using a shake

table frequency of $f = 2.45\text{Hz}$ and an amplitude $A = 1.5$, the second floor displacement was four times larger than the floor above, thus demonstrating the harmful effects of a soft story. If one floor displaces dramatically compared to the floors above it in an actual building, the building will collapse on itself. Simply adding lateral braces increased the stiffness to $19*EI$, compared to the original second floor stiffness of $4*EI$.

Dampers

The purpose of this experiment is to analyze the damper effectiveness in a super column structure. The basic building model is a four story, single bay structure that relies on super columns as the main contributor of stiffness. The super columns are composed of four, individual K'NEX rods at each of the primary corners running the height of the structure. The floor diaphragm is consistent for each level and braced to act rigidly. The only difference in the three structures is the lateral bracing configuration. As shown in Figure 5, the first model was a four-story building without any lateral force resisting systems. The second building was identical except for the addition of dampers on the second and third floors. The final model replaced the dampers with lateral braces. Three different tests were performed in order to create a more thorough comparison of the model.

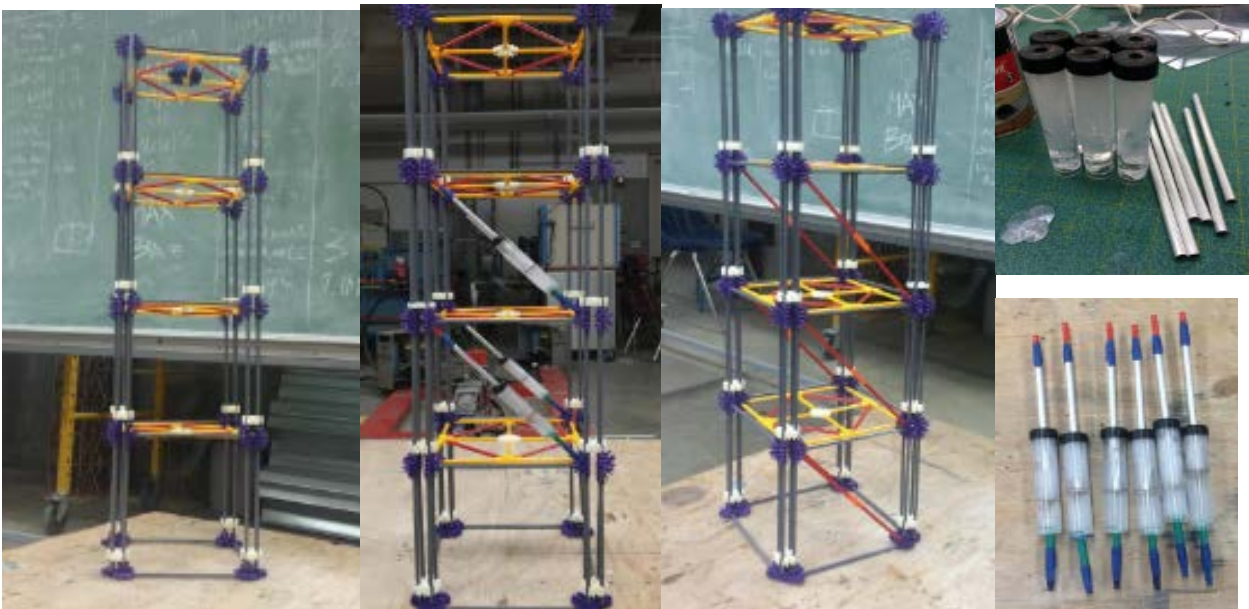


Figure 5: A four story building structure with viscous dampers is compared to buildings with and without lateral bracing

