SEEING AND TOUCHING STRUCTURAL CONCEPTS IN CLASS TEACHING

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This paper describes ways in which structural concepts can be made observable and touchable in class teaching. Physical models are used to illustrate structural concepts in conjunction with related engineering examples and links to appropriate research output. Six illustrative examples are provided in the paper. The approach seems to help students to grasp structural concepts and makes teaching and learning more interactive and interesting.

INTRODUCTION

The understanding of structural concepts is a key objective in the teaching of civil and structural engineering. Today many hand calculations are replaced by the use of computers however the understanding of structural concepts, which often came with hand calculations, cannot be replaced by computers. Alternative means of developing an understanding of structural concepts, so important for good structural design, are thus needed. It is also an understanding of such concepts that allows correct computer modelling and helps to enable checks to be made of the results of computer calculations.

There are often criticisms from the construction industry that graduates tend to place over reliance on the use of computers. Graduates are generally good at using computers but many are unable to judge whether the results obtained from computers are correct. This indicates that students may not be made adequately familiar with basic structural concepts during their university studies.

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The Standing Committee on Structural Safety (SCOSS) has published its twelfth report for the years between 1997 and 1999 [1]. The report provided nine recommendations on general principles and one of these related to the use of computers and university education. It stated that:

Those responsible in universities, the professional engineering institutions and government for the education of engineers and their continuing professional development should provide more guidance on understanding structural behaviour and its modelling for computer analysis, and on avoiding uncritical reliance on computer-generated results.

Feedback from industry and from students also places an emphasis on the significance of understanding basic structural concepts and on the need for developing new ways to illustrate these concepts in class teaching.

It has been observed in class teaching that students show a greater interest in topics which are demonstrated physically than in topics which are explained by words and blackboard/OHP diagrams alone. This paper illustrates how structural concepts can be introduced into class teaching in ways in which they can be seen and touched by using simple physical models.

THE APPROACH

Structural concepts and principles are abstract because they cannot be seen and touched directly. For instance, *force paths* transmit loads from their points of action to structural supports, and *resonance* describes vibration characteristics of a structure. Many students experience difficulties in understanding such concepts. If such concepts and principles could be made more observable and touchable, students would be better able to understand them and would be more attentive in class learning situations.

To enable this, three parallel themes are being followed towards:

- providing a series of simple demonstration models for illustrating structural concepts and principles in conventional class teaching which allow students to gain better understanding;

- providing associated good engineering examples to demonstrate the applications of the structural concepts and principles 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.

Structural concepts that can be physically demonstrated are identified then simple demonstration models to illustrate the concepts, suitable for class use, are made. Whenever possible, students help to design and make these models.

Engineering examples are examined and appropriate designs are selected for showing how related structural concepts can be applied in practice. Bad examples, such as collapses, are equally sought as these often show the consequence of the misunderstanding of structural concepts.

Although research and teaching are undertaken in parallel in universities, links between research output and undergraduate teaching are not always made early enough. Research output, which particularly concerns or illustrates structural concepts, is being converted to forms suitable for linking with simple demonstration models and practical applications for use in class teaching.

Table 1 summarises the contributions of the themes to the six typical examples that are described in the following sections.

Table 1: A Summary of Structural Concepts Illustrated

Structural Concept	Demonstration Model	Practical Examples	Research Input
Equilibrium	yes	yes	
Direct force path	yes	yes	yes
Relation between span and deflection	yes	yes	
Resonance	yes	yes	yes
Structural control	yes	yes	
People and vibration	yes	yes	yes

EQUILIBRIUM

Equilibrium is the most important concept in statics. Whilst students are taught at an early stage how to make use of equilibrium equations it is desirable to show them *how a structure achieves equilibrium and how the concept of equilibrium is used in practice.*

Students are asked to place a ruler to span between two round pens lying on their tables which of course they find easy to do. They are then asked to support the ruler with only one pen. This they struggle to do and the equilibrium achieved can be felt to be unstable.

A further demonstration used is the bottle-plate system shown in Fig.1a. Initially many are surprised that the system, supported on the narrow plate edge, is and feels so stable. Students are asked to explain how the equilibrium is achieved and to draw the free-body diagrams for the bottle-plate system, for the bottle and for the plate.

