

## Lesson 9: Structural Hazards

This lesson will introduce students to some of the basic concepts behind structural hazards in the context of earthquakes. Many cities have a variety of building sizes, shapes, architectural styles, and materials. This lesson covers the basic ideas concerning how structures respond to earthquakes using a tabletop exercise and three hands-on activities. The tabletop exercise consists of visual analysis of actual pictures taken in earthquake areas in Central Asia. The hands-on activities will explore how structures respond to applied loads.

In this lesson, the shake table activity is adapted from materials by D. Rathjen at the Exploratorium Teacher Institute (Rathjen, 2003). The wall model activity is adapted from materials from Seismic Sleuths (*FEMA/AGU*, 1994).

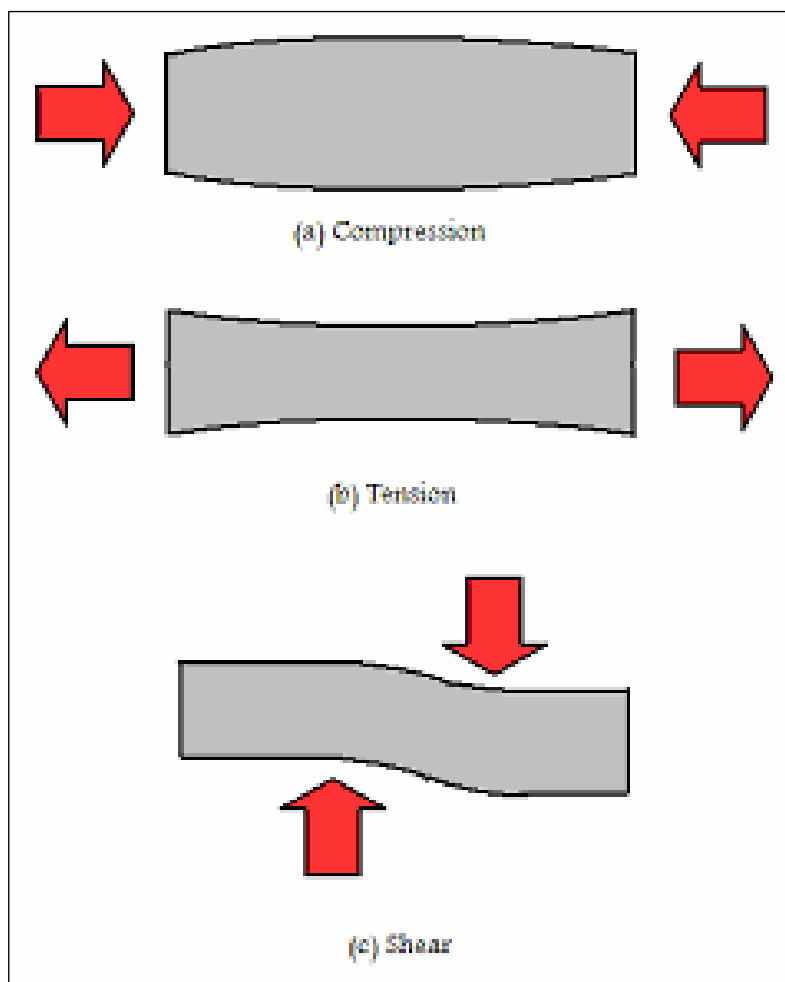
The tabletop exercise is expected to take about 45-60 minutes to complete. The hands-on activities are expected to take 2-3 hours total.

### Introduction

1. Begin by reviewing with the students the two basic types of earthquake waves: P and S waves. Compare and contrast their differences (P waves are compressional, longitudinal waves and generally less destructive than S waves; S waves are transverse waves that move perpendicular to the path of propagation). Surface waves are a combination of both P and S waves that cause most earthquake destruction, because they cause wave-like motion along both the horizontal and vertical axes that cause structural damage. Please refer to Lesson 6 for more information about seismic waves.
2. There are three different types of applied forces (loads) that will be covered in this lesson: compression, tension, and shear. Compression is when a force is applied inward against the face of a structural element, shortening it. Tension is when a force is applied that pulls outward against the face of a structural element, stretching it (for example, as when a rubber band is stretched). Shear is when a force is applied in parallel to the face of a structural element, at an angle that is perpendicular to either compression or tension forces. Shape a piece of silly putty into a cylinder and have the students duplicate these applied loads, witnessing the deformation of the structural element. Remind students of Lesson 4 where they used a ball of pizza dough to demonstrate this. Inform the students that even solid structural pieces made out of steel or stone deform in these ways in response to loads, even if the human eye cannot discern the tiny displacement of the piece. A diagram of the different load types and the resulting deformation of the structural element is provided in Figure 1.
3. Some materials and shapes can withstand the different types of loads better than others. For example, stone materials can handle compression well, but because they are brittle they do not attenuate tension well. Most metals, such as aluminum and steel, can handle all types of loads well if they are properly shaped. As an example of this, a circular tube can handle loads well, but the slightest defect in the shape (such as a dent or hole) will

greatly weaken the shape. To demonstrate this idea, begin with two identical cardboard paper towel tubes. Take one of the tubes, bend it to a 90 degree angle, and then straighten it again to its original shape. Erect both tubes vertically on the flat surface of a table about 30 cm from each other. Now place heavy weights (such as large books) on top of each tube, one at a time. The tube that was bent will not support as much weight as the unbent tube.

4. Different materials can be used together to build structural elements that react well to all load types. Concrete, a stony material, can be used to build a structure with steel bars along its length so that during compression, the stony material carries the load, but during tension, the steel carries the load.



**Figure 1.** Different applied load types.

## **Tabletop Exercise:** Uncle Architect

**Note!** This Tabletop Exercise was developed to help explain structural hazards associated with earthquakes. Structural hazards vary depending on the topography, geology, and architecture employed from region to region, as well as the workmanship and quality of materials used in individual structures. This exercise will explore some of the basic lessons that can be learned by observing actual structures that have survived earthquakes, and actual structures built in the aftermath of earthquakes.