The second building dampers consisted of a 6 inch plastic cylinder case with a $9/32"$ diameter aluminum rod, metal disk, hair gel, and contact cement. To ensure that these dampers were viscous, a quick hand calculation was done to check the stiffness of the systems. After testing different amplitude and frequency combinations on all three systems, it was concluded that the

relative drift due to ground motion was highest without braces and then decreased with the damping system. The lowest drift was associated with the braced system. However, this low drift was accompanied with a large natural frequency, which would affect the life safety performance of the building. Although the unbraced and damped systems had much larger deflections, the damage caused by this drift allowed the structure to dissipate energy. The braced structure deflected less compared to the damped structure; however, joints of the braced structure exposed to the high frequency ground motion tear apart with no warning, leading to structural collapse. The exact results are shown in Table 1

	Drift (in)	Stiffness (lbs/in)	Natural Frequency (1/s ⁻¹)
No Braces	2.25	0.529	2.440
Dampening Devices	2.3	0.517	2.414
K'NEX Brace	0.75	1.587	4.227

$$K = F/U$$

$$F = 1.19/32.2$$

$$U = \text{Drift (in)}$$

$$\text{ex) } K = (1.19/32.2)/(2.25) = 0.529 \text{ lbs/in}$$

$$w = \sqrt{K/M}$$

$$K = \text{stiffness (lbs/in)}$$

$$M = \text{mass (slugs)}$$

$$\text{ex) } w = \sqrt{0.529/0.0888} = 2.440 \text{ Hz}$$

Table 1: The drift, stiffness and frequency results for the three K'nex models shown in Figure 5

Natural Frequency and Building Height

Natural frequency is the number of cycles per second at which a structure experiences its largest displacements, velocities and accelerations. Natural frequency depends on mass and stiffness.

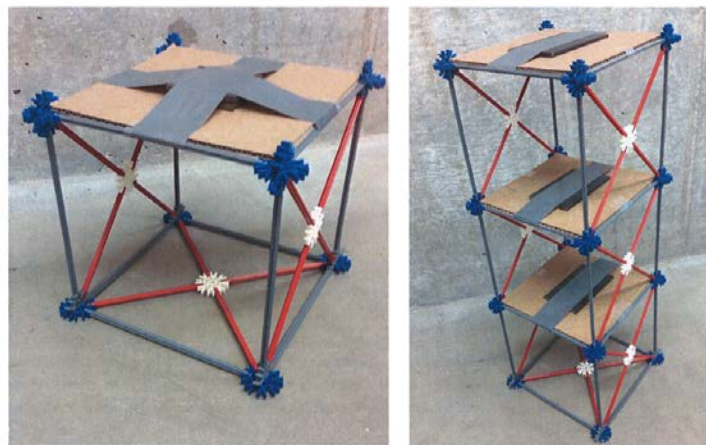


Figure 6: Buildings of different heights were investigated to determine the effect of height on natural frequency

In this experiment, masses were applied at each floor of buildings of varying heights using cardboard and tape as shown in Figure 6. The buildings were shaken along their weak axis to better see the deflections. When placed on the shake table, the frequency was slowly increased until reaching resonance as observed by the visible deflection. The single story building has a frequency of 2.9 Hz while the three story building had a natural frequency of 1.1 Hz verifying that taller buildings have lower frequencies.

Demonstration of Diaphragms

This experiment attempts to demonstrate the effects of increased floor stiffness on the deflection of a building system. Two three-story buildings of identical size were created. One used an x-braced system along each bay to create a rigid diaphragm with increased stiffness. The bracing was removed from the floor in the second building creating a flexible diaphragm and more closely resembling a moment frame as shown in Figure 7. The buildings were tested at a frequency of 2 Hz. and an amplitude of 0.5 in. As expected, the flexible diaphragm model deflected 2.5 time more than the rigid diaphragm model.

