Build a Better Wall*

How can we design buildings to withstand an earthquake?

Demo/lecture on how to design a structure to withstand an earthquake. Uses simple materials to engineer shear walls and is designed to allow students to experiment with methods to build shear strength into buildings.

Dr. Robert Butler, University of Portland OR demonstrates structural additions for building strength during an earthquake.

This activity is "designed to allow students to construct an understanding of how buildings respond to earthquakes. Lessons on building design and how earthquake forces act on various designs provide students with information on how to build earthquake resistant structures. Students then apply this knowledge by constructing testing devices and testing their designs. This unit is critical for developing students' understanding of why buildings collapse and what can be done to make buildings safer."

Two optional activities are included to explore earthquake hazards and building damage by constructing model buildings and subjecting them to ground vibration (shaking similar to earthquake vibrations) on a small shake table.

NGSS Science Standards

- From Molecules to Organisms—Structures and Processes: MS-LS1-8
- Motion and Stability—Forces and Interactions: HS-PS2-1, MS-PS2-2
- Energy: MS-PS3-2, HS-PS3-2, MS-PS3-5
- Waves and Their Applications in Technologies for Information Transfer MS-PS4-2
- Earth and Human Activity:MS-ESS3-2
- Engineering Design: MS-ETS1-1, HS-ETS1-1

Additional Resources

Videos

Lecture demo by Dr. Butler:
www.iris.edu/hq/inclass/lesson/413

How to build the demo set:
www.iris.edu/hq/inclass/video/253

Animations

Building Resonance: Structural stability during EQs

www.iris.edu/hq/inclass/animation/224

Internet Links

Design a bridge, add structural elements, then set off an earthquake!! Interactive program allows you to design the Bay Bridge...and then destroy it with an earthquake. Select bridge types, seismic safety features and earthquake type: **http://eduweb.com/portfolio/bridgetoclassroom/engineeringfor.html**

*Activity from FEMA **http://www.fema.gov/library/viewRecord.do?id=3558**.
NGSS standards are from the Cascadia Earthscope C_prfos_ic_lb Rqsl_kg Cbsa_rgml Npmep_k c+`glbcp (http://ceetep.oregonstate.edu/).

Structural Reinforcement:

The Better Building

RATIONALE

Students will learn how diagonal braces, shear walls, and rigid connections strengthen a structure to carry forces resulting from earthquake shaking.

FOCUS QUESTIONS

How may the structure of a building be reinforced to make it better able to withstand earthquake shaking?

OBJECTIVES

Students will:

1. Recognize some of the structural elements of a building.
2. Describe how the horizontal and vertical structural elements carry the horizontal and vertical loads of a building.
3. Describe how diagonal braces, shear walls, and rigid connections provide paths for the horizontal load resulting from an earthquake.
4. Observe how added structural elements strengthen a model wall to withstand shaking.

MATERIALS

TEACHING CLUES AND CUES

Jumbo craft sticks are available at craft and hobby stores. They are larger than ice cream sticks, about the size of tongue depressors.

You may want to build this model and the one in Lesson 4.3 at the same time, and introduce them both in the same class period. This would allow two groups to be actively engaged with the models of the same time.

MATERIALS

Teacher: for one model wall

- 21 jumbo craft sticks, about 15 cm x 2 cm x 2 mm thick sticks, about the size of tongue depressors.
- Electric drill with 3/16” bit
- Goggles for eye protection
- 1 piece of thin wood (about 2 mm thick) 45 cm x 6 cm (about 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
- 2 pieces of string, each approximately 25 cm (10 in.) long

Reinforcing elements for one wall:

- 1 piece of thin wood (about as thick as the craft sticks) 20 cm x 2 cm
- 1 piece of lightweight cardboard, about 15 cm x 15 cm (a little less than 6 in. square)
- 8 small paper clamps to fasten wood and cardboard

For each small group

- One set of the above supplies if they are each building a model wall
- One copy of Master 4.2b, Load Paths Worksheet
- Pens and pencils

PROCEDURE

Teacher Preparation

Assemble the model wall, following the diagram on Master 4.2a, Building a Model Wall, and try it out before class. Be sure the bolts are just tight enough to hold the structure upright when no force is applied.

A. Introduction

Tell students that this lesson is designed to demonstrate how the structural elements of a wall carry forces. The activity deals with three structural elements that carry the lateral shear forces caused by ground shaking during an earthquake: diagonal bracing, shear walls, and rigid connections. It is designed around an apparatus called the model wall. Remind the students that this is a model, designed to demonstrate only certain characteristics of real walls.