Read the following scenario, stopping to ask questions and discuss the material with your students at the indicated points, or when students ask questions that are relevant to the discussion of earthquake hazards:

Sami lives with his family in a city. A very powerful earthquake has recently destroyed many parts of their city. Fortunately, Sami's family was prepared for the earthquake with some basic supplies (specifically, a first aid kit, some food and water, and a family/community communication plan; earthquake preparations will be discussed in detail in Lesson 11). Now that the earthquake has passed, many people are beginning the difficult task of rebuilding the city.

Sami's uncle, Mr. Jamali, is an architect and he has become very busy, with people coming to him day and night to get their home rebuilt, to make repairs to damaged buildings, or to make modifications to their existing buildings to survive the next earthquake. Mr. Jamali is so busy that many of his best assistants are overwhelmed with work, and he has asked Sami for help. Sami will begin as an apprentice to Mr. Jamali, and will be given tasks that will train him to recognize the best design aspects of buildings that allow them to survive earthquakes. Sami's first job is to make a survey of the buildings around the city that stood through the earthquake. He drove around the city with his brother, took many pictures and notes, and is now reviewing them to find any patterns.

At first, there were so many pictures that Sami didn't know where to start.

**Question 1: What are some of the ways that the pictures can help Sami explore why some buildings can stand through earthquakes while others collapse? Why is it important to take notes that accompany the pictures?**

**Note!** This question is intended to be very general and is designed to encourage students to be aware of the limitations of the information collection process. There are many different possible answers that may or may not have anything to do with structural hazards. Encourage your students to share their ideas, and if necessary, have them look at the pictures and accompanying notes to help them get some ideas to get started.

**Potential answers:** *Human memory and thought selectively focus on specific topics or items of interest, while pictures capture an entire scene. The pictures contain lots of information that humans may not be paying attention to right away, or that humans might*

*need more time to process, therefore, they are a very helpful way of recording information about structures.*

*It is important to take notes that accompany pictures because it is easy to forget where or when a picture was taken, especially if many pictures were taken in a single day. Pictures also do not record important information that may help to understand why a particular building survived, such as how old the building is, or whether the soil was wet or loose, or whether the building was built on a slope. These details may be important for forecasting future problems that buildings may experience, such as liquefaction (see Lesson 7) or landslides (see Lesson 8).*

Sami decided to focus on pictures that showed buildings that stood through the earthquake next to buildings that collapsed partially or completely (such as pictures 1 through 6). That way, the strength of the earthquake and the composition of the soil that the structures are sitting on would be similar in the observed pictures. This helps to compare and contrast structures that collapsed or did not collapse during the earthquake under similar conditions.

**Question 2: Compare picture 1 and picture 2. What is the same and what is different about the construction styles and materials? What are some possible reasons why the buildings in picture 1 did not fully collapse, but those in picture 2 did?**

***Potential Answers:** According to the notes, both pictures were taken near the ancient ruins of the city. Both buildings used bricks, but the ancient ruins used mud bricks and the old buildings used modern stone bricks. Yet the ancient ruins are much older than the buildings that have collapsed in picture 2, and have survived the earthquake without collapsing their roofs. Presumably, the ancient ruins have also survived other powerful earthquakes over the past hundreds of years.*

*Some possible reasons: the ancient ruins used rounded arches to support the roof, while it looks like the newer buildings used straight walls and sharp angles, so arches and domes might survive earthquakes better than straight walls and box-like buildings. This idea is supported by picture 1, which shows that while the roof and connecting walls are still standing, the flat wall that is not part of the arches has collapsed. Alternatively, the ancient buildings in picture 1 may have been built with better craftsmanship than the buildings in picture 2. Sami should investigate these ideas by revisiting the sites and gathering more information before making any definite conclusions, though.*

Sami, while looking through all of his pictures, noticed that he was focusing on just the buildings, but that there were more than just buildings that survived the earthquake.

**Question 3: Look at pictures 3 and 4. What other objects in the picture, besides buildings, did not collapse during the earthquake? What features of these objects made them likely to survive, while other buildings collapsed? Are there other**

**hazards associated with these objects that are different from the hazards associated with buildings?**

***Potential Answers:** Anticipate many different answers from your students for these questions. Some of the objects include trees, electrical and telephone cable poles, cars, and signs.*

*Trees are earthquake-resistant because they have a very deep root structure that anchors them to the ground, and they are well-balanced on all sides. Wood, as a material, is very strong and light-weight. However, while trees may survive earthquakes better than some buildings, trees can also produce falling branches during earthquakes and should not be sought for shelter unless absolutely necessary. In general, it is best to minimize the amount of material over one's head during an earthquake.*

*The telephone and electrical poles are also anchored in the ground, but sometimes not as well as a tree. They must support weight that can pull in the direction of the cable, so that any disruption in balance ( i.e., caused by collapsing buildings, falling tree branches on the wires, etc.) can cause them to fall over. Cars and signs are very low to the ground and do not support any external weights, therefore they survive earthquakes very well unless they are crushed by something taller than they are.*

*Trees can produce falling branches. Electrical and telephone poles can bring sources of electrical shock down to where people are when they collapse. Cars have combustible fuel that can be released if something falls on them. Buildings should be designed to help reduce these hazards for people whenever possible.*

Sami noticed that while the buildings in pictures 4 and 5 also used the stacking of stones and bricks like the building that collapsed in picture 2 did, much of these buildings are still standing while others around them are not.