The concept of equilibrium is widely used in engineering practice and an example students can see and experience is the balanced barrier adjacent to the Department, Fig.1b. The balance weight fixed to the shorter arm allows the barrier to be opened easily. The many tower cranes on and around the campus are also good visual examples of the application of equilibrium.

a) A bottle-plate system

b) A barrier

Fig.1: How equilibrium is achieved

THE DIRECT FORCE PATH

When calculating the displacement of a pin jointed structure (*e.g*. a truss) at the point of application of a unit load, the following equation can be used [2]:

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

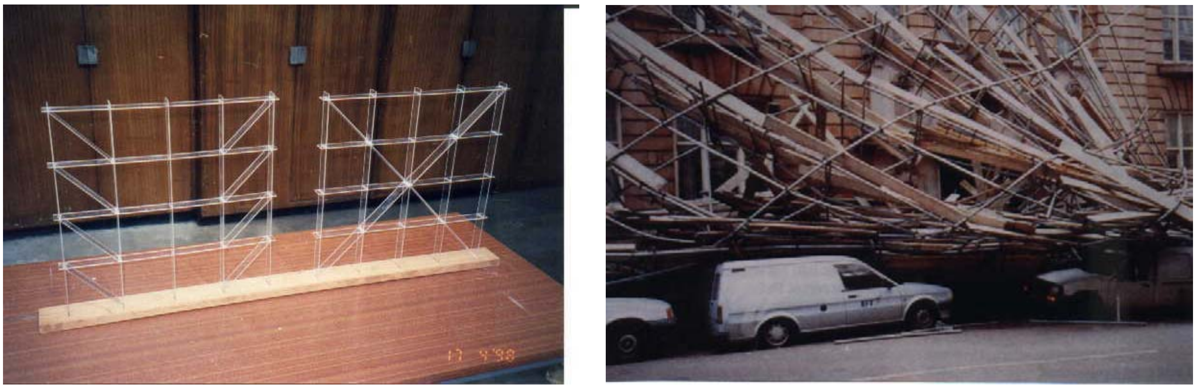
where N_i, L_i, E_i and A_i are the internal force, length, Young's modulus and area of the i th member of the M member structure, respectively. The inverse of this displacement is the stiffness of the structure at the point of application of the unit load. Recent research [3] has shown that two structural concepts can be derived from examination of Eq.1. They are:

- *The more direct the force path, the stiffer the structure.*
- *The more uniform the force distribution, the stiffer the structure.*

These concepts are important in design as an engineer needs to consider how the loads on a structure can be effectively transmitted to its supports before any detailed calculations are made.

In order to demonstrate the first concept, the physical models shown in Fig.2a were built. The two plastic frames have the same dimensions and use the same amount of material, the only difference being in the arrangements of bracing members. Students are asked to push a top end joint of each frame horizontally to feel the stiffness of each frame. They experience that the right frame is much stiffer than the left frame as the stiffness of the right frame is about four times that of the left frame. It is explained to students that the load they applied to the right frame is transmitted to its supports through a direct force path while in the case of the left frame the force path is zigzag.

The practical example shown in Fig.2b 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.