B. Lesson Development

1. Show students the model and tell them that it represents part of the frame of a building. 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, but try to keep the students focused on discovery, since in this activity they will see the architectural principles demonstrated. Explain to students that what they refer to as weight will be called the force of gravity in this lesson.

2. Now ask students to predict what would happen if you quickly pushed the base of the wall, simulating an earthquake. Remind them that an earthquake may cause ground shaking in many directions, but for now we are modeling shaking in one direction only.

3. Divide the class into the same seismic engineering teams (SETs) as for Lesson 1 and give each group one copy of Master 4.2b, Load Paths Worksheet. Invite students to take turns investigating the model’s response in their small groups.

VOCABULARY

Braces or Bracing: structural elements built into a wall to add strength. These may be made of various materials and connected to the building and each other in various ways. Their ability to withstand stress depends on the characteristics of the materials and how they are connected.

Lead: the sum of vertical forces (gravity) and horizontal forces (shear forces) acting on the mass of a structure. The overall load is further broken down into the loads of the various parts of the building. Different parts of a building are designed and constructed to carry different loads.

Lead path: the path a load or force takes through the structural elements of a building.

Rigid connections: connections that do not permit any motion of the structural elements relative to each other.

Shear force: force that acts horizontally (laterally) on a wall. These forces can be caused by earthquakes and by wind, among other things. Different parts of a wall experience different shear forces.

Shear walls: walls 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.

Structural elements or structural features: a general term for all the essential, non-decorative parts of a building that contribute structural strength. These include the walls, vertical column supports, horizontal beams, connectors, and braces.

a. Instruct one student in each group to push at the bottom of the model from the lower right or left side. (When pushed just fast enough, the model should collapse at the first floor only.) Ask students why the other floors didn't collapse. (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.)

b. Direct students' attention to the load path diagrams on Master 4.2b and explain that pushing the base of the building is equivalent to applying force horizontally to the upper stories. A force applied horizontally to any floor of a building is called the shear force on that floor. Shear forces can be caused by the ground shaking of an earthquake as well as by high winds. Invite students to carefully apply horizontal forces at different points on the model to simulate earthquake shaking. (Earthquakes affect buildings at ground level.)

4. Ask students how they could add structural elements to create a path for the load to follow to the ground when strong forces act upon the structure. Help the students discover the effect of adding a shear wall, diagonal bracing, and rigid connections, using string, cardboard, extra wood, and clamps, as in the diagrams on the master. On each of the three diagrams provided, have students draw a force arrow (a vector) and trace the path the force takes to the ground.

5. Challenge students to design and build three different arrangements of the six structural elements depicted on the worksheet. Each time they modify the design they must modify the diagram to show the new load path. Check each structure and diagram until you are sure that students understand the concepts. When a structure is well reinforced, you should be able to push on the upper story and slide the whole structure without any of the walls failing.

6. Either have the groups discuss the questions on the master, with one student recording each group's response, or ask individual students to write responses to specific questions. After all the groups finish the questions, have a reporter for each SET present its response to one of the questions. Allow the class to come to some consensus on their responses to that question, then proceed to another group until all the questions have been discussed.

C. Conclusion

As a closing activity, challenge a volunteer to remove an element (a craft stick) that, according to the load path diagram, is not carrying any load. Have the student unbolt one end of that element and push the reinforced structure to see if it holds. It will, if the load path is correct.

Finally, help the students connect the behavior of their model walls to their mental images of real buildings during an earthquake. Emphasize that the back and forth, horizontal component (or shearing) of ground shaking is the force most damaging to buildings. Buildings are primarily designed to carry the downward pull of

TEACHING CLUES AND CUES

This activity is designed as a demonstration or as a group activity. If you decide to have each group build a model wall you will need more materials.

Encourage students to choose roles within their SETs and later report their results by role, with the technician reporting the data, the engineer describing the calculations, the scientist explaining the relationships, and the coordinator facilitating.

Students may try both pushing the structure directly and moving the table. Shaking the table on which the structure rests would simulate the transfer of energy from the ground to the building.

