# VISUALISATION TEACHING OF ENGINEERING MECHANICS CONCEPTS AND STRUCTURAL DESIGN

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## ABSTRACT

The present paper shows some basic demonstration models used in the visualisation teaching of engineering mechanics and structural design for different engineering program undergraduates. A series of engineering examples using either computational conceptual illustrations or physical models including more complicated 3-D models will be provided. The main initiative is to integrate the physical with the computational through a mix of models and well chosen computer visualisation. The aim is to help students to understand the main concepts in engineering mechanics and structural design at various undergraduate programmes.

**Keywords:** Visualisation teaching; Engineering mechanics; Computer aided teaching; Civil engineering; Educational pedagogy

## INTRODUCTION

The understanding of engineering mechanics concepts is one of the key objectives for engineering undergraduate teaching particularly in civil and construction engineering. In the Manchester Centre for Civil and Construction Engineering, it has become more and more prominent as problem-based learning (PBL) and student-centred learning (Murray, 2002) have been introduced and discussed. Students need prior experience of basic mechanics knowledge and concepts when embarking some structural design or project-related courses. In the past some of this understanding has been developed through coursework practice with hand calculation, but now such practice and hand calculation are being replaced by new learning methods and the use of computers. Hence, a compatible method of gaining an understanding of mechanics concepts is very much needed to provide the structural intuition which solely computer based analyses lack (Diana,1999).

## RATIONALE

In civil engineering, engineering mechanics concepts are closely associated with structural design and some project-related courses. It has been observed in class teaching that students show a greater interest in topics which can be visualised and demonstrated physically than those explained by words and blackboard/OHP diagrams. Generally, engineering mechanics concepts and structural design can be illustrated at three levels depending on the requirement for the students of different programs, that is:

*Level 1*, element or member level, one-dimensional or simple 2D structural members such as beams, rods, shafts, thin plates (main concepts include stiffness, strength, stability, properties of cross-sectional area);

*Level 2*, simple structure level, mostly combined 2D structures such as frames, trusses, etc. (topics in mechanics and structural design are mainly deformation, displacement, effect of loading, support and joints);

*Level 3*, complicated structure level, 3D and general engineering structures or projects (optimal design, global stability, pre-stressing are the main topics concerned).

It should be noted that a clear classification of different structural mechanics concepts is impossible and unnecessary. The above level classification is for the convenience of the illustration of the different structural mechanics concepts which are associated with the main topics of the different levels of undergraduate teaching. Some topics such as strength, stability etc., are common issues in all levels but the emphasis of the illustration is different. Detailed visualisation methods for the three levels of conceptual illustrations are given in the following chapter.

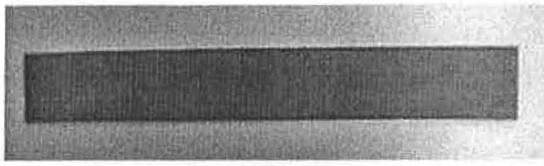
## METHODOLOGY

### Level 1

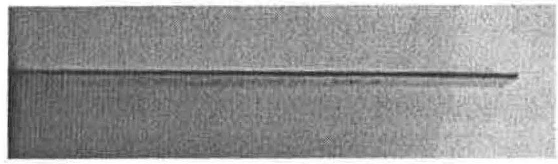
Here emphasis is on the basic principles of engineering mechanics, concepts of strength and stability. Combined with theoretical teaching, corresponding physical models are needed. Because the problem is relative simple, illustration is mainly conducted by these physical models directly.

### Stability and buckling

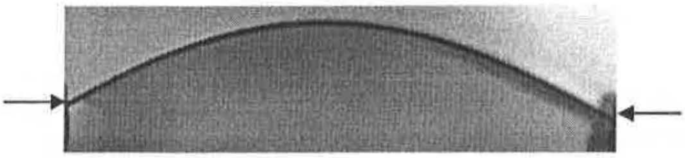
An example is fig.1 which shows a model which demonstrates the concept of compression stability and buckling. Fig.1a is a rectangular cross-sectional specimen. The compressive forces equilibrate in axial direction. When forces are smaller than certain values, the specimen keeps its original straight configuration (stable, fig.1b)). Once the forces reach the critical values, it will deform excessively under small changes in force (buckling, fig.1c)). Every student can experience and observe such a phenomenon. The specimen always bends with respect to a cross-sectional axis, in which the second moment of cross-sectional area has the minimum value.



