



Seeing and Touching Structural Concepts in Class Teaching

Manchester Centre for Civil and Construction Engineering
UMIST



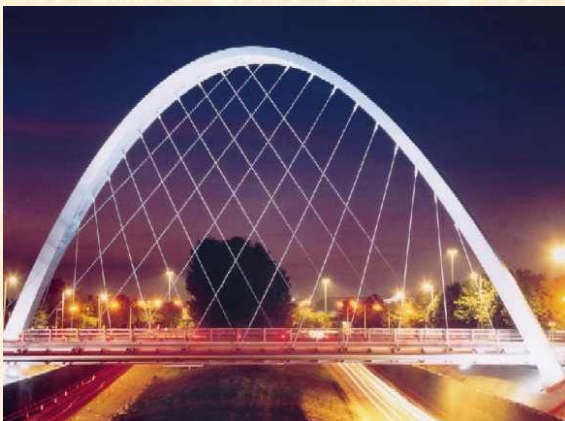
Introduction

The understanding of structural concepts is a key objective in the teaching and learning of civil and structural engineering. Today many hand calculations are replaced by the use of computers, but the understanding of structural concepts, which often come with hand calculations, cannot be replaced by computers.

Structural concepts are abstract as they cannot be seen and touched directly and many students experience difficulties in understanding such concepts. If structural concepts could be made more observable and touchable, students would be better able to understand them and would be more attentive in class learning situations.

Approach

Three parallel themes are developed, which allow students to see and touch structural concepts, as illustrated in the figure on the right, as follows:



- Providing a series of simple demonstration models for illustrating structural concepts in class which allow students to gain better understanding.
- Giving associated good engineering examples to demonstrate the applications of the concepts which help to bridge the gaps between students' knowledge and practice.
- Converting appropriate research output which particularly involves structural concepts into teaching material to improve existing course contents.

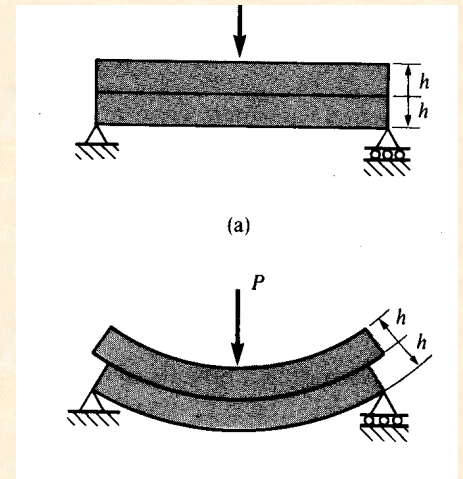
Outcome

- Helps students to grasp structural concepts and understand better how structural concepts can be applied in practice
- Makes teaching and learning more interesting and interactive and students more receptive to the presentation of theory

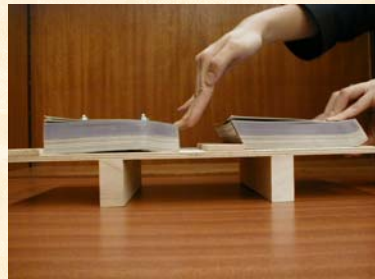
The effect of shear stress

The effect of shear stress has been demonstrated imaginatively in textbooks as shown in the figure on the right. If two beams are glued together, shear stresses must exist between the contact surfaces of the two beams; If no friction exists between the contact surfaces of the beams, the upper beam will slide with respect to the lower beam

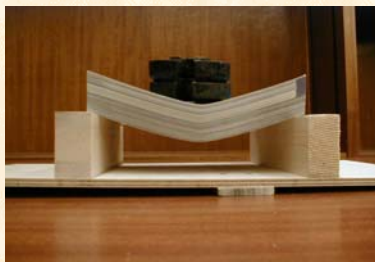
However, with careful examination it can be noted that the upper beam is actually longer than the lower beam in the second drawing opposite.



a). Two catalogues, one bolted



b). Deformation due to a shear force



c). Bending of unbolted catalogue



d). Bending of bolted catalogue

The phenomena can be demonstrated in another manner. Take two identical thick catalogues and pass bolts through one leave the other unbolted (Fig.a). Each catalogue can be considered to be made up of hundreds of very thin 'beams'.

