Images of forces

G. Sandberg Lund University, Lund, Sweden
K-G. Olsson Chalmers University of Technology, Gothenburg, Sweden
M. Lund Architect, Hillerød, Denmark
J. Lindeman Lund University, Lund, Sweden

Abstract

The paper discusses how courses in mechanics can be taught to industrial design students and architectural students in a manner aimed at presenting concepts in such a way that mechanics becomes an inspiration for the design process rather than a limitation to it. In the courses of this sort that have been held, emphasis has been placed on the use of software for facilitating an intuitive understanding of physical matters related to mechanics and how that understanding can be transformed into design sketches. ForcePAD is a comprehensible software for making sketches and investigating patterns in mechanics. Its aim is to enhance the conception of such factors as balance, weight, stability, rest and movement, support forces, stress fields, and deformation. The paper is based on experience with classes of this sort taught both at Chalmers University in Gothenburg and at Lund University, the weekly tasks students have been given in courses of this type being discussed.

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Introduction

Within industrial design and architecture the structural properties arrived at in the buildings and objects produced are often a consequence primarily of artistic intuition, of strict topology or use of readymade solutions. Their function however is often to carry a load. The aim of teaching should be to make the pattern of abstract forces involved both inspiring and readily accessible to the student of design so that the structure, rather than simply being a functional necessity, provides an image of forces.

Both Mechanics and Structural Mechanics introduce abstract symbols, conceptions and contexts, such as those of forces, mass, equilibrium, friction, centre of gravity, stability, tension, compression, and fracture, to mention but a few. Conceptions of this sort, which provide a means of better understanding the action of structures, are a consequence of the science paradigm, being based on objective qualities that are independent of our subjective interpretation of them. Courses here have the immediate practical goal, of course, of providing the understanding and the tools needed for the designing of structures. However, courses should also be taught in such a way that they become a source of inspiration in matters pertaining to design. Although the conceptions of mechanics are abstract, they relate to our understanding of how constructions form a well-functional structural system. It is also one of the great strengths of mechanics that both the conception and context exist in physical shapes, mechanics allowing us to experiment with materials and shapes so as to create the basis for an intuitive interpretation of the abstract content of the conceptions. We readily understand what is heavy, light, stable, in equilibrium or seems to be out of balance, or when the structure seems to be at the boundary of what it can withstand in term of exterior forces. The abstract, absolute thinking of science is related to our intuitive understanding since it takes as its reference the world around us, which we can observe and interpret in everyday life. Since the abstract ideas of mechanics exist in the form of physical shapes or are related to these, students can be trained to use them as sources of inspiration in design tasks and in preliminary sketches for these.

The context of mechanics provides a language, one that constitutes the basis for precision in design experiments. Design tasks can also be coupled to inner abstract ideas, the context of which is not a direct consequence of our immediate interpretation of shapes and is to a considerable degree independent of what our eyes alone can perceive. These experiments in shapes enable both analysis and synthesis to be carried out, an abstract content being transformed into actions by the hand. Thus, mechanics can also provide training in areas where abstract language does not necessarily take on a physical shape; it is serving as a metaphor for how we interpret such non-tangible systems.

In the following, two tasks students were given are described. Brief accounts of discussions with students are presented to indicate how the processes referred to above influenced them and allowed them to use elements of mechanics as a source of inspiration.

Examples - weekly tasks

Life-drawing

The mechanics of rigid bodies provides us only some few parameters by which such bodies can be controlled. In two dimensions, there is the centre of gravity together with three conditions of support. In three dimensions, there is an additional three conditions of support. Can this provide the basis for non-trivial reflections regarding a particular context and for exploiting the precision of scientific methods? If we leave the context that interests us, even in only a very slight way, through becoming so preoccupied by precision that we find ourselves completely within a neutral engineering frame of reference, the physical experiencing of this context and our possibilities of investigating how we perceive it may readily become lost.