(a) plane view of the specimen



(b) side view of the specimen



(c) buckling due to compression

*Fig.1 Compressive stability and buckling*

**ACCORDING TO THE EULER BUCKLING FORMULATION, THE CRITICAL BUCKLING FORCE IS**

$$P_{cr} = \frac{\pi^2 EI}{(\mu l)^2} \tag{1}$$

Where $\mu$ is called coefficient of length, which reflected the influence of support at the ends. $EI$ is the stiffness of bending and $I$ is the second moment of cross-sectional area, $l$ the length of the specimen.

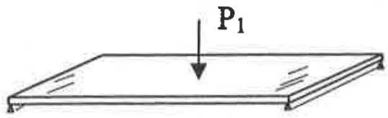
Assume the constraints in the ends are same in all directions, the smaller the $I$, the less the critical force $P_{cr}$. Our colleagues have done some demonstration modelling work in stiffness and properties of cross-sectional area, etc. Interested readers can refer to Ji and Bell (2000).

## Strength

Classic strength theory states that failure load (force) of a structural member is proportional to the product of the equivalent stress $\sigma_e$ (based on criterion of maximum tensile stress, maximum tensile strain, maximum shear stress or maximum strain energy) and its applied area. For a member of cross-sectional area $A$, its failure load is given by (Gere and Timoshenko,1991)

$$P = A\sigma_e \tag{2}$$

which can be proved by loading capacity of any elastic members (string, spring, thread, rod, etc). Students have very little problem with such strength concepts. A piece of glass plate, however, provides students a chance to re-think the definition of strength. Fig.2a is a simply supported thin glass plate while Fig.2b is the same glass plate with a very tiny through cut in the bottom surface of the plate. The loading capacity of the latter is much smaller than that of the glass plate shown in Fig.2a ($P_2 << P_1$). This phenomenon cannot be explained by the classic strength theory and equation (2) because the difference between the effective cross-sectional areas in both cases is negligible.



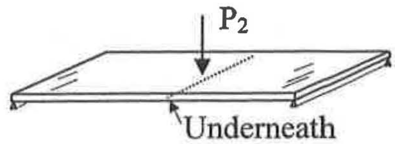




*Fig.2a A simply supported glass plate* *Fig.2b A glass plate with a fine cut*

Actually, students have already touched upon the innovation strength concept in fracture mechanics. Using this simple demonstration model, they gain and keep such an idea which cannot be obtained from computer simulation.

**St. Venant's principle and limitation**

*St. Venant*'s principle states that under two statically equivalent force systems, the stress distributions far from the loading points are the same. In a single system with forces in static equilibrium, there is no stress influence outside the range of the applied forces. The concept can be illustrated by either a unidirectional rod loaded under the self-equilibrium forces (Fig.3a) or a long wire specimen cut by pliers or scissors (Fig.3b).

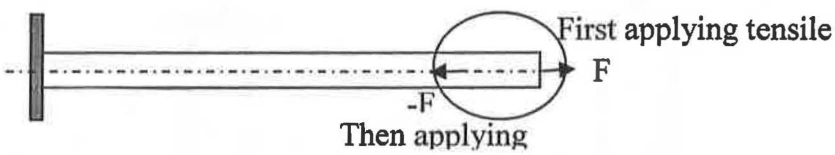



*Fig.3a Unidirectional rod loaded under the self-equilibrium forces*

In Fig.3a, the stress outside the circled area of the rod is zero and support *O* can be removed.