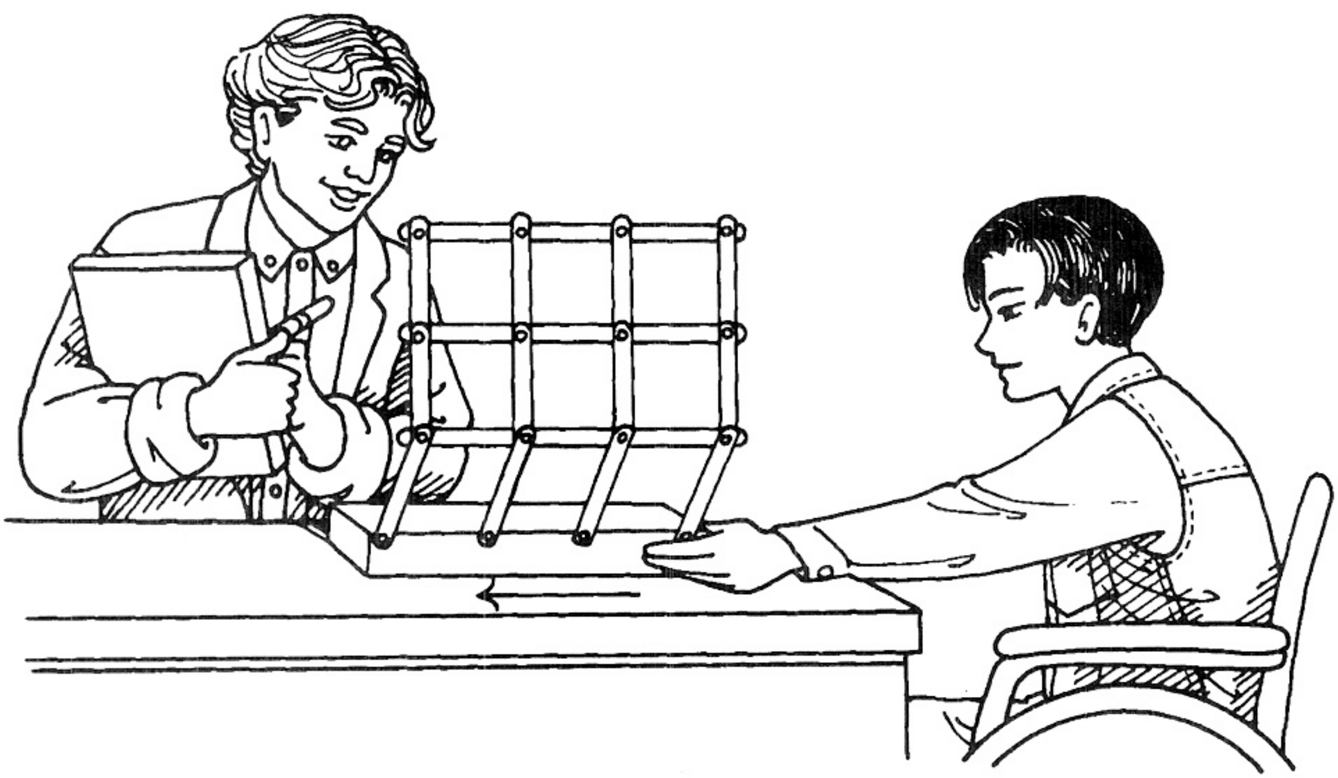
gravity, but to withstand earthquake shaking they need to be able to withstand sideways, or horizontal, pushes and pulls.

ADAPTATIONS AND EXTENSIONS

1. Challenge students to find the minimum number of diagonal braces, shear walls, or rigid connections that will ensure horizontal stability in their models.

2. Invite students to design, construct, and test other structural elements that could make buildings earthquake-resistant, such as square rigid connections. Some might try putting wheels or sleds on the bottom of their buildings.

3. If you have some very interested students, you may give them access to all your building supplies and challenge them to design and construct larger structures. Ask students to consider how they could design a building so that the ground shaking does not transfer to the building. There are new technologies that allow the ground to move, but not the building. One of these is called base isolation. Have students research this topic in periodicals. (See Unit Resources.) ▲

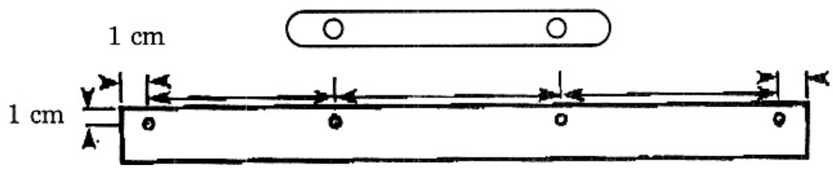


Building a Model Wall

1. Stack 21 craft sticks one on top of the other. Wrap a rubber band around the center to hold them together. Using a 3/16 in. bit, carefully drill a hole through all the sticks at once, 1 cm from the end of the stack. Drill slowly to avoid cracking the wood.