This first example starts in our perception and ends with a precise physical aspect of that perception. The volume, the density and the location of a collection of individual elements that possess mass govern the location of the center of gravity in a body or a system of bodies. One of the first exercises in rigid body mechanics that students of architecture at Chalmers University of Technology carry out aims at providing insight into this, and to train students in the use of the principles involved as a means of expression in the designing a building. After a brief introduction concerning the physical concepts of gravity and centre of gravity and use of them as metaphors in painting, students are ready to gain their own experience in such matters. They are given a piece of grey cardboard and a stick of white chalk, as well as a stick of black chalk, and gather around a living model. The goal of the exercise is to express, through use of the concept of centre of gravity, the balance inherent in the model. The white chalk is used to draw two types of abstract entities: a vertical line through the centre of gravity and the support or supports involved. The black chalk is used to indicate the balance around the vertical line through describing and interpreting the volume, the density and the arm movement. Twice during the exercise students are interrupted in their work to take part in a group discussion of how the balance the model demonstrates can be expressed, and how the physical entities involved can be interpreted.

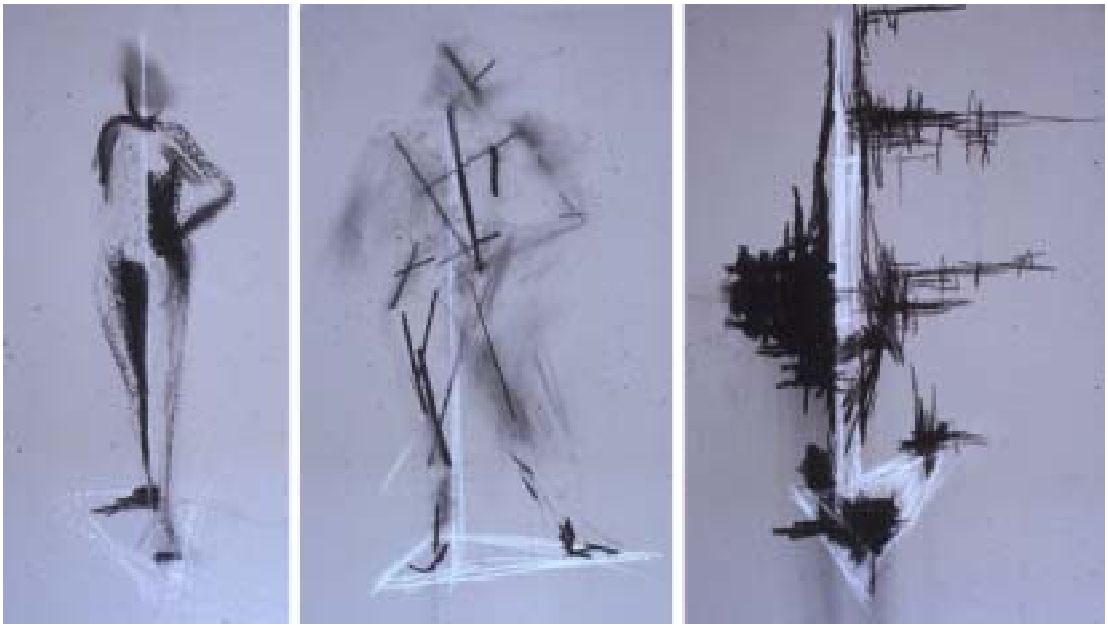

Figure 1: Life drawing with focus on balance around the centre of gravity

The initial instructions are as follows: Use the white piece of chalk to look for the abstract entities, and use the black piece of chalk to examine the balance, either with areas of varying greyscale or with straight lines of varying length. Despite these instructions most students work with outline drawing and assembling a body configuration – not with density, levers, and moments. The discussion after the first intermission takes as a starting-point the difference between instructions and what is done. Most of the students then wipe out their black coal drawing, see the middle drawing above, and start all over.

This part of the exercise deals primarily with reflections on human perception and on physical necessities and principles. Students are asked, so as to strengthen the insights they have gained into the physical appearance of a balanced state, to analyse their drawings and make the center of gravity visible on the computer screen by the use of the computer program ForcePAD. They can also experiment with their drawings by adding or subtracting some particular mass or masses and tracing the consequences this will have on the force-of-gravity arrow, see Figure 2 (a-c) below .

The global equilibrium, which is governed by Newton's second law, requires in the two-dimensional case that three equilibrium equations be fulfilled, two for translation and one for rotation. The direction and magnitude of the reacting forces, if these are statically determinant, are dependent upon the position and direction of the movements that are prevented from occurring.