Fig.b: Apply a horizontal force to the top right edges of the two catalogues. It is apparent that the thin pages slide over each other in the unbolted catalogue.

Fig.c and Fig.d show the bending deflections of the two catalogues under the same weights. The bolts provide shear resistance between the pages of the bolted catalogue and make it much stiffer than the unbolted catalogue.

Bending

Many members in engineering structures are subjected to bending. However, students often do not understand the assumptions used in the bending theory of beams, which are:

- Plane cross sections of a beam remain plane and perpendicular to its neutral axis after bending.
- Elongation occurs on one side and shortening on the opposite side of the beam.

Using the sponge model shown in the figure on the right, students can use a protractor to measure the angles between the cross-section lines and the neutral axis, and use rulers to measure the distances between two adjacent sections in the top and bottom layers of the beam.



Warping

When one end of the sponge beam is restrained, twisting the beam at the other end shows that

- The cross sections do not remain in a plane.
- The angle between the vertical and horizontal lines is not 90°

Stress distribution

Stress, in physical science and engineering, is force per unit area within material which arises from externally applied load, and is the ratio of the force to the area to which the force is applied. Thus,

the smaller the area, the higher the stress

Place a balloon on the bed of nails and add weights gradually to the balloon (Fig.a)

Place another balloon on a single nail. The balloon bursts immediately when in contact with the nail, as the small area of contact results in a high concentration of stress (Fig.b)



(a)

(b)



The tilt of the world's most famous tower, the Leaning Tower of Pisa, grew out of a fundamental error. With the tower's foundation not much wider than the diameter of the tower itself, an excessive amount of weight is concentrated on a small area of soft soil.

Over 700 years, the soil has settled unevenly under the weight of the tower causing it to lean

Prestressing

Prestressing is a technique that generates stresses in structural elements before they are loaded, making the elements stiffer and increasing their load capacity. The technique has been used in buildings, floors and bridges. How prestressing increases load capacity of a structure can be demonstrated as follows:

- The wooden cubes separated have no load capacity. (Fig.a)
- Add weights and the wire becomes tight providing prestress between the cubes, forming a structure, which is able to carry weights. (Fig.b)



Toronto CN Tower

One inspiring example of prestressing technique is the 1815 ft tall Toronto CN tower, the tallest free-standing structure in the world. Gently tapering as it rises, the tower is made of prestressed concrete. The tower is so stiff that a 120 mile per hour wind would create barely discernible wobble at the sky-pot level.



a). No prestress applied



b). Prestress applied

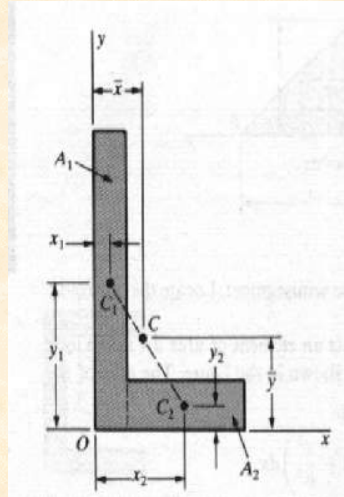
Centre of mass in a plane

Centre of mass is the point at which a body will balance if supported. It is easy to find the mass centre of a book by using our index figure to support the book.

For an L shaped area it is possible to calculate the mass centre of the area, but it is difficult to lift it at its mass centre.

This is demonstrated by balancing a spoon and a fork, which are assembled to form an L shape, with a toothpick on the edge of a wine glass.

The contact point between the toothpick and the wine glass is the centre of the mass of the combined spoon and fork.