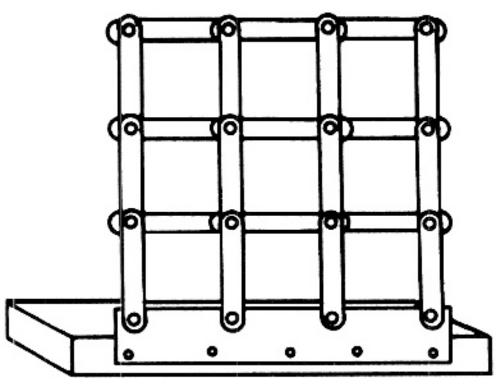
2. Select the thinner of the two large pieces of wood (45 cm x 6 cm). Drill a 3/16 in. hole 1 cm from one end and 1 cm from the edge. Measure the distance between the holes drilled in the craft sticks and space three more 3/16 in. holes at that distance 1 cm from the edge so that a total of four holes are drilled (see illustration).

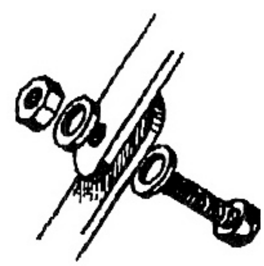
3. Use the small wood screws to mount this piece of wood on the base (the 2 x 6), fastening at the bottom and in the center. Leave the pre-drilled holes sticking up far enough above the top to accept the drilled craft sticks.



4. Using the bolts, washers, and nuts, assemble the craft sticks to build a model wall.

5. Experiment with tightening bolts and washers until they are just tight enough for the wall to stand on its own.





Load Paths Worksheet

Name ____ Date _____________________

A. Failing Wall

Observe and explain how the wall fails when its base is shaken rapidly back and forth, simulating the motion of a building hit by S waves during an earthquake. Tighten all the nuts just enough to allow the joints to move. Sharply push the base a few centimeters horizontally (right or left).

1. What part of the wall fails first?
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2. Imagine how the horizontal force you applied to the base travels to the upper parts of the wall. What caused the first structural failure?____
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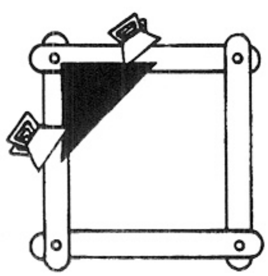
B. Load Paths with Additional Structural Elements

1. Pick up the two rigid connections, one shear wall (cardboard), one solid diagonal brace, and two pieces of string. Add structural elements to your wall to provide paths for the horizontal forces, or loads, to travel through the wall. Study the diagrams below to see how these structural elements provide load paths.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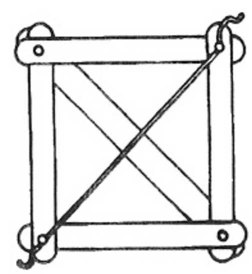
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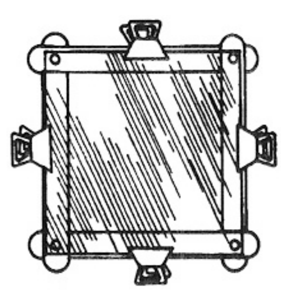
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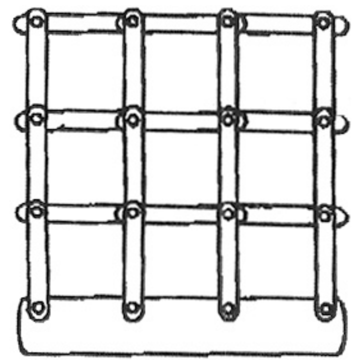
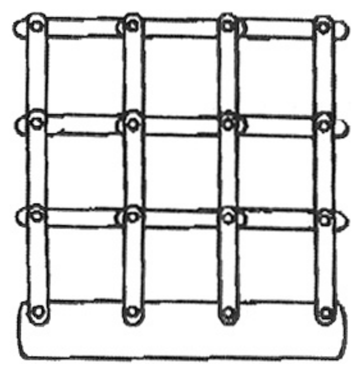
Use arrows to show the load path on each diagram.