**Question 4: Look very closely at the buildings in pictures 4, 5, and 6. What is different about these buildings, and why would these differences help them to better survive earthquakes?**

***Potential answers:** If you look closely, you will see that the standing walls in picture 4, 5, and 6 are reinforced with steel, although the manner of reinforcement is different for each picture. Picture 4 shows an example of using steel cross-beams with brick-inlay walls. In the building in picture 5, the walls are made of cement and stones, and the non-reinforced front walls have collapsed. But the exposed surviving walls in picture 5 all show steel rods running throughout the wall (there are steel rods protruding from the front face of the upper wall. Steel rods can be seen running parallel to length of the walls on the lower floor in a couple of places where the cement has chipped or fallen away). In picture 6, a similar, smaller structure next to the large, standing building has steel protruding from the top surfaces, and perhaps was being built by the same people who built the large building behind it. It is evident from the wall exposed on the lower right side of the large building that it is not completely brick, but only brick inlay walls within*

*a reinforced frame. The cracks on the upper floor of the bigger building on the right show where the frame has torn away from the bricks, even though the exterior paint is still intact.*

*Steel reinforcement is very important in terms of strengthening brick or stone walls because it adds tensile strength (the ability to withstand tension loads). This means that the wall can be stretched (lengthwise or side-to-side) without breaking easily. Rocks and bricks can handle compression loads very well. However, a stone or brick wall, when stretched in response to a tension or shear load, will crack and collapse at much lower loads than they can withstand under compression. During an earthquake, vibrations stretch, compress, and shear all of the pieces of a structure. Steel is much more flexible material than stone. Therefore, the combination of steel with brick or stone means a wall can be compressed, stretched, and sheared and be expected to survive an earthquake.*

Sami began to notice throughout the day that collapsing walls doesn't necessarily mean that the roof will collapse, especially when the walls are reinforced with steel. However, as Sami spoke with people around the city, he heard again and again that roof collapse is a serious hazard. Many people were injured, trapped, or killed when heavy roof materials fell on them as the structure collapsed.

**Question 5: Compare pictures 7 and 8. What is different about the roofs of these buildings, compared to the roofs of the buildings in other photos? Why might these roofs survive an earthquake better?**

***Potential Answers:** The roofs of most of the buildings in pictures 7 and 8 are made of lightweight and flexible materials, namely wood and thin sheets of metal. The roof materials in the other pictures were primarily heavy, inflexible pieces of mud, brick, stone, or cement.*

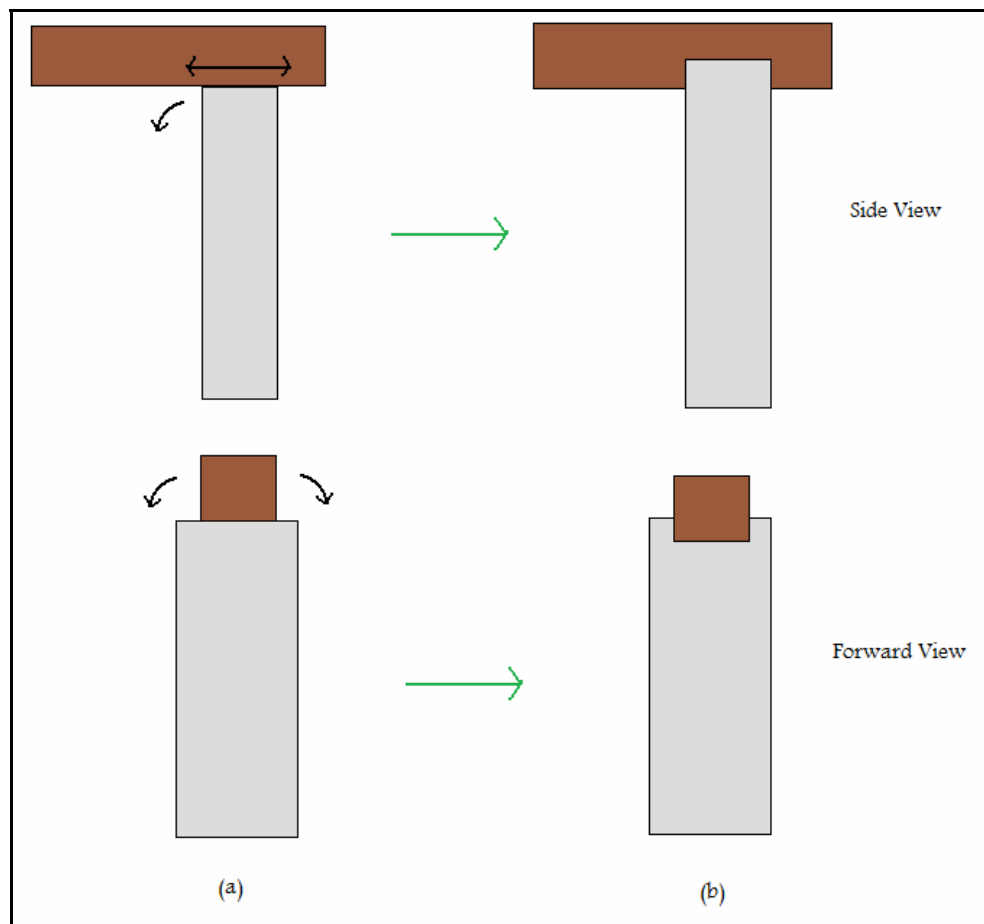
*Wood and metal are better than the heavy materials in earthquake-prone areas for many reasons. The most obvious reason is that when these lightweight structures collapse, the roof materials are much lighter, so they cause much less injury to people trapped inside the buildings if they collapse. In addition, because the lightweight materials are more flexible, they also keep their shapes when they fall during an earthquake. This means that there may be more empty spaces within a collapsed structure that people can survive in when the building collapses around them (by contrast, a stone or brick roof will tend to collapse into a pile with few empty spaces inside).*

Sami visited a home that was being built by his uncle with a lightweight roof, but something about the way the beams were attached to the reinforced cement columns bothered him. He took pictures of these attachments and took them home to think about what was bothering him. While speaking to survivors of the earthquake, Sami learned that wooden walls, beams, and boards are shaken so much that they can actually shift side-to-side, or even bounce up-and-down at their attachment points as the earthquake occurs.