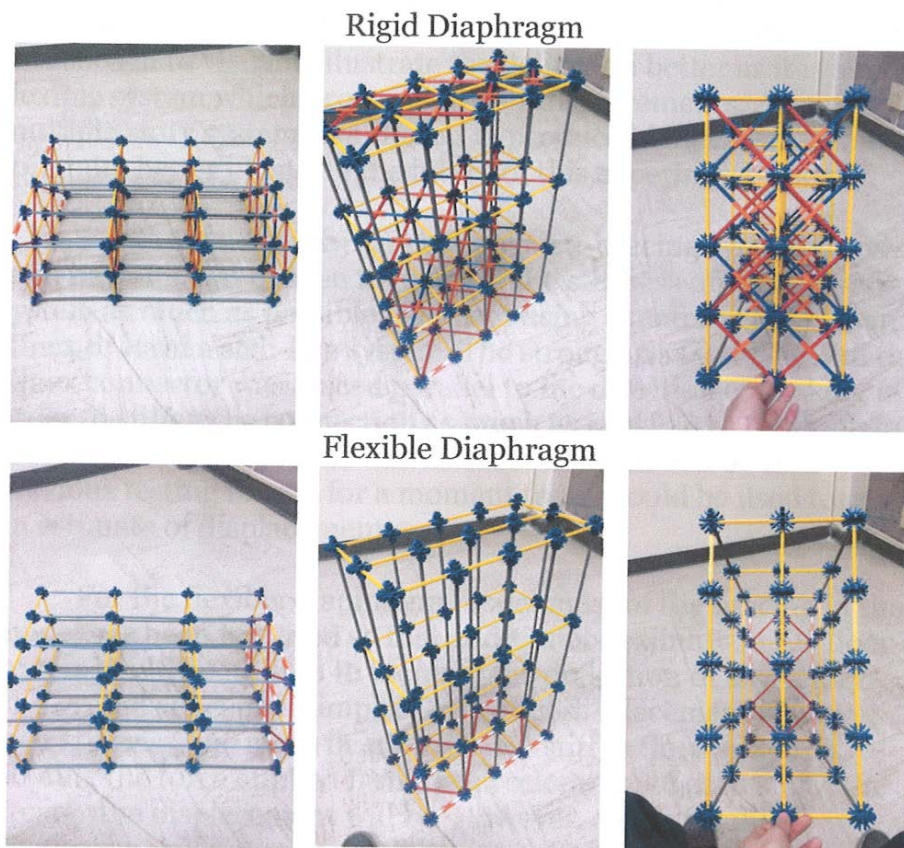


Figure 7: K'nex models for Rigid and Flexible Diaphragms.

Mode Testing

A 12 story, three bay by three bay K'nex structure was constructed with weights added on every third floor. The lateral load system was a braced frame in one direction with a moment frame in the other direction. Each building had a fully braced diaphragm in the horizontal direction. The purpose of this experiment is to capture all three modes of vibration as shown in Figure 8. With an amplitude of 0.5 in., the shake table frequency was increased by 0.01 Hz until the first mode was observed. The sequential frequency increase continued through the detection of the other two modes. All three modes were observed but it was concluded that K'nex connections do not represent fixed connections and do not allow for a sufficiently consistent stiffness to match a modal analysis spectrum.