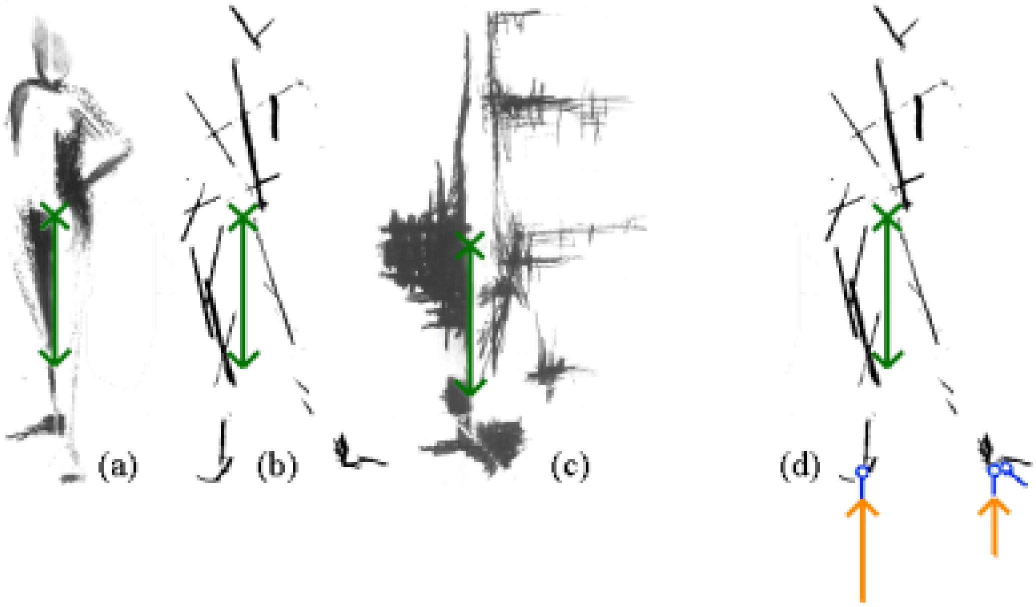

Figure 2: The green arrow shows the computed position of the resulting gravity force. (d) The blue bars indicate the position and direction of support and orange arrows represent the computed reaction forces.

The exercise also aims at enabling students to investigate the physical meaning of a movement's being prevented from occurring. They are to ask themselves what the supports are and what the consequences would be for the reacting forces if the position and/or the direction of a support were changed. On the computer screen, students can also carry out their own experiments in adding support or supports to the human body they have drawn, see Figure 2 (d). The actions and supports that they provide a living model with are to a considerable degree obvious, whereas in the exercises students take part in following this, dealing partly with natural and partly with built objects, they can have greater difficulties in grasping the supports involved and how they act.

The statics of rigid bodies is a small part of classical mechanics and is primarily an extension of Newton's first law. In textbooks on engineering mechanics, this part of the theory usually occupies only a few pages, partly because of the simple mechanism governing it – that of equilibrium – and partly because of the trivial mathematical tools available for solving predefined problems that are presented there. Nevertheless, it is the basis for very essential decisions to be made in the design process, those regarding the contact the body in question is to have with the external environment, requiring that one consider carefully the consequences that different types of contact – involving the position and the directions of the support – would have. Choices made here affect the overall behaviour of the body, including the shape that is optimal, the need of external forces, the size of the forces of contact between the body and the surrounding material, and the like.

A tripod

One task given to first-year students of industrial design at Lund University is described for students as follows:

"Three points are defined in a horizontal plane and form an equal sided triangle. The side length is 1400 mm. A fourth point is defined 600 mm above this plane. At this position in space you shall be able to place an item weighing at least 5 kg. The size of the base area of item is 100×100 mm. The material is corrugated paperboard in sheets of the size 1000×600 mm. You can assemble the material by using glue, staples, or by knitting. But you have to choose only one of these means. The support of the structure must be within a circle with the diameter of 100 mm. The structure will be judged by the way it expresses how the load is carried, including how the load is transmitted from loading position to the support positions in the corners of the triangle. The structure should be as light as possible and a volley ball should be able to roll under it."