**Question 6: Look at the close-up of the roof attachment in picture 8. What do you think bothered Sami about the way the wooden roof beam sits on the column? How would you design the column attachment differently for earthquake-resistance?**

*Potential Answers: The wooden beams are resting on a flat surface on top of the cement column. If wooden beams and boards can shake side-to-side, back-and-forth, or up-and-down during an earthquake, it is likely that these wooden beams will be shaken off the top of the column, perhaps leading to collapse of the roof structure.*

*One better way to design this attachment would be to create a groove or pit that the wooden beams rest in. This makes it far more difficult for the wood to be shaken off of the attachment point, and after the building stops shaking the wooden beam will come to rest within the groove, as shown in Figure 2 below.*



**Figure 2.** A diagram showing the mounting of a wooden beam on a flat column surface (a) and on a notched or grooved column surface (b). The black arrows show possible directions of movement during an earthquake that would cause the wooden beam to fall off the column in example (a), but these movements are constrained by the notches in example (b).

## **Tabletop Experiment: Building and Reinforcing Structures**

Now that students have had a chance to observe and think about actual structures that have or have not survived earthquakes, they have the opportunity to explore structural hazards and mitigation techniques in the following 3-day lesson. On Day 1, students build model structures and describe what may happen to them when a load is applied. On Day 2, students build and test models on a shake table to understand how a structure reacts to vibrations of different frequencies, and explore the phenomenon of resonance. On Day 3, students build a model wall to learn how structural elements such as diagonal braces, shear walls, and rigid connections strengthen a structure.

### **Materials**

#### **DAY 1:**

1 set of Styrofoam blocks, various sizes  
Pieces of string, each 30 cm long  
Paper clips  
Toothpicks  
A brick or a heavy item  
A band saw (to cut Styrofoam)  
Drinking straws  
Straight pins

#### **DAY 2:**

1 Earthquake Shake Table – See: [http://www.exo.net/~donr/activities/Shake\\_Table.pdf](http://www.exo.net/~donr/activities/Shake_Table.pdf)  
1 set of wooden blocks, various sizes  
1 set of Styrofoam blocks, various sizes

#### **DAY 3:**

Copies of Handout No. 1a and 1b (one per group)

##### Materials for one model wall:

21 jumbo craft sticks, about 15 cm x 2 cm x 2 mm thick  
Electric drill with 3/16" bit  
1 piece of thin wood (~2 mm thick) 45 cm x 6 cm (~18 in. x 2 in.)  
1 piece of sturdy wood (2 x 6) for a base, about 45 cm (18 in.) long  
16 machine bolts, 10 x 24, about 2 cm long (.75 in.)  
16 machine screw nuts, 10 x 24  
32 washers, #8  
7 small wood screws

##### Reinforcing elements for one wall:

2 pieces of string, each ~25 cm (10 in.) long  
1 piece of lightweight cardboard, ~15 cm x 15 cm (a little less than 6 in. square)  
8 small paper clamps to fasten cardboard

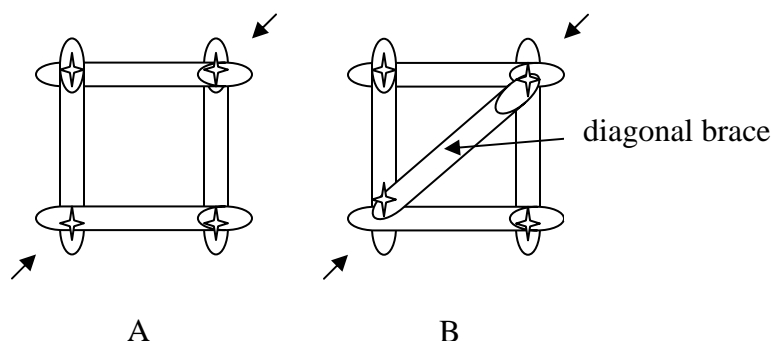


**Note!** The shake table and model wall setups should be constructed and tested well before the lesson begins. It is recommended, whenever possible, that the students are involved in the construction of the setups.

### Procedures (DAY 1)

1. Divide students into small groups. Provide each group with pieces of Styrofoam, strings, paper clips, and toothpicks. Explain to each group that they are a team of seismic engineers, and are expected to build the strongest structure possible given the materials listed above for Day 1 activities. Tell them they have 20 minutes for this activity. This activity is designed for students to have some fun, and their efforts should not be criticized.
2. Ask each group to select a spokesperson. The spokesperson should bring the structure to the front of the classroom and describe it (i.e. why they built what they did).
3. Now ask all students to predict what would happen if you place a heavy item (like brick) on their structure. Explain to students that the heavy item simulates the static force of gravity (vertical load) that every structure must carry. Explain to students that Styrofoam is quite strong for its weight, so the heavy item can also represent the weight of all non-structural elements of a building (e.g. floors, wall coverings, electrical wiring, etc.). Explain to students that some building materials are strong, capable of supporting a lot of weight while others can be weak, collapsing if too much weight is placed on them.
4. Now ask students to predict what would happen if they shook the base of their structures. Allow them to test this gently on their structures. Encourage them to share their observations.

**Note!** Structures with triangular shapes may withstand the shaking better than square (or blocky) structures. Ask students why this may be the case. To enhance their understanding, provide each group with 4 drinking straws and four straight pins and attach them in the following manner (shape A):



Ask students to grab the square by opposite corners and squeeze (shape A). They will notice how easily they can change its shape. Now ask them to add another straw (a slightly longer straw) connecting two opposite corners (shape B). Students should be able

to note how the diagonal straw stiffens the structure. Tell them they have just created triangles and diagonal bracing to make a sturdier structure. This is because the applied loads (the force on the structure caused by squeezing the corners) either stretch or compress each straw in a triangle. Narrow structural pieces are strongest when stretched or compressed but they are weakest when they must bend, shear, or when the load is transmitted through joints. For shape B, the diagonal brace is compressed and carries most or all of the applied load, therefore the diagonal brace strengthens the structure.