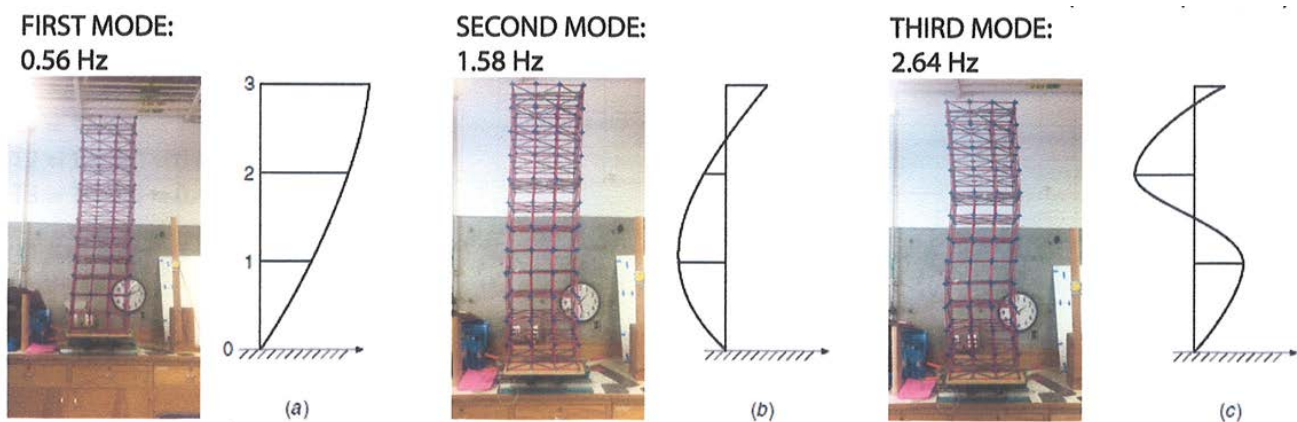


Figure 8: The frequency on a tall building was increased to capture three modes of vibration

Base Isolation

This lab demonstrates the effect of a simple base isolator on a six-story moment frame building. The moment frame building was built using the stiffness of the K'nex joints to model moment connections. The structure was subjected to two tests: one test with a base isolator and one test without. The base isolator consists of an interior truss to support the moment frame, and an outer truss that connects to the ground (i.e., the base of the shake table). The inner and outer trusses are connected by pin-attached members that creates a swing to allow freely-rotating movement as shown in Figure 9. The swings provide a degree of separation between the moment frame structure and the motion of the ground. The natural frequency of the building is calculated as 1.54 Hz using a lumped mass at the top of the structure and a stiffness determined by a simple displacement test. The shake table vibrated the moment frame structure and verifies its natural frequency. The structure was then connected to the base isolator and shaken again at the same frequency. The base isolator caused a significant reduction in maximum deflection, and no significant difference in natural frequency.



Figure 9: The six story building (left) and the base isolator system (right) to which the building is attached

The Mass Damper Poodle

The K'Nex Poodle was constructed based on the idea of tuned mass damper. Tuned mass dampers are devices used to reduce the amplitude of vibration in structures by means of pendulums, fluids, or springs. In the event of seismic ground motions, tuned mass dampers reduce the amount of displacement and damage that a building may experience. The word “tuned” refers to the fact that these dampers are typically designed to work with a building’s natural frequency in order to work efficiently and effectively.

In constructing the poodle, four identical legs are used as the base. The legs are attached to the body via a track. The legs remain fixed as the body moves back and forth above it as shown in Figure 10. In order to prevent the load from being entirely unbalanced, the weight at the front of the building was counteracted with some weight added to the rear of the building (i.e. the tail of the Poodle). The body was designed to move freely in response to a ground motion applied by the shake table. Acting as the tuned mass damper, a metal architectural scale was attached to the body in a pendulum-like fashion. Motion of the damper in relation to the body movement was observed and analyzed for a range of amplitudes and frequencies.

The body of the Poodle was left hollow to allow for the addition of a mass during the actual shake test experiment. This method of construction allowed for two types of tests to be performed. In the first test, the mass was securely attached to the frame and not allowed to move freely, and in the second test, the mass was suspended into the cage and allowed to swing back and forth. The tuned mass damper was effective in absorbing kinetic energy and prevented the body from moving independently of the legs. The period predictions were matched when the

damper moved faster than the body during high frequency and high amplitude ground motions. Based on the mass period of 0.236 seconds, the natural frequency of the mass was 4.23 Hz.