The major question for the student to consider here is how the solution arrived at expresses the external load and the path of the internal load, i.e. how the visible structure reflects the stresses present in the material, and how the material is utilized to accommodate these stresses. Students are to make sketches of the design of the structure intended. They are also to present arguments in support of their solution. To illustrate this, consider how two of the students presented and developed their arguments. Their brief sketches are presented in Figure 3 below. The drawing to the left, (a), represents their first suggestion. The basic idea was to have the loading position encircled by the structure. Since large parts of the structure do not contribute to the load-bearing capacity, one can ask whether it is possible both to let their intention of encircling the load be fulfilled and to let each part contribute to supporting the load. Allowing the structural parts to meet above the loading position would be one solution.

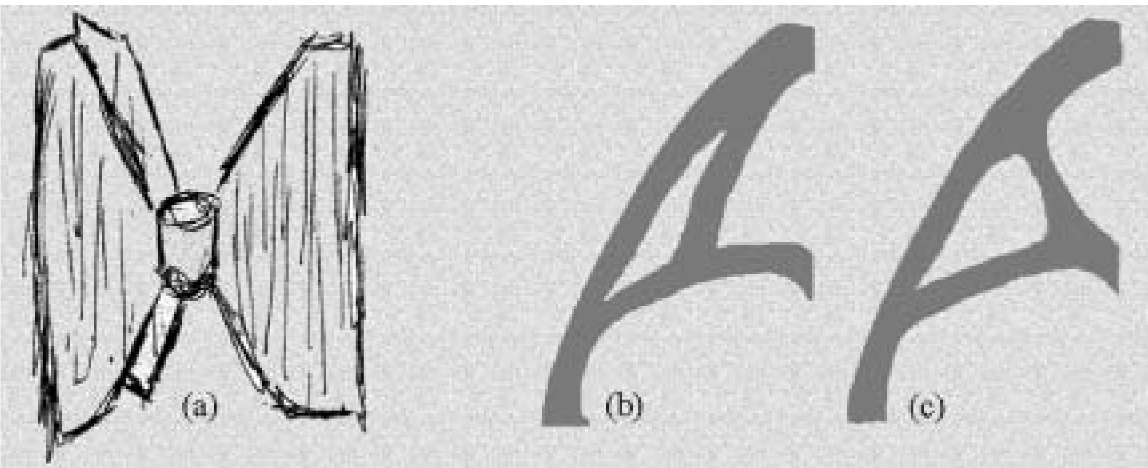

Figure 3: The first suggestion for the tripod that the structure should encircle the load, (a). Two suggestions for one leg of the tripod, (b)-(c)

(b) shows their first proposal along this line, in connection with which they argued for letting all the structural elements have the same visual direction. One could call the three parts involved the long element, the lower element, and the connector. Visual interest in the junction between the connector and the lower element is created here. It is not evident, however, that this is favourable from a structural point of view. Their third proposal is shown to the right, (c). Here the connector shows the flow of forces in the external load instead, interest being directed at where the load is placed. Quick simulations also indicate the flow of the internal forces here to be different.

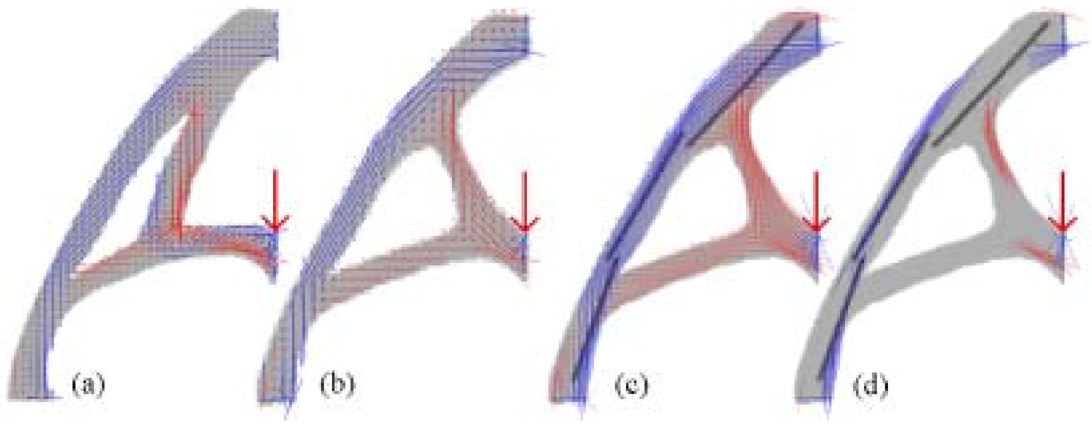

Figure 4: Stresses in one of the legs of the tripod, blue indicates compression and red indicates tension stresses, (a) first attempt, (b) final solution, (c) stiffeners have been attached, and (d) only high levels of stress are shown.