(Optional) Ask the students to determine, without touching the structure, whether the diagonal brace in structure B above also helps to support the structure if the structure is squeezed at the other corners that the diagonal brace is not attached to (upper left and lower right corners)? Why or why not? After the students have discussed and formed a hypothesis, allow them to test their hypothesis using the model. The answer should be yes, it does support the structure even if it is squeezed at the corners that the diagonal brace is not attached to. In this case, the brace is stretched as the joints transmit the load throughout the structure. Since narrow structural pieces such as straws are strongest when they are stretched or compressed, the structure is still stiffened. Have the students discuss their answers and compare it to the behavior of the model.

5. Now ask them to predict what would happen if they held the base of their structures and pushed horizontally on the top. Allow them to test this gently on their structures, and share their observations with the classroom. Explain to them that buildings experience horizontal forces during earthquakes, and one way to simulate these forces is simply to push or pull a structure from the side. These forces cause compression, tension, and shear throughout the building structure, depending on how the structure is built.

### **Procedures (DAY 2)**

1. Divide students into small groups. Provide each group with a set of wooden blocks. Ask each group to build a simple structure, but strong enough to survive the vibrations of a shake table. Explain to them they can use as many blocks as they want to build their structure. Allow 10 minutes for this part of the activity.

**Note!** You may want to explain to your students what a shake table is, particularly if they did not assist you with its construction. A shake table is a device that simulates an earthquake. Earthquake engineers and technicians use shake tables to observe how their building models respond to earthquakes. Show students the shake table they are going to use to test their structures. Allow them to take a close look at its components. Explain to them the purpose of each component. Refer to the link provided at the end of the lesson for detailed information about the shake table.

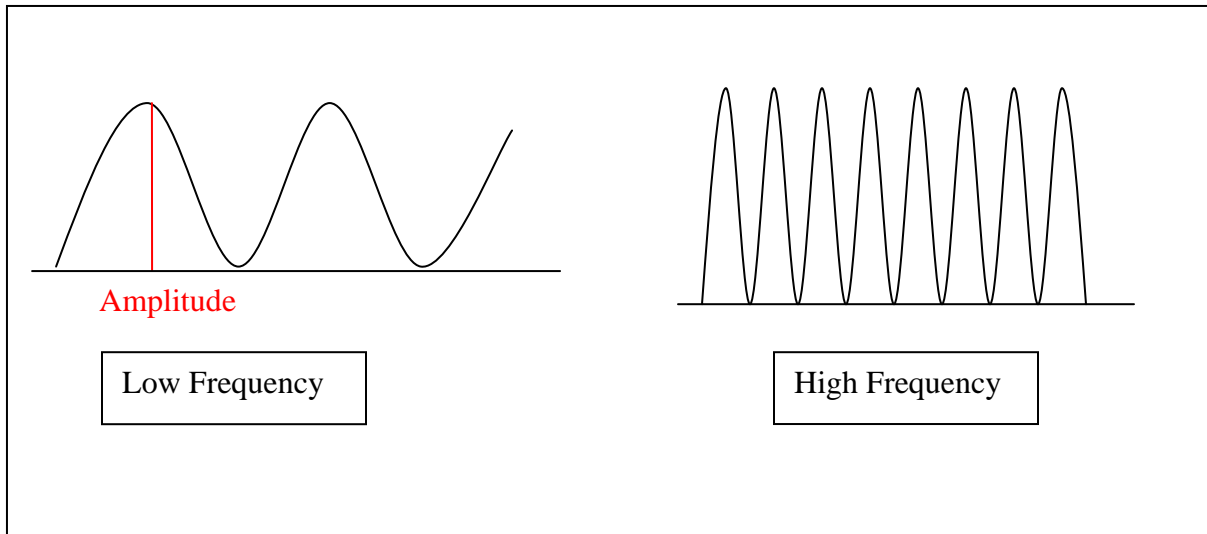
2. Now ask a spokesperson from each group to bring the structure to the front of the class. The spokesperson should describe their team's structure before placing it on the shake table. Encourage all students to predict what would happen to the structure when the shake table starts to vibrate. Explain that the motor speed is adjusted with the potentiometer, allowing the shake table to vibrate at different speeds. Ask the

spokesperson to start with a slow motion and gradually increase the motor speed. Ask all students to observe what happens to the structure. Allow all groups to test their structures.

3. Encourage students in each group to discuss why their structures collapsed or did not collapse. Ask them to pay attention to the height, weight, and shape of their structures when discussing the response of their structures to the shaking. Students may argue that tall buildings collapsed quicker than short buildings, or wide structures survived better than narrow structures. Ask students to predict what would happen if buildings of different heights are next to each other when vibrating due to an earthquake. Allow students to test this using two structural models side-by-side on the shake table. The building may hammer together or collapse on one another during powerful earthquakes.

4. Now is time for introduction to the concepts of amplitude, frequency, and resonance. Ask students what they already know about these concepts. Some students may know, for instance, that resonance and frequency are used in describing the tone of musical instruments and the quality of sound produced by different recording techniques and players. When explaining amplitude, remind students of what they learned in Lesson 6 (seismic energy). Amplitude is a measurement of the energy of a wave. In this activity, amplitude is how far to the side the block or structure moves. Frequency is the rate at which a motion repeats (or oscillates). In this activity, frequency is referred to the number of oscillations in an earthquake wave that occur each second or each minute. In earthquake engineering, frequency is the rate at which the top of a structure sways. You may want to draw something similar to Figure 3 when discussing the above terminologies. Resonance is an increase in the amplitude of a physical system (students' structure models, in this case) that occurs when frequency of table shaking is close to the natural frequency of the structures.

Define natural frequency for the students: the frequency of vibration (or oscillation) which an object or system of objects (a building for example) will exhibit according to its structural design and building materials. To help the students understand the idea of natural frequency and resonance, discuss instances of natural frequency that surround the students in their everyday lives. When a student is playing on a swing, the student is moving at the natural frequency of the swing/student system. When a friend pushes on the swing to make the student go higher, the friend is pushing at the natural frequency of the swing/student system. This causes resonance, so that every time the student is pushed, the student goes higher on the swing and the amplitude of the swinging increases. If the friend does not push at the natural frequency of the system, the student will not go very high in the air and resonance will be lost. The same effect happens to buildings during an earthquake. If the earthquake vibrations push on a building at or near its natural frequency, it will begin to resonate, causing the building to move with greater amplitude until some part of the building collapses or fails and the building falls apart.