a) The demonstration model b) The collapsed structure

Fig.2 The effect of force paths

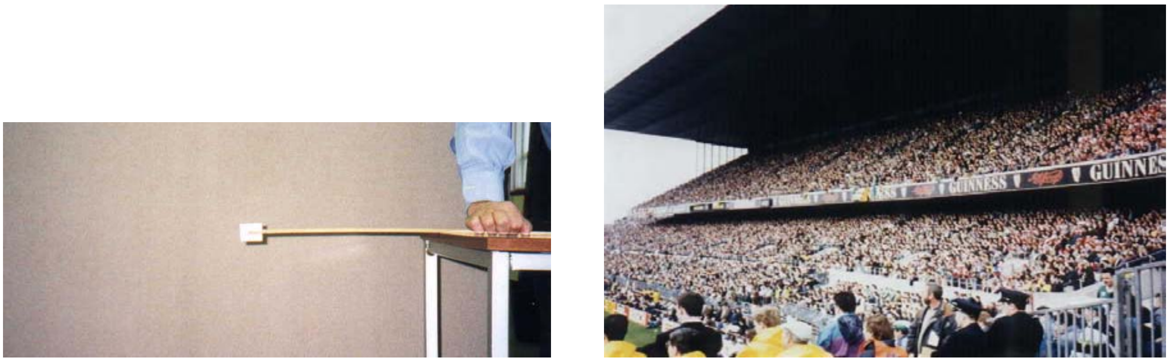
RELATION BETWEEN SPAN AND DEFLECTION

Why can we not build cantilever grandstands, such as that shown in Fig.3b, with longer spans that would increase seating and service areas without occupying further land? The question is posed to attract the attention of students at the start of a lecture on calculating the deflections of beam members. Students may give different answers and are then told that the answer and demonstrations will be provided during the lecture.

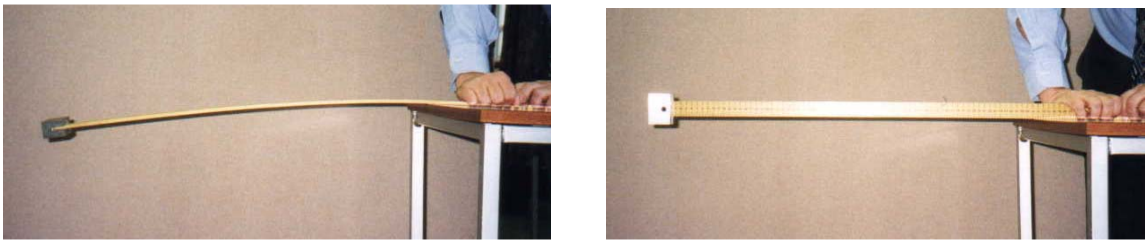
Students are shown how to derive the following formulae [2] for the maximum deflections of a cantilever carrying a point load at its free end (Eq.2a) or a uniformly distributed load (Eq.2b):

$$\Delta = \frac{PL^3}{3EI} \quad (a) \qquad \Delta = \frac{qL^4}{8EI} \quad (b) \qquad (2)$$

Eq.2a indicates that *if the span of the cantilever is doubled then its maximum deflection will be multiplied by a factor of eight*. This effect is demonstrated simply with a 1-metre wood ruler that has a weight attached to its free end. First students observe the displacement at the free end of the cantilever with a span of 350mm (Fig.3a) and then see a much larger end displacement when the span becomes 700mm (Fig.3c). Although no measurements may be taken in the class, students are able to see the significance of span in the relationship shown in Eq.2a. and they are also able to feel how the flexibility (*inverse of stiffness*) of the cantilever increases with span.



a) The deflection of a cantilever (1) b) A grandstand full of spectators



c) The deflection of a cantilever (2) d) The deflection of a cantilever (3)

Fig.3: The Relationship between span and deflection

If the ruler is then turned through 90 degrees about its longitudinal axis, the second moment of area will be enlarged $(h/b)^2$ times and correspondingly the deflection reduces significantly as shown in Fig.3d. This demonstrates that *an increase in the depth of the cantilever is more effective than an increase in its width to reduce deflections.*

It is pointed out to students that the relationship between deflection and span is more exaggerated for a cantilever carrying distributed load as indicated by Eq.2b. *For a cantilever carrying a uniformly distributed load, its end deflection is proportional to span to the power of four, i.e. if the span increases by say only 10%, the deflection will increase by 46%.*

RESONANCE

Resonance is an important concept in vibration. Students are introduced to the concept in their pre-university studies but many have not 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 dance frequencies matches a natural frequency of the structure [4]. A video, based on an actual research investigation, is first shown to students in which fewer than 20 individuals jumped up and down in a large grandstand following a given music beat. Even though the beat frequency was slightly different to a natural frequency, excessive vibration of the grandstand is apparent.