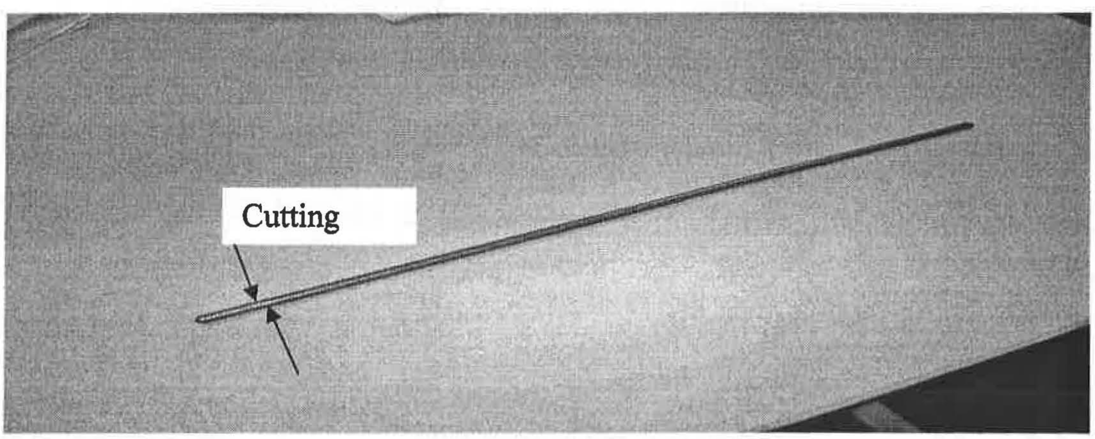



*Fig.3b A wire specimen under the self-equilibrating shearing (cutting) forces*

For the demonstration in Fig.3b, there is no stress at all at one end of the wire while it is being cut off in the other end.

Of course, *St. Venant's* principle has its limitations which can be demonstrated by a thin-walled structure (Fig.3c) under a self-equilibrating force system at one end as shown. Detailed description of this concept and principle is beyond the requirement of Level 1.

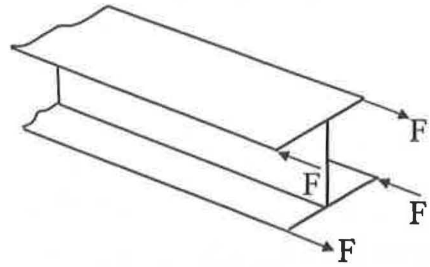
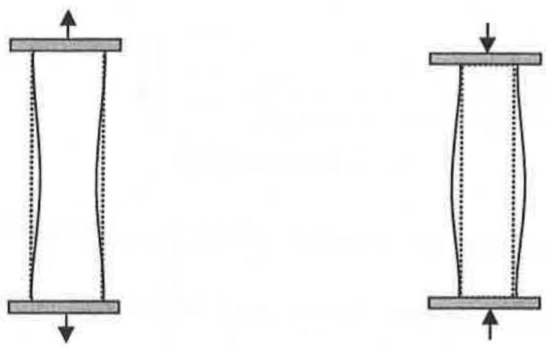



*Fig.3c Not applicable for St. Venant's principle*

**Engineering strain and Poisson's ratio**

Generally, a grid rubber or sponge beam specimen is used to illustrate the concepts of strain and Poisson's ratio. The deformation of the specimen for the demonstration, however, is not always uniform due to stress concentrations or the influence of support (boundary condition). Fig.4 is shown the schematics of tension (Fig. 4a) and compression (Fig.4b) deformations of a model.



(a) tension (b) compression

*Fig.4 Deformation of a uniform straight beam*

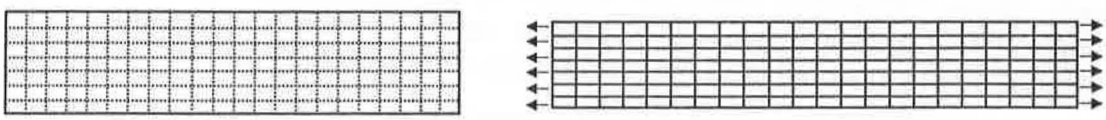
The students think that the engineering strain is variable in the specimen (which is true). Since the Poisson's ratio is defined by the ratio of transverse strain to the longitudinal strain if the loading is applied in the longitudinal direction, i.e.,

$$\nu = | \varepsilon_T / \varepsilon_L | \quad , \qquad (3)$$

it seems as if Poisson's ratio might not be a constant. The misunderstanding is due to an inappropriate model demonstration and boundary constraints. This problem can be resolved in level 2 demonstrations.