**Figure 3.** Amplitude of a wave, and high versus low frequency

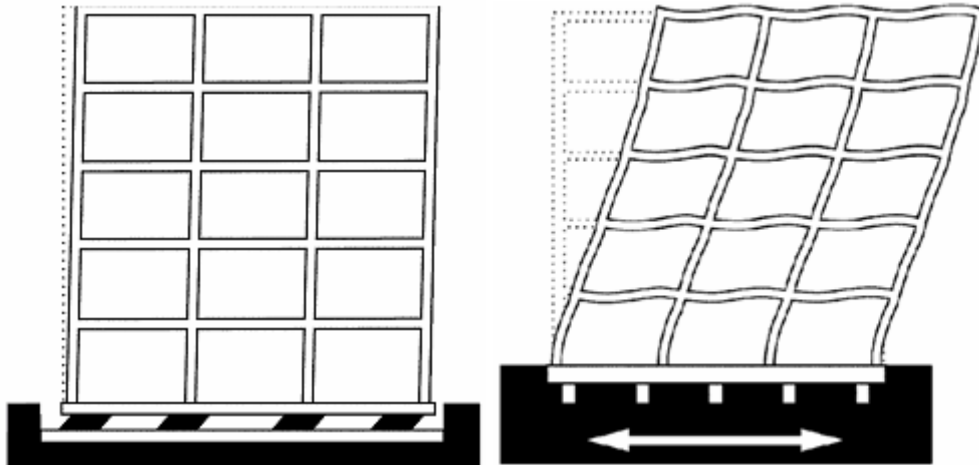
5. Now draw a connection between the above concepts. Explain to the students that all objects or all structures (which are collections of attached objects) have natural frequencies. Explain that during an earthquake, buildings oscillate, and if the frequency of oscillation is close to their natural frequency, resonance may cause severe damage. Now place one of the wooden block structures on the shake table and encourage students to look for the presence of resonance as the table shakes. For particular motor adjustments, there may be certain places where the structure may be almost still, while at other places it vibrate widely. This may be true for only parts of the structure but not the entire structure. For example, a part of a structure may exhibit notable vibration at a particular motor adjustment while another adjustment (faster or slower) causes almost no vibration. It is also possible that one structure may topple under conditions that hardly cause another to vibrate.

Allow all groups to test their structures (or simply a wooden block) for new observations. To do so, ask a student to place a block so that it is standing vertically on the shake table. Have the student slowly turn through different frequencies using the control knob of the shake table. At lower frequencies, the block should not respond much. At a certain frequency, the block will begin to shake excessively and perhaps fall over. This is the natural frequency of the block. If the student turns through this frequency quickly enough, the reaction of the block will not be so excessive and the block may continue to stand even though the shake table is moving faster. Some blocks may have a natural frequency that is outside the range that the shake table can provide. Have the student attempt to identify the natural frequency of many different lengths of blocks, block structures, or other long, slender objects in the classroom that can stand on their own, in a similar manner. Allow plenty of excess time for the students to experiment with the shake table and their structures or blocks, and to ask and attempt to answer their own questions.

6. Explain to students that one way to protect a building from resonating with an earthquake is to isolate its foundation or base from the ground with devices much like wheels. This technique is called “base isolation” used by structural engineers who place

buildings on devices that absorb energy so that ground shaking is not directly transferred to the building (Figure 4). An appropriate analogy would be the relationship between automobiles and their suspension system of springs and shock absorbers, which cushion the occupants from a bumpy ride.

(Optional): If time allows, provide students with standard small wheels to be added to their models. Allow them to test their structures (with the wheels attached to their base) one more time on the shake table.



**Figure 4.** Earthquake response of a base-isolated building versus a conventional fixed-based building (from: <http://06earthquake.org/new-technologies.html>)

To slow down structure oscillation and to dispel seismic energy, seismic engineers may also use dissipaters. These are devices mounted among some elements of the building. During an earthquake, dissipaters are subjected to movements which are relative to each other. Dissipaters slow down the vibration by dissipating viscous or friction energy when the structure oscillates.

7. Encourage students to think about other ways of reducing resonance in a building. Ask them what other structural elements they can add to their buildings that would allow them to better withstand earthquake loads. This topic is discussed further in Day 3.

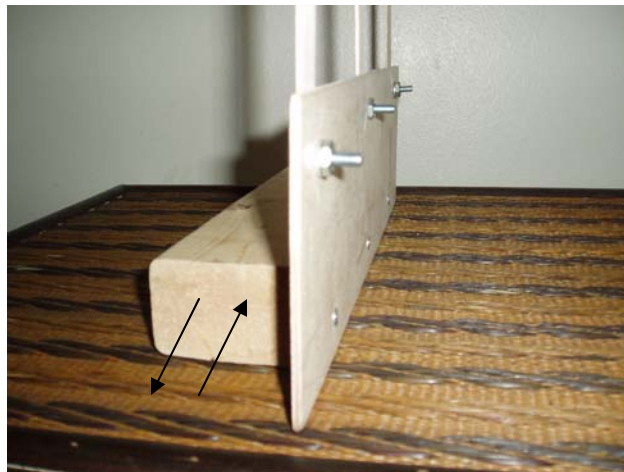
### **Procedures (DAY 3)**

1. Tell students they are going to assemble a model wall and predict what would happen if they push the base of the wall (simulating an earthquake). They are then given materials to reinforce their model and test again.
2. Divide students into small groups. Provide each group with enough material (base, craft sticks, screw nuts and washers) to assemble a model wall (Figure 5). Ask them to

make sure that the joints are just tight enough to hold the upright shape of the wall, but loose enough to be moved easily. You may choose to assemble one model and use it in front of the classroom.