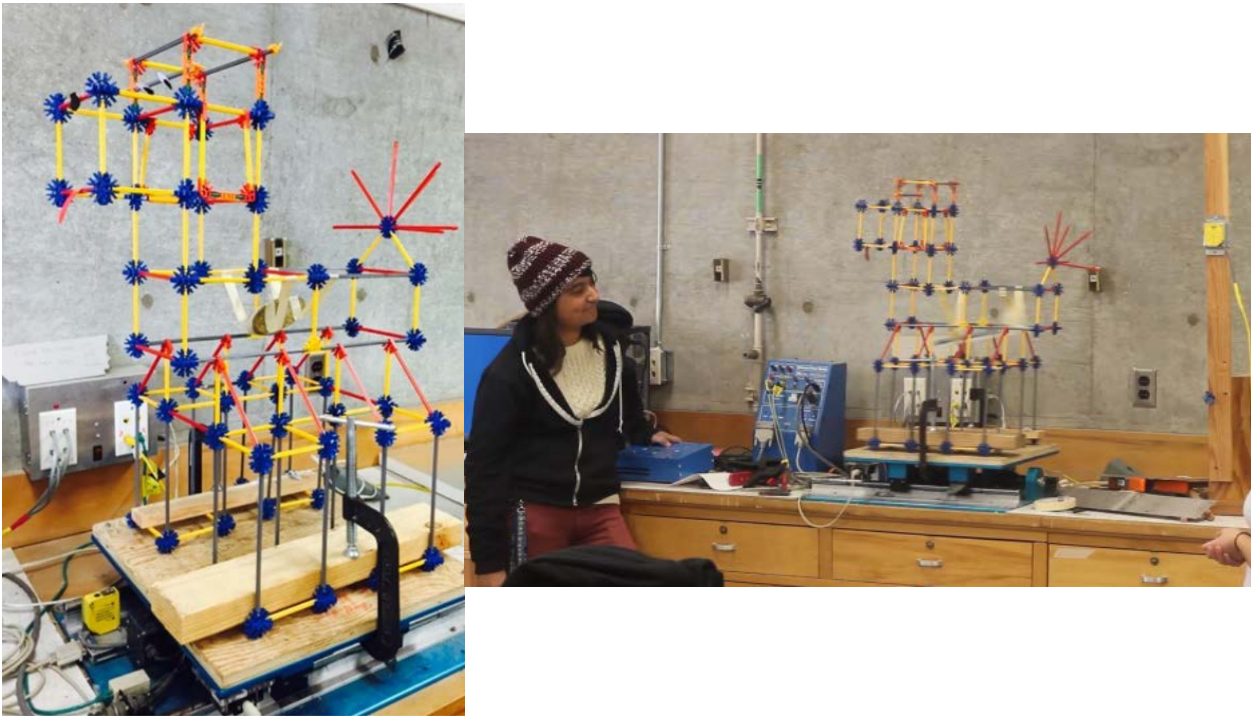


Figure 10: A structure in the shape of a poodle illustrates the benefits of a tuned mass damper

Other Experiments

There were numerous other experiments designed over the three years that this exercise has been conducted. Figure 11 shows photos of the more interesting ideas from other student experiments. These ranged from modelling an existing library building and a ferris wheel to immersing a model in a tub of jello to simulate a base isolation system. The students proved to be highly creative. As with any endeavor, some of the experiments worked wonderfully and some did not. Some students sometimes learned more and gained greater insights when the experiment did not work as intended. The collection of student feedback as part of the assessment process indicated that the exercise is worthwhile and should be continued.

Assessment

The students in ARCE 483 completed a survey on the value of this experience to help assess the usefulness of K'nex product for conducting seismic experiments. They were asked for open-ended responses as to whether the K'nex pieces were useful in designing their shake table experiments, what worked well using K'nex pieces and what were the limitations? The most common responses describing the usefulness of K'nex were the ease with which a structure could

be assembled, the versatility to be able to create many unique structures, the ability to devise something that physically demonstrates a theoretical principle, the hands-on nature of the product, and the belief that their K'nex models were legitimately able to illustrate the high level seismic concepts targeted in the experiments. The limitations cited were the reliance on 45 degree angles to create structures, the restriction to certain sized pieces, the lack of consistency in strength of the joints, the inability to model a moment resisting joint, and fatigue in the joints over time.



Figure 11: A sampling of other experiments not described in this paper

The students were also asked to rate on a Likert scale of 1 (lowest) to 5 (highest) how their understanding of a key seismic concepts increased due to design and testing using Knex equipment. Similarly, they were asked to rate how their enthusiasm for seismic concepts increased due to designing and testing with K'nex equipment. Figure 12 shows the graphical

results of these two questions. The average for the first question on how understanding was increased was 3.87 and for the question regarding increased enthusiasm, the average was 4.25. Clearly, the enthusiasm generated was greater than the increased understanding, but both were quite high and support continuation of the assignment.