**Level 2**

Considering the knowledge, skill and the higher cost required in making physical models for this level and the difficulty in realising the practical boundary conditions as shown in Fig.4, a computational modelling technique will be mainly used for this level demonstration. Considering again the problem encountered in Fig.4, a uniform rectangular computational model as shown in Fig. 5a can be used as an alternative. In this case the force can be applied evenly in the end of the model. The Poisson's ratio is proportional to the ratio of the contraction to elongation of the model. It is more likely that students prefer to use a computational model. Currently there are many commercial packages available to do this calculation and demonstration, such as ANSYS, ABQUS, LUSAS, S-Frame Structural Analysis, etc. Most students have an essential skill to deal with the education version of the packages (e.g., ANSYS, LUSAS) after attending a 2-hour lecture and half a day of training in interface and basic commands. Students' literacy in computers and software is far more than expected. The knowledge they have is enough to do computational simulation of some basic concepts which are mainly concerned in Level 2 engineering mechanics teaching.



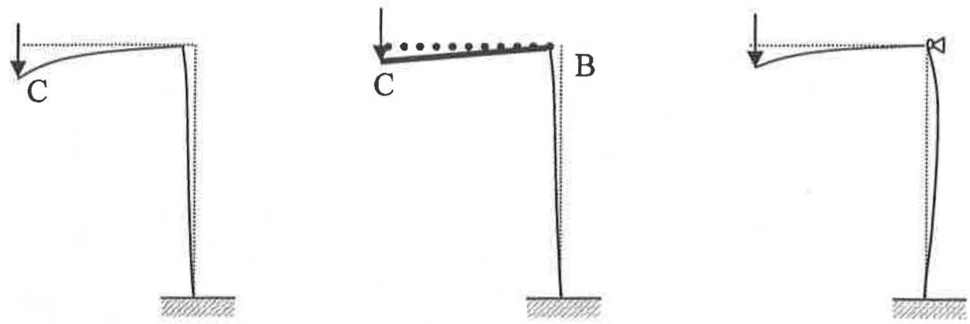
(a) Meshes (b) Deformation

*Fig.5 LUSAS model of uniform beam*

## INFLUENCE OF SUPPORT AND MATERIALS ON DISPLACEMENT OR DEFORMATION

In structural design, maximum displacement or deformation as well as the maximum stress are always concerns. They are, in turn, influenced by the supports, loading (magnitude and position) and material properties of structural members. How to show these effects is one of key issues in our visualisation teaching.

In Fig.6a a frame structure is subjected to a vertical load at point C where displacements have maximum values. Fig.6b shows the influence of different material properties of member BC on the displacements at point C and Fig.6c the effect of different boundary conditions. All the results are given computationally. The advantages of these numerical simulations are not only to supply quantitative analytical results but also to provide a free choice of materials and supports. Furthermore, the effects of external loading and geometric properties of any structural members can also be changed easily. The structural design can make use of these advantages, which can not be provided efficiently in the demonstration of simpler physical models (level 1).

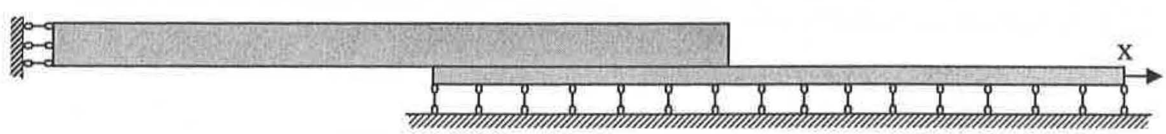



(a) (b) (c)