**Figure 5a.** Model wall (front and back)



**Figure 5b.** Closer view of the base

3. Now ask students to describe the components of the wall, and ask them “what holds this wall up?” The answer is in the interaction of the vertical and horizontal elements to withstand the load of the structure. Explain to students what they refer to as weight will be called the force of gravity in this activity. Ask students to predict what would happen if you push the base of the wall side-to-side (as arrows show in Figure 5b.), simulating an earthquake.

**Note!** Earthquakes may cause ground shaking in many directions (see Lesson 6), but in this activity students model shaking in one direction only.

4. Instruct one student in each group to gently move the bottom of the model from the lower right or left side back and forth (as arrows show in Figure 5b.). When pushing fast, the model should collapse at the first floor only. Ask students why the other floors did not collapse. Ask them to point out where the weakest parts of the wall are based on the collapsed pattern. (The first floor collapsed because it was too weak to transfer enough horizontal force to move the upper stories. It could not transfer the shaking to the upper stories.)

5. Explain to students that pushing the base of the building is equivalent to applying force horizontally to the upper stories. Invite students to gently apply horizontal forces at different points on the model to simulate earthquake shaking.

6. Now ask students what could be done to strengthen the model wall. Students need to think about different ways through which the load can travel to the ground when strong forces act on the structure. Provide each group with pieces of cardboard, paper clamps, string, extra craft sticks, and a copy of Handout No. 1a and 1b. On the diagram provided in Handout No. 1a, ask each student to draw a force arrow (a vector) and trace the path the force takes to the ground. Review students' diagrams to ensure their understanding of the concept.

7. Now challenge students to design and build three different arrangements of the structural elements. Each time they modify the design, they must modify the diagram to show the new load path. Students must test the strength of their model walls to ensure survival of all floors when a force is applied. When a structure is reinforced well, students should be able to push on the upper story and slide the whole structure without any of the walls failing.

**Note!** There are many possible configurations that will produce a structure that can resist applied forces. However, the minimum configuration must include a continuous load path from the upper left hand corner down to the base of the structure.

8. Invite students to discuss the questions listed in Handout No. 1b. Ask one student per group to record each group's response. After all groups finish the questions, have a spokesperson from each group present students' responses to one of the questions. Allow the class to come to some consensus on their responses to that question, and then proceed to another group until all the questions have been discussed.

**Caution!** Discuss with the students the similarities and differences between the wall model and what real walls experience during an earthquake. The primary difference is that earthquake surface waves shake buildings back-and-forth (horizontal) AND up-and-down (vertical), whereas this model only simulates horizontal forces. In addition, the shaking motion of an earthquake applies forces with changes in direction and magnitude in a complicated way, but this model is best for studying steady, unidirectional applied



loads. Steady, unidirectional loads are also known as ‘static’ loads, whereas changing loads are known as ‘dynamic’ loads.

9. Explain to students that seismic engineers use similar methods to provide earthquake reinforcement for existing buildings. Engineers tend to use a combination of techniques to complement the strengths and weaknesses of each approach, which include use of diagonal braces, shear walls, and rigid connectors. Diagonal braces (craft sticks in this activity) are usually built into a wall to add strength. Shear walls (cardboard pieces in this activity) are added to a structure to carry horizontal shear forces. These are usually solid elements and are not necessarily designed to carry the structure’s vertical load. Rigid connections (paper clamps in this activity) do not permit any motion of the structural elements relative to each other.

10. Conclude this activity by helping students connect the behavior of their model walls to their mental images of real buildings during an earthquake. Emphasize that the back and forth motion, horizontal component of ground shaking is the force most damaging to buildings. Buildings are mainly designed to carry the downward pull of gravity, but to withstand earthquake shaking they need to be able to withstand sideways, or horizontal, pushes and pulls.

#### **USEFUL INTERNET RESOURCES & REFERENCES**

Rathjen, D., 2003, Shake table, Exploratorium Teacher Institute, San Francisco, California, [http://www.exo.net/~donr/activities/Shake\\_Table.pdf](http://www.exo.net/~donr/activities/Shake_Table.pdf)

Seismic Sleuths: A teacher's package on earthquakes, produced by the American Geophysical Union with support from the Federal Emergency Management Agency: [http://eric.ed.gov/ERICDocs/data/ericdocs2sql/content\\_storage\\_01/0000019b/80/15/c5/13.pdf](http://eric.ed.gov/ERICDocs/data/ericdocs2sql/content_storage_01/0000019b/80/15/c5/13.pdf)





**Picture 1.** Ancient ruins of city. Mud bricks. Flat terrain. 200-300 years old.



**Picture 2.** Old part of city near ancient ruins. Standard bricks. 30-70 years old. Original building was 3 stories tall; only parts of back wall remain. The metal rods were not part of the original building that collapsed. Flat terrain.



**Picture 3.** Industrial part of city, across from the steel foundry. Standard bricks and steel shacks. Flat terrain. 10-30 years old.



**Picture 4.** North edge of industrial part of city, next to residential area. Only surviving building on block. Collapsed buildings were made of standard brick. Flat terrain. 10-30 years old.



**Picture 5.** Center of residential area. Collapsed front walls were stacked brick and stone mixed with cement and mortar. Remaining structural walls were all intact. Gently sloping terrain. 10-30 years old.



**Picture 6.** Eastern edge of residential area near the mountains. Flat terrain. All blue buildings built by same company with similar methods. Minimal structural damage, some small wall collapse. 10-20 years old.





**Picture 7.** Western edge of residential area near the river. Flat terrain. Brick building almost completely collapsed. Minimal structural damage to metal buildings. 10-30 years old.






**Picture 8.** Eastern edge of residential area near the mountains. Sloped terrain. New construction site (after the earthquake).