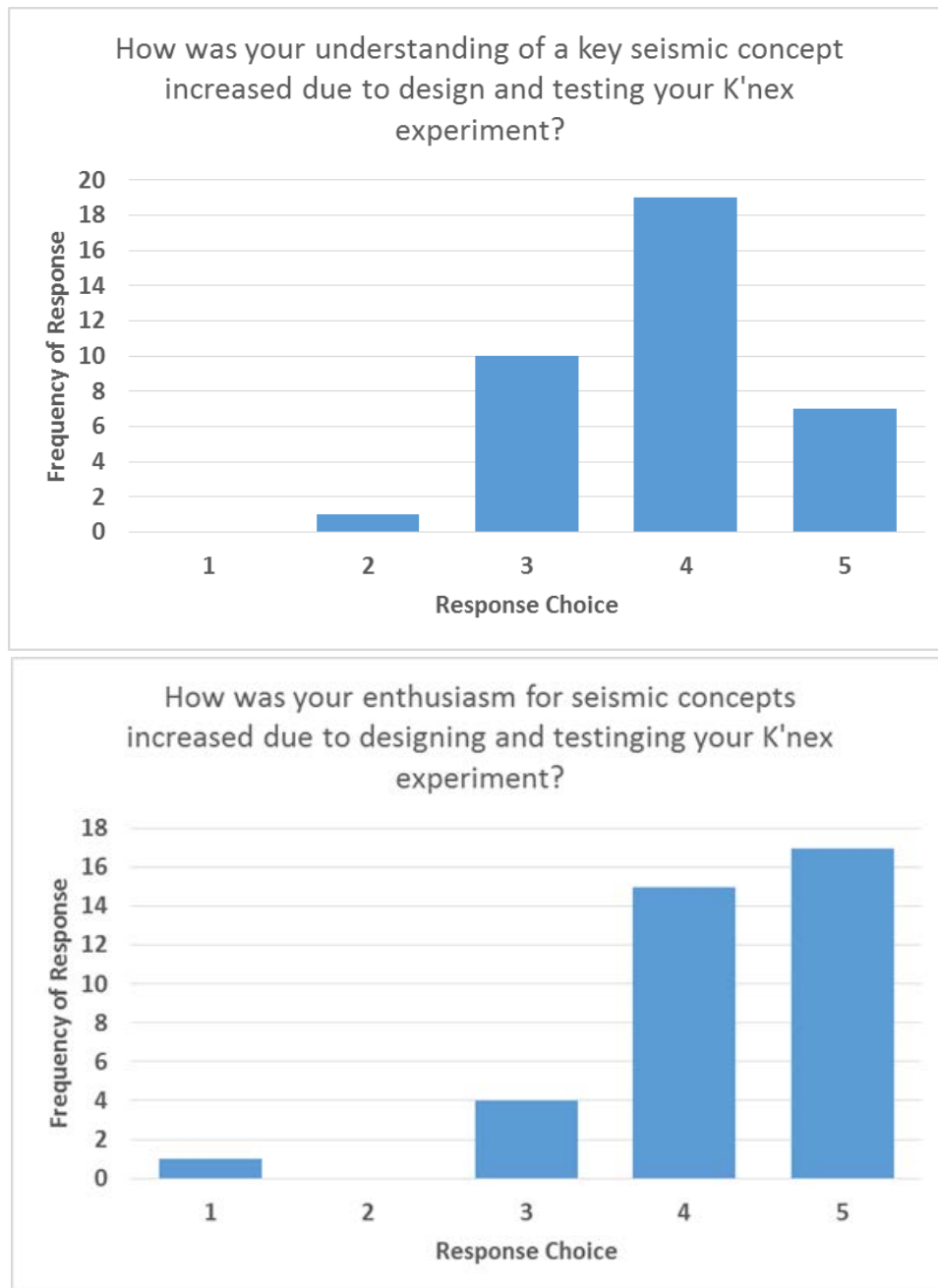


Figure 12: The responses of 37 students to how their understanding and enthusiasm were effected by using K'nex

Finally the students were asked to respond to the following multiple choice question:

What statement below most accurately reflects your opinion of using K'nex pieces in a technical engineering course?