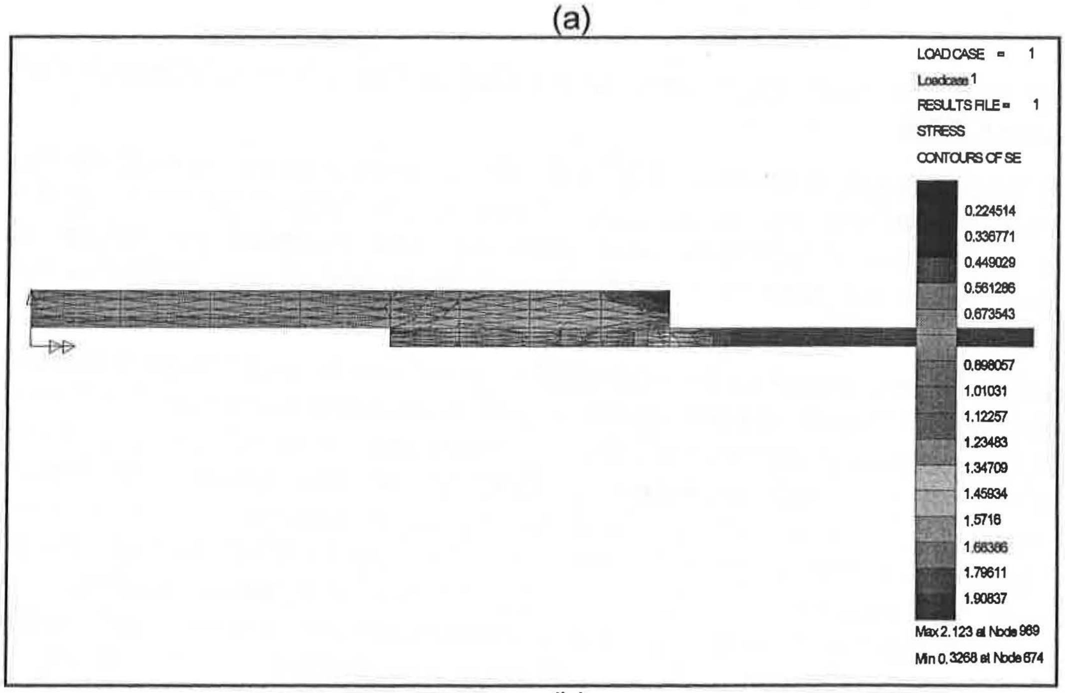
*Fig.6 Frame structure*

**STRESS DISTRIBUTION**

Another visualisation demonstration (computing) in engineering mechanics teaching is to show stress distributions within structural members. For example, Fig.7a is a welded plate structure under a x-direction tensile force at one end in which it is assumed that material of the structure is uniform. The elastic stress distribution within the structure (Fig.7b) by LUSAS clearly shows where the maximum equivalent forces are. Obviously, physical model demonstrations are unable to give this visible stress distribution.




(a)




(b)

*Fig.7 Stress distribution of a combined plate structure*

**Level 3**

In this level, the illustration of mechanics concepts is more profound. Global stability, pre-stressed equilibrium and structure, optimal design etc. are some of important issues to be dealt with in this level. Because the software available (education version) is not suitable to illustrate the current concepts effectively although the undergraduate students' numerical computation abilities are adequate for complicated calculations in this level, our interest again moves back to demonstration with solid models. Some complicated 3D models have had to be built in a special conceptual design course, under the supervision of project investigators. In past year, several groups of civil and structural engineering students have made a few selected 3D physical models of actual structures or buildings. On completion of these models students have understood the functions and structural behaviours of the component parts and their interaction. This is of great help in their subsequent studies and career development. A few examples of visualisation teaching in this level are discussed below.

**GLOBAL STABILITY**

Problem: a combined circle column structure subjected to a compressive load along its axial direction as shown in Fig.8. The diameter of part AB is four times of part BC. Both parts have the same length. Determine the stable behaviour and critical loading P based on the knowledge in level 1.

Before observing this demonstration, most students thought the part BC would first become unstable and that the loading capacity is determined by the Euler formulation of Eqn(1). However, having been asked about the effect of constraints at point B, they then offer a variety of speculations. In fact, it is a global stability problem of a whole column with varying cross-section and the both parts will be unstable simultaneously. After observing this demonstration, students should have more recognition of stability and of the suitable application of Euler formulation.