Whereas the proposal at the left in Figure 4, (a), gives rise to an unclear and mixed stress field, the connector and the lower element having both tensile and compressive states, the proposal (b) is better coordinated. The lower element and the connector are both exposed to tensile forces, which of course is favourable (remember, the tripod is constructed of corrugated cardboard). The compression evident in the long element needs to be dealt with by use of additional stiffeners (c-d), which were introduced in the final solution.

The tripod ready for testing is shown in Figure 5. Loads were applied until the structure collapsed. This particular tripod yielded with grace under the ultimate load, its rotating downwards as the legs collapsed. Even after the collapse the solution selected looks interesting, since the failure tells such a clear history, see Figure 6.

Figure 5: The final solution for a load-carrying tripod.

Figure 6: Loading of the structure (left) and the structure as it appeared following failure (right).

One can conclude, on the basis of the results of these brief tasks, that the experiment the students conducted and their discussion of it made them aware of the qualities of the material involved and how these can be used to express and articulate the shape of the structure created and to design and link together its various parts. These qualities are not readily apparent without a tool to make them visible.

Reflections on force and form

An industrial designer picks her pencil and starts drafting. What you expect to see is either a soft sketch grasping the outer shape imagined, or an abstract diagram indicating the inner functional relations and technical interactions. The two different modes of drafted form seldom meet. They represent two diverse paths of specialisation within the profession.

Some industrial designers emphasise the art of giving form to matter. Design is regarded as a semi-free expression of art, "to sculpture with a purpose" or "to mould a complex synthesis into a simple form". Other designers favour the analytical approach. The design process is described in terms like "the problem comes first" or "to solve a problem".

However there is a third way for the designer to practise in between the pure shape moulding or the simple problem solving.

Design is inventing. It is about finding shapes that not only have an interesting appearance but also actually are able to contain certain tangible properties. Streamlining is the classic case. Design is about finding solutions to precisely stated problems too, that results in expressive and original products. The Walkman is such an example.

Designing force-carrying structures is about inventing too. A structure that integrates strong spatial qualities with effective use of its material is second to none. Think about the Gothic cathedrals from eight hundred years ago. The delicate stone ribbons embrace the interior space like fan-shaped laces. They are true minimal structures that should be compared to the most efficient aeroplane construction and yet they allow their space to be penetrated by the light from the sun and the sky and allow their space to be cooled by natural ventilation through the open ribbons.

The seams of vintage yacht sails follow a similar structure. They function as a stiffening reinforcement of the sail to prevent sacking. Today, yacht sails are cast in polyester or similar plastic materials with reinforcement of stiffer textiles placed in the same fan-shapes like the seams in the old sails. And in different products from the simple disposable cardboard cups for lunch break coffee to the most advanced communication satellites in outer space the art of achieving the highest stiffness from the smallest amount of material is the essential challenge for the industrial designer.

The method at hand, using ForcePAD, gives the inventive industrial designer an efficient tool to obtain immediate feedback from her sketches, when structural efficiency is of main concern. The feedback of ForcePAD is a two dimensional grid-map where the direction and intensity of the highest stresses suggest a structural pattern where material could be condensed in order to obtain most stiffness. The method is not a magic box, and there are no automatic solutions. The classic image of the stress trajectories from Carl Cullman's grafic-statics from the 1860s only suggest and never define the optimal material efficient structure. And the contemporary computer algorithms that robotically design the most efficient structure do not invite dialogue in the model-man interface. However with the open structure of ForcePAD the industrial designer has a chance to impose her other constraints and play with the possibilities in the design process. And step-by-step the designer builds an experience by herself that enables her to integrate structural shapes with efficient force carrying abilities, with forms and spaces that are both interesting and expressive.