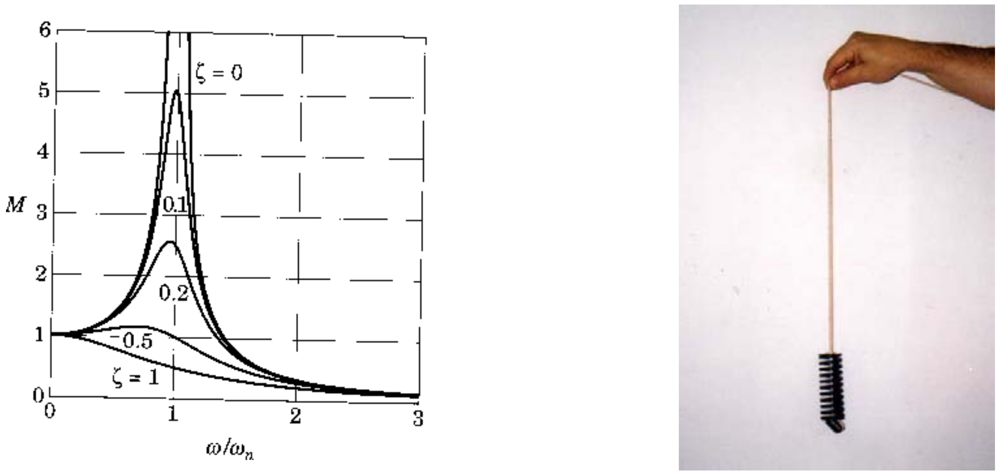
Theory familiar to most students shows that for a SDOF system subject to a harmonic load the dynamic magnification factor for the system, defined as the ratio of the maximum dynamic displacement to the maximum static displacement, is [5]:

$$M = \frac{\Delta_d}{\Delta_s} = \frac{1}{\sqrt{(1-\beta^2)^2 + (2\zeta\beta)^2}} \tag{3}$$

where β is the ratio of the load (or base movement) frequency to the system natural frequency and ζ is the critical damping. The variation in dynamic magnification factor with β, shown in Fig.4a, indicates that:

- *when the load frequency is less than a quarter of the structure natural frequency, dynamic displacements are close to the static displacement,*
- *when the load frequency is more than twice the structure natural frequency, dynamic displacements are much less than the static displacement,*
- *when the load frequency is equal to the structure natural frequency, resonance will occur and dynamic displacements can be many times the static displacement.*

These theoretical predictions can be conceptually demonstrated and experienced with a simple model comprising an elastic string and a weight, which form the SDOF system shown in Fig.4b.



a) The magnification factor

b) A SDOF system

Fig.4: The dynamic magnification and resonance

The person holding the string first moves his/her hand slowly up-and-down which creates a movement of the mass almost the same as the hand movement. When the hand is moved quickly up-and-down, the hand movement is much larger than the movement of the mass. Finally, when the hand moves up-and-down at a frequency close to the natural frequency of the system, resonance develops and the movement of the mass is much larger than that of the hand.

STRUCTURAL CONTROL

Structural control is a means of improving structural behaviour and reducing structural response. It may be passive, requiring no energy input, or active, requiring energy input [6]. Passive structural control has been used successfully in many structures.

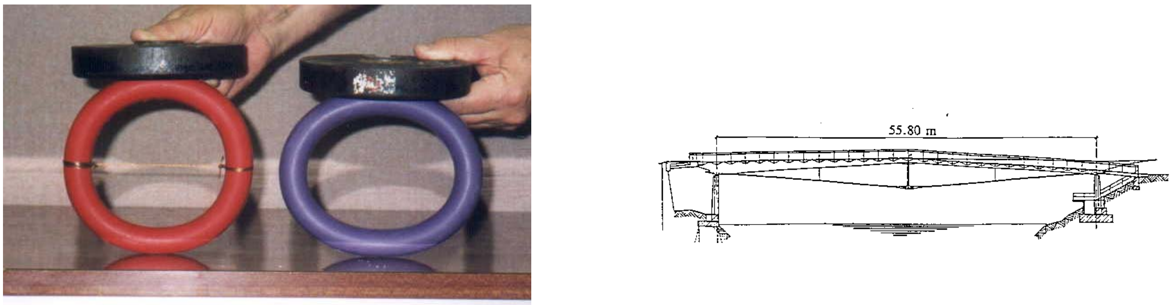
The concept of structural control involves the incorporation of a device within a structural system that may offset some of the effects of external loads or may balance some of the internal forces before the forces are transmitted to the structural supports.