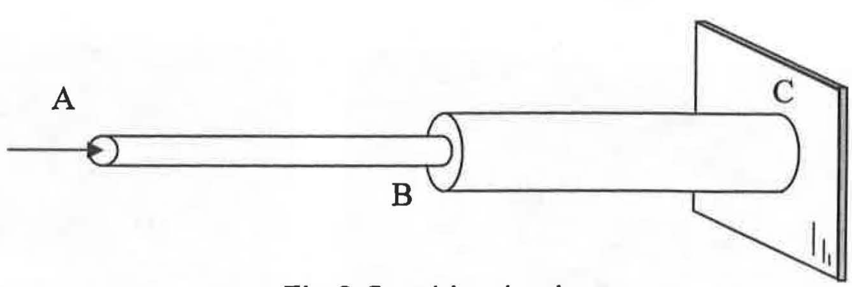
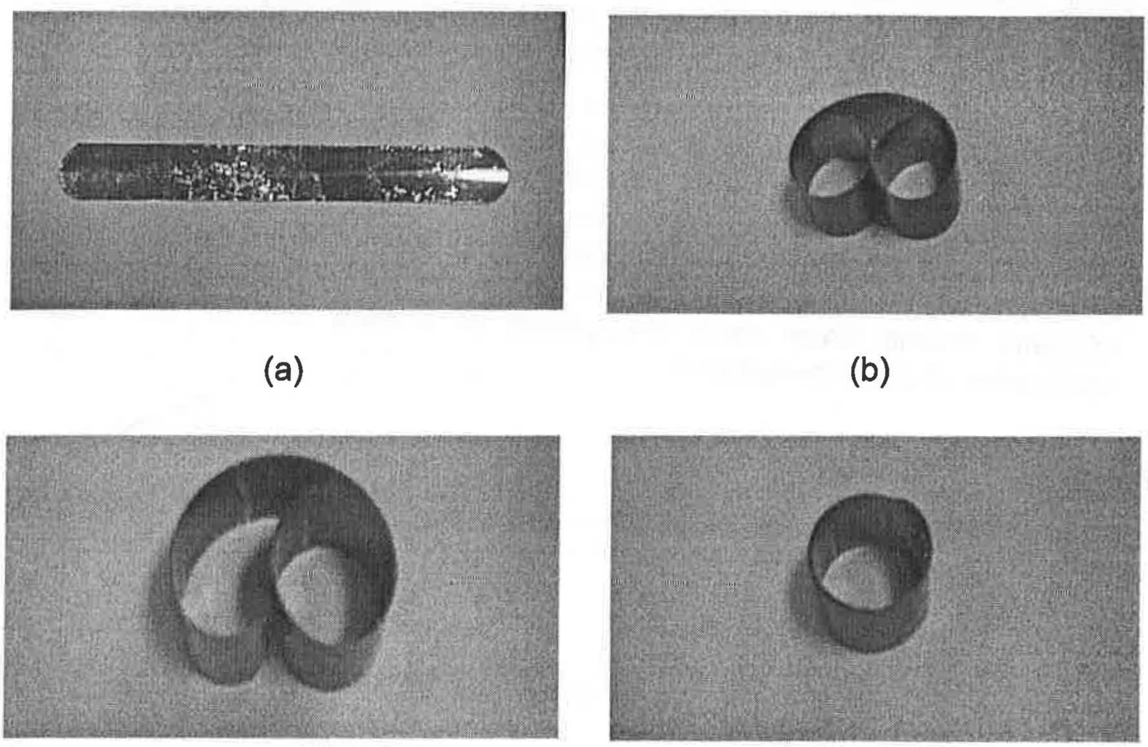



*Fig.8 Combined column*

## PRE-STRESSED STRUCTURES AND EQUILIBRIUM

Pre-stressed structures are one of the major developments in the design of civil engineering structures. How to show the 'prestress' effect in lecture class is indeed a tough problem for our teaching. 'prestress' can improve the stress distribution within a structure to meet the limitations set by material properties. The stress in pre-stressed structure is due to a self-equilibrating internal force system. The equilibrium is random (it may be stable or unstable). Fig. 9a shows a thin beam structure composed of several pre-stressed laminates, in which some layers are in pre-tension in longitudinal direction and some others in transverse direction before bonding them together. The structure does exhibit self-equilibrium but becomes a curved flat shell which indicates that the self-equilibrium is reached in a complicated 3-D stress state. The structure has a strong resistance to the bending in one of the out-of-plane directions but is weak in the opposite direction. Fig. 9b and Fig. 9c show two possible equilibrium states (both unstable) initiated by a random disturbance at the ends of the beam and Fig.9d is a stable equilibrium state for this pre-stressed structure. By this observation, students know more about the functions and effects of 'prestress'. It gives a direct indication that using 'prestress' but with appropriate caution could be a possible choice in some cases of design.