This chart was adapted from the “Seismic Sleuths”, a publication of the American Geophysical Union and the Federal Emergency Management Agency

**Load Path with Additional Structural Elements**

Use materials provided to add structural elements to your wall to provide paths for the horizontal forces, or loads, to travel through the wall

<p>1. Push the third level of your wall. If the elements you added provided a load path to the base, the base of the wall should move. If they do not, the wall will fail somewhere. When you discover a setup that works, diagram it and sketch the load paths with arrows on the adjacent right column. Identify whether each element is experiencing tension, compression, or shear loads.</p>			
<p>2. Design and build another set of additional structural elements. Sketch the load path here. The base of the model wall should move when lateral force is applied to the top elements.</p>			
<p>3. Design and build a third set of additional structural elements. Use as few additional elements as possible. Sketch the load path and have your instructor check it. Test your load paths by removing elements not in the path to see if the building will stand up to a force.</p>			

**ANSWER KEY**

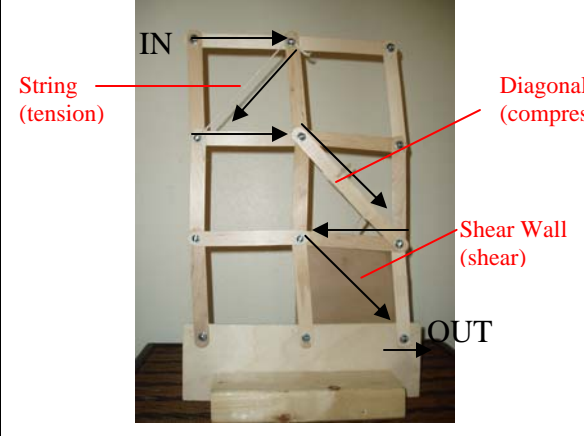
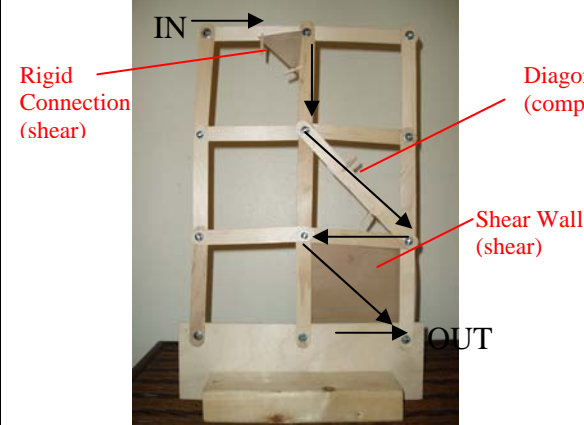
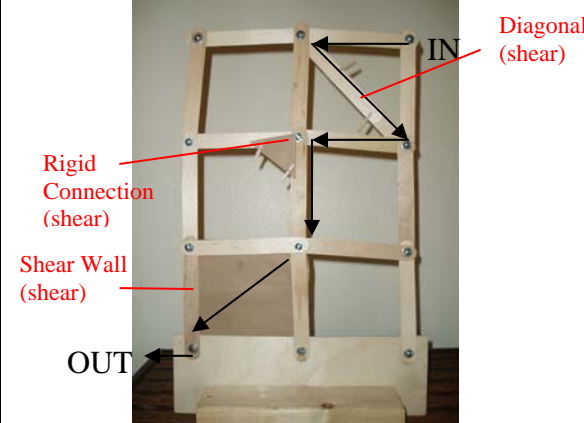
Handout No. 1a

Name: \_\_\_\_\_

This chart was adapted from the “Seismic Sleuths”, a publication of the American Geophysical Union and the Federal Emergency Management Agency

**Load Path with Additional Structural Elements**

Use materials provided to add structural elements to your wall to provide paths for the horizontal forces, or loads, to travel through the wall

<p>1. Push the third level of your wall. If the elements you added provided a load path to the base, the base of the wall should move. If they do not, the wall will fail somewhere. When you discover a setup that works, diagram it and sketch the load paths with arrows on the adjacent right column. Identify whether each element is experiencing tension, compression, or shear loads.</p>	 <p>String (tension)</p> <p>Diagonal Brace (compression)</p> <p>Shear Wall (shear)</p> <p>IN</p> <p>OUT</p>
<p>2. Design and build another set of additional structural elements. Sketch the load path here. The base of the model wall should move when lateral force is applied to the top elements.</p>	 <p>Rigid Connection (shear)</p> <p>Diagonal Brace (compression)</p> <p>Shear Wall (shear)</p> <p>IN</p> <p>OUT</p>
<p>3. Design and build a third set of additional structural elements. Use as few additional elements as possible. Sketch the load path and have your instructor check it. Test your load paths by removing elements not in the path to see if the building will stand up to a force.</p>	 <p>Rigid Connection (shear)</p> <p>Diagonal Brace (shear)</p> <p>Shear Wall (shear)</p> <p>IN</p> <p>OUT</p>

Handout No. 1b

Name: \_\_\_\_\_

These questions are from the “Seismic Sleuths”, a publication of the American Geophysical Union and the Federal Emergency Management Agency

Discuss the answers to the following questions. One student should write down students’ responses to the questions.

1. What is a load path?
2. Why must additional structural elements be added to a wall before it can carry horizontal forces?
3. How many additional elements did you need to add?
4. Why doesn’t the force take some path other than the one you diagramed?

**ANSWER KEY**

Handout No. 1b

Name: \_\_\_\_\_

These questions are from the “Seismic Sleuths”, a publication of the American Geophysical Union and the Federal Emergency Management Agency

Discuss the answers to the following questions. One student should write down students’ responses to the questions.

1. What is a load path?

*The path that the load (force) follows through the structural elements of a building.*

2. Why must additional structural elements be added to a wall before it can carry horizontal forces?

*Normally, buildings only have to support a vertical force (gravity). When horizontal forces are applied, as in an earthquake, additional elements are needed to carry them.*

3. How many additional elements did you need to add?

*Each joint needed only one additional structural element. Only one joint on each floor is needed to carry a horizontal force that is transmitted throughout the entire wall, in this model.*

4. Why doesn’t the force take some path other than the one you diagramed?

*The diagram shows the places that are strong enough to carry the load. If there were more than one place, the load (or force) would travel through both.*