Passive structural control is demonstrated in a simple manner with two rubber rings as shown in Fig.5a. A wire is tied across a diameter of one of the rings.

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 felt.

It is explained that the force in the wire increases as the applied load increases, and produces a bending moment in the ring in the opposite direction to the bending moment caused by the external load. In this way, the wire balances some of the internal forces and reduces the response of the ring. The material used in the wire to create this structural control is negligible compared to the material used in the original system.

A bridge that uses the concept demonstrated with the rubber rings is shown in Fig.5b.



a) Deformation of two rings

b) A bridge

Fig.5: Passive structural control

PEOPLE AND VIBRATION

The natural frequency of a single degree of freedom system is fundamental in dynamics and as most students would know is calculated from the mass and stiffness of the system. Inert systems are relatively easy to deal with but it is less clear how to determine the natural frequencies of systems in which the masses are due to human beings. The human body is in fact traditionally considered as an inert mass. For example, the following question is taken from a well known textbook on Mechanics [5]:

> A 55-kg woman stands in the centre of an end-supported beam (Fig.6a) and causes a mid-span deflection of 22mm. If she flexes her knee slightly in

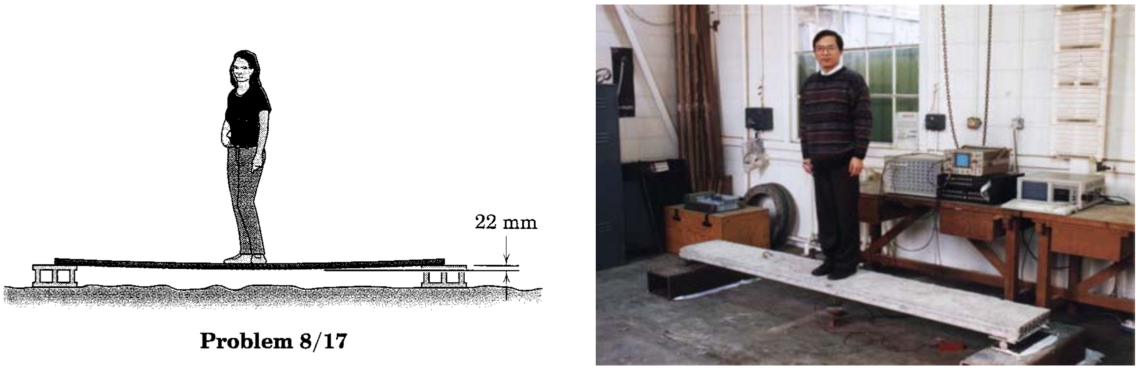
order to cause a vertical vibration, what is the frequency of the motion? Assume elastic response of the beam and neglect its relatively small mass.

To obtain the answer given in the book, the frequency of the human-beam system is worked out as follows:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{mg}{\Delta}\frac{1}{m}} = \frac{1}{2\pi}\sqrt{\frac{g}{\Delta}} = \frac{1}{2\pi}\sqrt{\frac{9810}{22}} = 3.36Hz \tag{4}$$

i.e. the woman's body is considered to be an inert mass. However recent research [6] indicated that *a stationary human body acts as a mass-spring-damper rather than an inert mass in a vibrating environment.*

To demonstrate the concept, the natural frequency of a test rig is first measured. The rig is loaded with a steel plate of known mass and the frequency re-measured. Students observe *a decreased frequency due to the added mass*. The plate is then removed and replaced by a student and the natural frequency is again measured showing *an increased frequency and significantly increased damping due to the inclusion of a person*. The experiment is repeated with several students to establish the concept. Associated research work has been carried out with a concrete beam replacing the test rig as shown in Fig.6b.



a) Woman standing on a beam   b) Real person standing on a beam

Fig.6: People and vibration

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.

CONCLUSIONS

The approach described in this paper has been found to help students to grasp structural concepts and to understand better how structural concepts can be applied in engineering practice. The use of simple demonstrations in lectures, which enable students to actually feel what is happening, has been found to make them more receptive to the presentation of theory. The demonstrations, in breaking up the delivery of theory, tend to lighten the atmosphere and this seems to result in better overall concentration.

ACKNOWLEDGEMENT

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