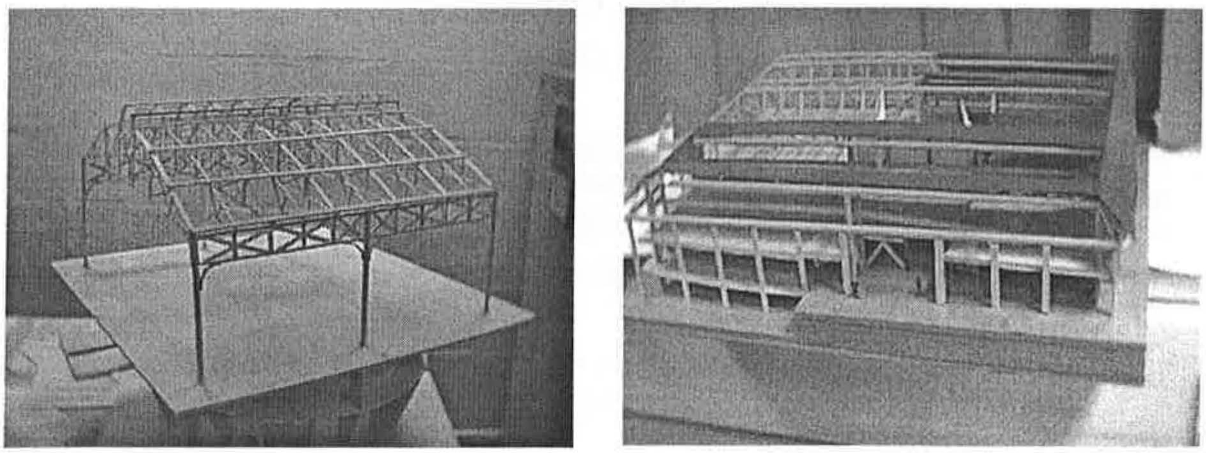
(a) (b)

(c) (d)

*Fig.9 Prestressed Laminated Beam Structure And Its Equilibrium State*

### Structural design and optimisation

Students can be shown these concepts by practical 3-D structural models. Besides layout, scale etc., mechanics concepts and associated issues are always concerned. Fig.10a and Fig.10b are two typical models in our visualisation teaching. Students can not only view the structures but also touch them and feel the reliability of the design. For example, the function of bracing can be convinced easily. From the models in Fig.10, all students can tell and explain the difference of structural rigidities in different directions. It is very convenient to add or remove a structural member to the models. The optimisation issue can be effectively introduced in such demonstration teaching. A very good demonstration model to show the optimal layout of structural members will be soon introduced in our teaching. Here the emphasis is on the overall structural design which can only be showed qualitatively by 3-D models.



(a) (b)

*Fig.10 3-D demonstration models*

## CONCLUSIONS

Manchester Centre for Civil and Construction Engineering has suffered from the consequence of the well-documented national decline in mathematical ability and, more importantly the problems students have in integrating mathematics with mechanics. As problem-based learning (PBL) and student-centred learning have been introduced and discussed in the centre, conventional lecturing closely associated with pure mathematics, such as engineering mechanics, has become progressively less popular among the students. On the other hand, computing and computer-related courses, projects etc., have got more attractive. The current visualisation teaching which gets the students involved, requires certain computing literacy and shows concrete modelling work, is an useful exploration in reinforcing abstract mechanics concepts. The initial response is positive, particularly to the visualisation teaching of level 1 and level 2. The demonstrations reveal consistently the high levels of enthusiasm generated in the students. More demonstration models are required. It is expected that the effect of level 3 visualisation teaching will be reflected in year 3 or year 4 students' project-related courses or design work.

## ACKNOWLEDGEMENTS

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## REFERENCES

Diana Laurillard (1999). Rethinking University Teaching: A framework for the effective use of educational technology. Routledge, London

Gere J M. and Timoshenko S. P. (1991), Mechanics of Materials, Chapman and Hall, London

Ji T. and Bell A. J. (2000), Seeing and touching structural concepts in class teaching, Proceedings of the Conference on Civil Engineering Education in the 21st Century, Southampton, UK, 26-28, April 2000

Ji T (2001), Concepts for Designing Stiffer Structures. Private communication, UMIST

Murry P E. (2002), SLICE Handbook on students-centred learning in construction education. University of Plymouth, May 2002