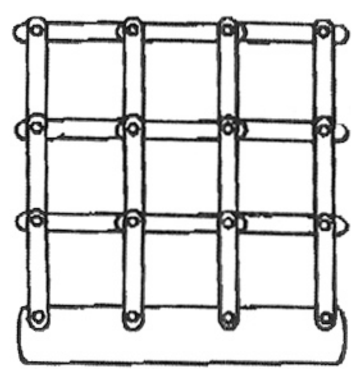
2. Put additional structural elements on your wall and push the third level. If the elements you added provided a load path to the base, the base of the wall should move. If they do not, the wall will fail somewhere. When you discover a setup that works, diagram it and sketch the load paths with arrows. Have your instructor look it over before you continue.



3. Design and build another set of additional structural elements. Sketch the load path here and have your instructor check it. Be sure each member of the team designs a set. The base of the model wall should move when lateral force is applied to the top elements.



4. 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. Be sure each member of the team designs a set. Test your load paths by removing elements not in the path to see if the building will stand up to a force.



C. Summary

1. What is a load path?

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

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

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4. Why doesn't the force take some path other than the one you diagrammed?

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Load Paths Worksheet (key)

A. Failing Wall

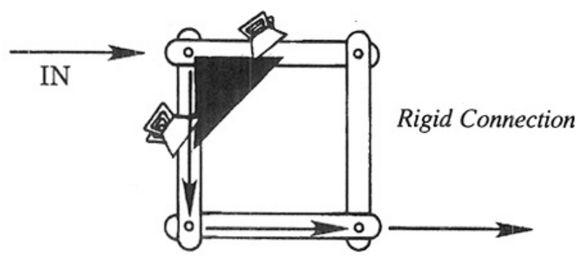
Observe and explain how the wall fails when its base is shaken rapidly back and forth, simulating the motion of a building hit by S waves during an earthquake. Tighten all the nuts just enough to allow the joints to move. Sharply push the base a few centimeters horizontally (right or left).

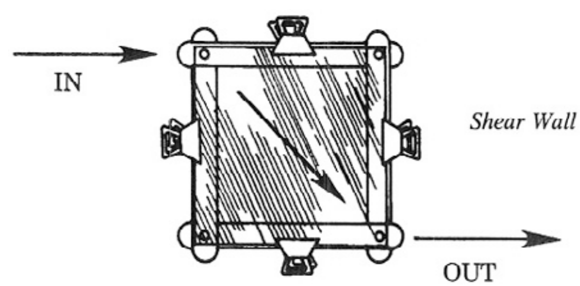
1. What part of the wall fails first? *The first floor*

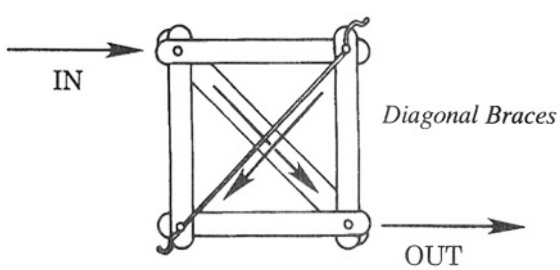
2. Imagine how the horizontal force you applied to the base travels to the upper parts of the wall. What caused the first structural failure? *The first floor has to carry all the load to the upper stories. It transfers forces to move the upper stories.*

B. Load Paths with Additional Structural Elements

1. Pick up the two rigid connections, one shear wall (cardboard), one solid diagonal brace, and two pieces of string. Add structural elements to your wall to provide paths for the horizontal forces, or loads, to travel through the wall. Study the diagrams below to see how these structural elements provide load paths.

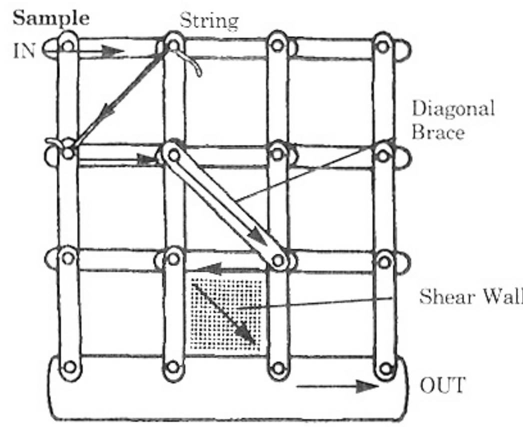




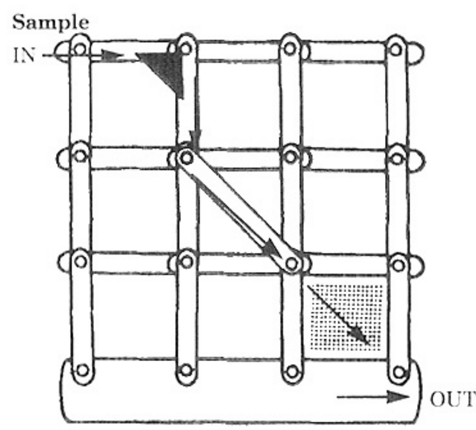


Use arrows to show the load path on each diagram.