An example in textbooks



Demonstration of mass centre

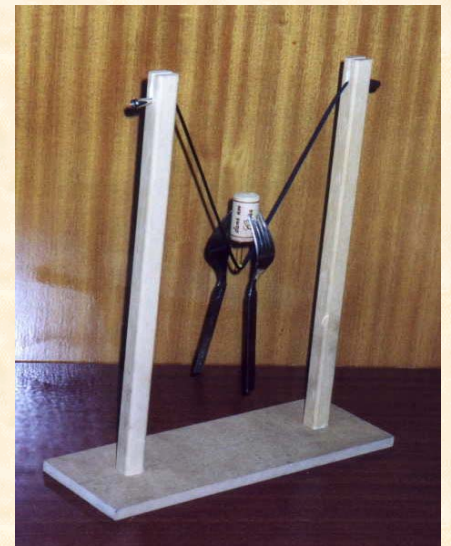
Centre of mass in the vertical direction

The lower the centre of mass, the more stable the structure.

This concept is simple but useful. There are several ways to demonstrate the statement. One of them is given as follows

A pin is pushed into a cork to form a lightweight system. Balancing such a system on a string steadily is an impossible task because the centre of mass of the system is high and the centre falls outside its supporting point.

With the addition of two forks at the sides of the cork, the pin can support the cork and forks on a string steadily. This is because the mass centre of the new system is lowered to a position beneath the point of the support.



Lowering the centre of mass



A tower crane and its base



This concept is important in designing structures. Many structures are built with larger bases to lower centres of their masses, which eliminates or reduces the risk of overturning due to wind load.

A tower crane is a common piece of plant on construction sites. Its heavy base is purposely designed to lower the gravity centre and to increase stability of the tower.

The relationship between span and deflection

Why can we not build bridges, such as that shown in the figure on the right, with longer spans and fewer columns which would give wider passage to shipping?

Students are shown how to derive the following formula for the maximum deflection of a cantilever carrying a point load at its free end



(a)



(b)



(c)

$$\Delta = \frac{PL^3}{3EI}$$

The equation indicates that

- If the span of the cantilever is doubled then its deflection will be multiplied by a factor of eight
- An increase in the depth of the cantilever is more effective than in its width to reduce deflections

These effects can be demonstrated using a 1-metre wood ruler that has a weight attached to its free end.

1. Observe the displacement at the free end of the cantilever with a span of 350mm. (Fig.a)
2. See a much larger end displacement when the span becomes 700mm. (Fig.b)
3. Notice a significantly reduced displacement when the ruler is turned through 90 degrees about its longitudinal axis. (Fig.c)

Equilibrium

Students are taught at an early stage how to make use of equilibrium equations but it is desirable to show them how a structure achieves equilibrium and how the concept of equilibrium is used in practice.



A bottle-plate system

A demonstration of equilibrium is the bottle-plate system shown in the figure. The system, supported on the narrow plate edge, is and feels very stable. Students are asked to explain how the equilibrium is achieved and to draw the free-body diagrams for the bottle and for the plate.

Balanced barriers can be found in many places, such as the one adjacent to the Department. The balance weight fixed to the shorter arm allows the barrier to be opened easily.



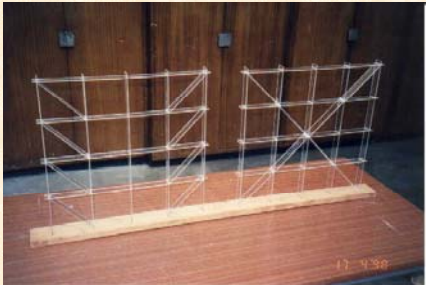
A Barrier

The direct force path

Research has identified three structural concepts particularly useful for designing stiffer structures which can be derived from an equation taught in the first year course in Civil Engineering. They are:

$$\Delta = \sum_{i=1}^M \frac{N_i^2 L_i}{E_i A_i}$$

- The more direct the internal force path, the stiffer the structure
- The more uniform the internal force distribution, the stiffer the structure
- The smaller the internal forces, the stiffer the structure



The two plastic frames shown have the same dimensions and use the same amount of material, the only difference between them being in the arrangements of bracing members. Pushing a top-end joint of each frame horizontally, one feels that the right frame is much stiffer. It is explained to students that the load on the right frame is transmitted to its supports through a direct force path while the force path in the left frame is zigzag.