- a. They are useful and enhance the learning experience
- b. They are not particularly useful but they are fun and enhance the learning experience.
- c. They neither supported nor detracted from my learning experience
- d. The requirement to use K'nex posed a needless constraint that detracted from my ability to conduct a seismic experiment
- e. They are cute toys that have no place in the engineering classroom.

The responses show that 31 students chose (a) and 7 students chose (b). No student picked any of the other responses indicating unanimous positive feedback toward the inclusion of K'nex in the assignment. No students resented that they were being asked to use children's toys to conduct an upper-division academic exercise.

Conclusion

The series of experiments conducted in the ARCE 483 Seismic Analysis and Design course along with the feedback from the students who conducted them clearly demonstrates the useful and creative nature of using K'nex toys in the engineering classroom. While K'nex product has been shown to be highly effective for creating models, supporting competitions and illustrating basic concepts in freshman experiences and lower division engineering courses, it can also support more highly technical concepts. K'nex rods and connectors are versatile, reusable, relatively inexpensive and fun. The primary colors, ease of use, and variety of possibilities send the message that engineering does not have to be hard and that every student can do it. The K'nex pieces are also helpful in attracting new students to engineering who might think that the subject is either too boring or too scary.

The next step internally is to continue building on this assignment and conduct a more sophisticated assessment of its effectiveness. As future students have access to a growing database of previous experiments, they will be able to improve on what has already been done and create better and more creative uses of the product. K'nex product has been used effectively in other ARCE courses such as ARCE 106 (Introduction to Building Systems), ARCE 315 (Large Scale Structures), and ARCE 306 (Matrix Analysis of Structures). There are certainly opportunities in other courses that are limited only by the imagination of the faculty and students.

Externally, the program will continue to work with the K'nex Corporation to demonstrate that there is a legitimate market for their product outside the K-12 educational market. Cal Poly is

not the only university that sees the value of K'nex in the engineering classroom. Since other programs in other universities have also successfully used K'nex to teach engineering, there needs to be a sharing of ideas, innovations and best practices. The ARCE program at Cal Poly is leading the effort to start a consortium of universities that would facilitate such collaboration and dialogue with the goal of incorporating the K'nex Corporation as part of the effort.

Bibliography

¹ Ressler, S. "The Project Management K'nexercise: Using Role-Playing to Facilitate Learning About Design and Construction." 1998 ASEE Annual Conference and Exposition Proceedings, ASEE, 1998.

² Estes, A., LaChance, E, and Ressler, S. "K'nexercise: Introducing Students to the Key Participants in the Design-Construction Process." 2002 ASEE Annual Conference and Exposition Proceedings, ASEE, 2002.

³ Estes, A.C., and Baltimore, C., "Using K'nex to Teach Large Scale Structures to Architects and Construction Students", 2014 ASEE Annual Conference and Exposition Proceedings, ASEE, Indianapolis, June 15-18, 2014.

⁴ ABET Inc. "Criteria for Accrediting Engineering Programs," Effective for Evaluations During the 2015-2016 Accreditation Cycle, Engineering Accreditation Commission, Accreditation Board for Engineering and Technology, ABET, Inc., Baltimore, Maryland, 2015.

⁵ K'nex Corporation. K'nex Education, <http://www.knex.com/Educators/> accessed January 24, 2016

⁶ Estes, A.C. and Ressler, S.J. "Surviving ABET Accreditation: Satisfying the Demands of Criterion 3" Paper 2007-875. 2007 ASEE Annual Conference and Exposition Proceedings, ASEE, Honolulu, June 24-27, 2007.