2. Put additional structural elements on your wall and push the third level. 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. Have your instructor look it over before you continue.



3. Design and build another set of additional structural elements. Sketch the load path here and have your instructor check it. Be sure each member of the team designs a set. The base of the model wall should move when lateral force is applied to the top elements.



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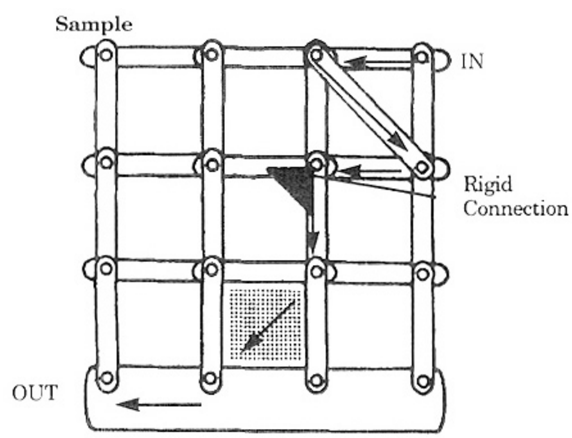

C. Summary

1. What is a load path?
The path that the load (or 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 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 needs only one additional structural element. Only one joint on each floor needs to carry the horizontal force, in this model.

4. Why doesn't the force take some path other than the one you diagrammed?
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.

4.1a MASTER PAGE

Teacher Background Reading

Building Engineering

During an earthquake, a marked spot on the Earth might be seen to move erratically, tracing out a random path resembling that of a wandering insect. “Ground motion” is a literal description, since the ground moves (generally for a distance measured only in centimeters) relative to its starting point. The ground motion that is important in determining the forces on a building is acceleration. As the seismic waves move through the ground, the ground moves back and forth. Acceleration is the rate at which ground movement changes its speed.

Two other unit measures are directly related to acceleration. Velocity, measured in centimeters per second, refers to the rate of the motion at a given instant. Displacement, measured in centimeters, refers to the distance an object is moved from its resting position. If you move your hand back and forth rapidly in front of your face, it might experience a displacement of 20 to 30 centimeters in one second and its acceleration and velocity may be quite high, but no damage will be done because the mass of your hand is low. In a building with a mass in the thousands of metric tons, tremendous forces are required to produce the same motion. These forces are transmitted throughout the structure, so if the movement repeats for some minutes the building may shake to pieces.

To overcome the effects of these forces, engineers rely on a small number of components that can be combined to form a complete load path. In the vertical plane, three kinds of structural systems are used to resist lateral forces: shear walls, braced frames, and moment-resistant or rigid frames. In the horizontal plane, diaphragms (generally formed by the floor and roof planes of the building) or horizontal trusses are used. Diaphragms are designed to receive lateral force between the vertical resistance elements (shear walls or frames). Shear walls are solid walls designed to carry the force to the vertical resistance system. In a simple building with shear walls at each end, ground motion enters the building and moves the floor diaphragms. This movement is carried by the shear walls and transmitted back down through the building to the foundation. Braced frames act in the same manner as shear walls, but may not carry as much load depending on their design. Bracing generally takes the form of steel rolled sections (I-beams), circular bar sections (rods), or tubes. Rigid frames rely on the capacity of joints to carry loads from columns to beams. Because these joints are highly stressed during movement the details of their construction are important. As a last-resort strategy, rigid frames use the energy absorption obtained by deformations of the structure before it ultimately fails.

Architecturally, rigid frames offer a certain advantage over shear walls or braced frames because they tend to provide structures that are much less obstructed internally than shear wall structures. This allows more freedom in the design of accompanying architectural elements, such as openings, exterior walls, partitions, and ceilings, and in the placement of building contents, such as furniture and loose equipment. Nevertheless, moment-resistant frames require special construction and detailing and therefore, are more expensive than shear walls or braced frames.

Note: *Adapted from FEMA 99, October* 1990, Non-technical Explanation of the NEHRP Recommended Provisions.