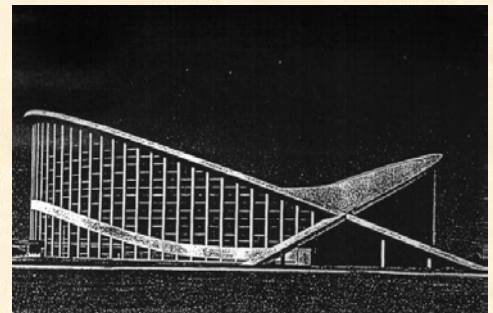
The practical example shown to the right illustrates the importance of understanding and providing force paths. In this scaffolding structure no diagonal (bracing) members were provided, i.e. no direct force paths were provided, which produced a structure that did not have enough stiffness and it collapsed under wind loads alone.



The 100-storey 344m tall building, the John Hancock Centre, Chicago, shown in the figure on the left, used global cross-bracing to the perimeter frame tube. Some \$15 million was saved just on the conventional steelwork by using the bracing to create a direct force path.



The collapsed structure



Raleigh Stadium, North Carolina

Smaller internal forces

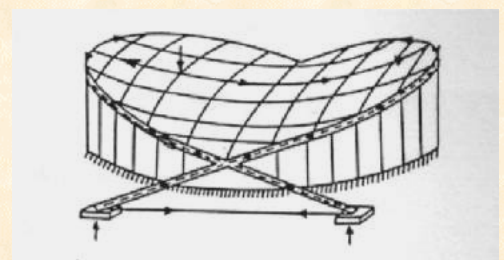
The implementation of the third concept can be expressed as a criterion:

If a device, or a structural element, can be incorporated into a structure and the device can offset some of the effects of external loads or balance some of the internal forces before the forces are transmitted to the structural supports, the structure will be stiffer.



The figure on the left shows two identical rubber rings and a wire is tied across the diameter of the left ring. The same weight is placed on the top of each ring and the reduced deformation of the tied ring is apparent and its increased stiffness can be seen and felt.

The figures above show the Raleigh Stadium and the force path diagram. Part of the horizontal components of the compressive forces in the arches are balanced by the underground ties, which have a similar function to the wire in the demonstration rings.



Force path diagram

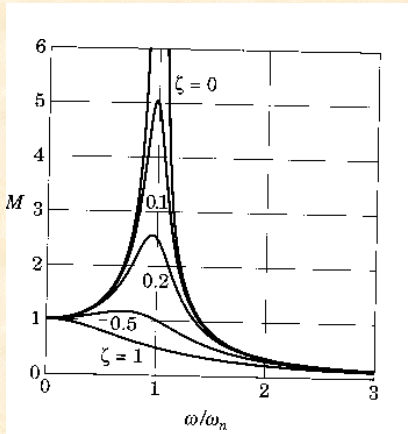
Resonance

Resonance is an important concept in vibration. Students are introduced to the concept in their pre-university studies but they may not have actually seen or felt resonance.

An interesting example of resonance, relevant to students, occurs in the response of structures to human dance activities when one of the jumping frequencies matches a natural frequency of a structure, such as occurs at pop concerts



At a pop concert

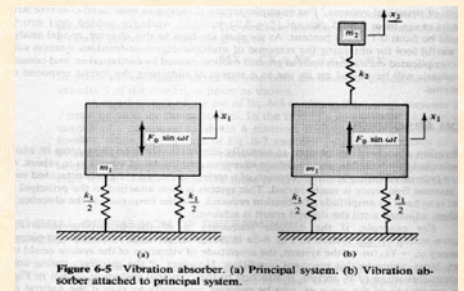
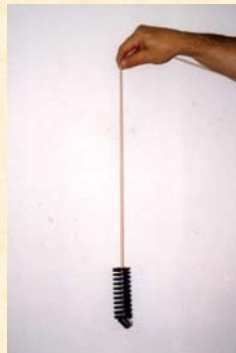


The maximum response of a single degree-of-freedom system subject to a harmonic load can be illustrated graphically as shown in the diagram on the left, which indicates:

- When the load frequency is less than a quarter of the frequency of the system, the dynamic displacements are close to the static displacement.
- When the load frequency is more than twice the frequency of the system, dynamic displacements are much less than the static displacement.
- When the load frequency is close to the frequency of the system, resonance will occur and dynamic displacements can be many times the static one.