ForcePAD

ForcePAD is an educational software programme developed at the Division of Structural Mechanics at Lund University in collaboration with the Division of Building Design at Chalmers. Although it was conceived for use by students of industrial design and architecture, we believe it can be useful for other categories of students as well, due to its unique features. ForcePAD deals with a variety of different matters of physical character within the area of mechanics, such as the centre of gravity, loads, support reactions, deformation, and internal stresses.

A unique feature of it is its simple interface, which clearly mirrors the physical constituents involved. The interface mimics the conditions that sketching on a sheet of paper represents. The immediate consequences of adding material or a line or removing material by scratching, in terms of changes in form, adds to the simplicity of working with it, allowing ForcePAD to become an intimate part of design sketching in an educational context. Our experience with it is that it supports in a very genuine way a reflective process on the part of the user, providing both insight and inspiration in forming materials into shapes for creative and constructive ends. The programme supports an iterative process of reflective optimisation that the user is guided through, rather than its being software for simply an automatic optimization of shapes. Despite its not being software for advanced mechanical analysis, hidden within it are in fact some advanced finite element tools having optimizing characteristics computationally.

The figure below shows the interface. Through moving the cursor across the screen one can build up the shape desired. The grey scale is the metaphor for the amount of material or the stiffness. By adding support conditions and forces the student can launch computations that provide information about the internal stresses and deformation patterns. It is simple also to scan a picture or a drawing and paste it in on the ForcePAD working screen.

The ForcePAD application is implemented by use of a single-document interface (SDI). Thus, only one document or model can be opened at any given time, reducing the complexity of the interface. To make the interface as direct and as easy to use as possible, it was decided to remove the pull-down menus found in most standard applications. Instead, toolbars with large and multicoloured icons are employed. The left toolbar contains tools for creating and modifying the model, whereas the right one contains archive and cut-and-paste functions. The visualisation of displacements and stresses is controlled by use of a tabbed property page at the bottom of the window.

ForcePAD is implemented in C++. User-interface components are implemented by use of the FLTK 1.1.x library [1]. OpenGL [2] is used to implement ForcePAD's 2D drawing functions. OpenGL is a software interface to 2D and 3D hardware which enables the direct and rapid visualisation of displacements and stresses to be performed.

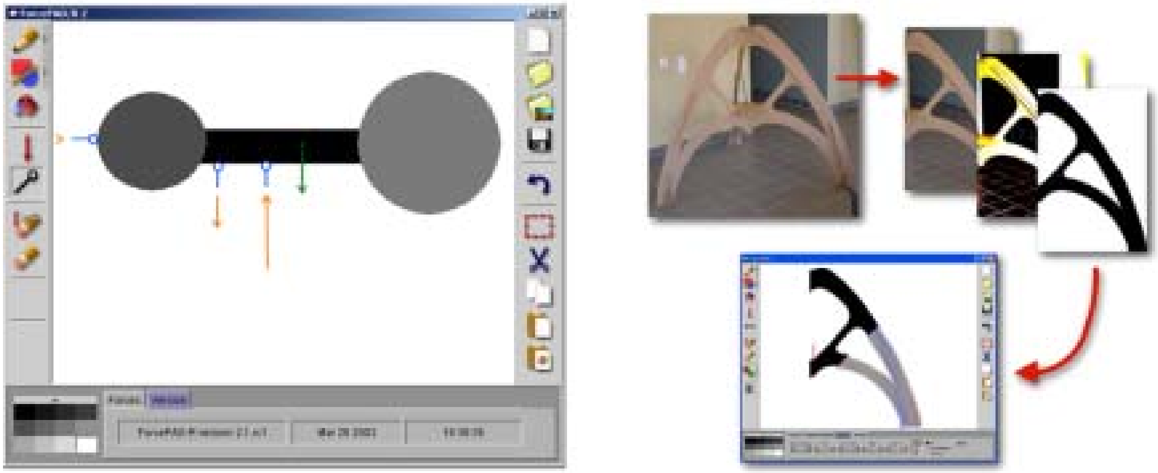

Figure 7: The transition from a physical object to a photo or sketch that is pasted in on the ForcePAD-window so as to display the object's non-tangible qualities.

References

[1] Fast Light Toolkit, http://www.fltk.org, 2002

[2] OpenGL, http://www.opengl.org, 2002

[3] The homepage of ForcePAD
http://www.byggmek.lth.se/bmresources/forcepad/forcepad.htm