The theoretical predictions can be demonstrated with a simple model comprising an elastic string and a weight which form the SDOF system shown on the right.

Moving the support up-and-down with different speeds, the phenomena mentioned above can be observed.



a). A SDOF and a TDOF systems

Vibration reduction

Tuned mass dampers are now widely used in engineering for reducing levels of vibration. The concepts of the damper can be illustrated by a two-degree-of-freedom system in which a mass-spring system is added to the base mass-spring system, shown in Fig.a. The equation of response of a TDOF system is rather complicated and the reduction of vibration is unlikely to be visualised from the equation.



The Millennium Bridge on the opening day

Fig.b shows a model of a SDOF and a TDOF systems.



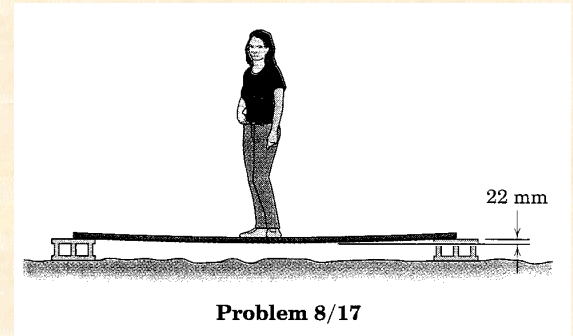
b). A model of a SDOF and a TDOF systems

The effect of the vibration reduction due to the added mass-spring system can be demonstrated in a simple manner. Move the two main masses down by the same distance then release them, to observe that the main mass on the right vibrates less than the one on the left.

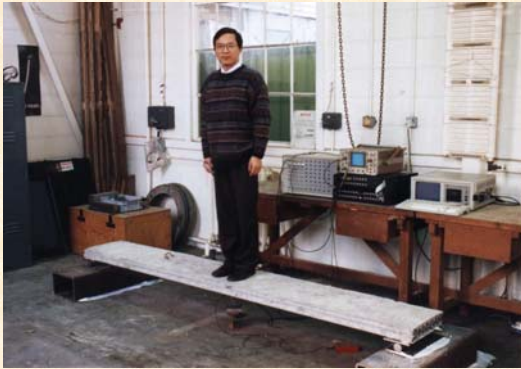
Tuned-mass-dampers will be used in London Millennium Bridge to reduce human induced structural vibrations.

People and vibration

Human body mass is traditionally considered as an inert mass in structural vibration. For example, a question is provided in a well-known textbook on Engineering Mechanics where a woman's body is considered to be an inert mass, as shown in the figure on the right.



A woman standing on a beam



Real person standing on a beam

A test conducted for a similar situation as shown in the figure on the left found that *a stationary human body acts as a mass-spring-damper rather than as an inert mass in a vibrating environment.*

In order to pass this new knowledge to students, a test rig was built to demonstrate the findings.

The demonstration and observation are summarised:

- Measure the natural frequency of the test rig.
- Add a metal plate on the rig.
- Measure the frequency of the rig with the added plate. (A decreased frequency will be observed as expected)
- Remove the plate and invite a student to stand on the rig.
- Measured the frequency of the rig with the student. (An increased frequency with significantly increased damping will be observed)



A test rig



A grandstand full of spectators

It is valuable that students themselves are part of a demonstration, which can convince them that the human body is not an inert mass.

The demonstration makes students question preconceived ideas, even those mentioned in textbooks, and introduces them to the role of research.

During the experiments students are additionally introduced to methods of making dynamic measurements, acceleration-time histories and frequency spectra.

Students are also shown the applications of the findings:

- Grandstands full of spectators
- Floors used for pop concerts
- Indirect measurement of the natural frequency of a chicken
- Improvement of human comfort in a working environment
- Reduction of human induced structural vibration



A chicken perched on a beam