AN APPROACH TO TEACHING ARCHITECTURAL AND ENGINEERING STUDENTS UTILIZING COMPUTATIONAL MECHANICS SOFTWARE FORCEPAD

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SUMMARY: The paper discusses how courses in mechanics can be taught to architectural students in such a way that concepts are presented to them in a manner making mechanics an inspiration for the designing process rather than simply imposing limitations on it. In courses of this sort that have been held, emphasis has been placed on the use of software to facilitate an intuitive understanding of physical relationships in the area of mechanics, as well as on transforming such an understanding into design sketches. ForcePAD, a readily comprehensible software package of this sort developed for making schematic 2D sketches and investigating different patterns in the area of mechanics, is presented. Originally, it was developed as a tool for providing a basic introduction to mechanics for students of civil engineering. The package aims at enhancing an understanding of such factors as balance, weight, stability, rest and movement, support forces, stress fields, and deformation. The paper is based on experience with classes taught both at Lund University and at Chalmers University in Gothenburg that have made use of this package (Olsson, 2003). The types of weekly tasks students have been given, as well as how the educational conceptions utilized in these courses have influenced the design of the ForcePad software, are discussed.

KEYWORDS: teaching, mechanics, software, ForcePAD.

1. INTRODUCTION

Designing is to invent. It concerns the finding of shapes that not only are interesting in appearance but also possess certain tangible properties. Designing force-carrying structures is no exception to this. A structure that integrates strong spatial qualities with effective use of material is second to none.

Teaching mechanics to design students involves providing them the ability to go on from investigating specific properties to active articulation and expression of ideas in design, from inner structure to outer contour. The means of achieving this include simple sketching, together with rapid actions and responses aimed at investigating an object's mechanical properties such as those of contour deformation, and the forces and force fields involved.

In industrial design and architecture, the structural properties arrived at in the buildings and objects produced are often a consequence primarily of artistic intuition, or of the use of strict topology or of readymade solutions. The concrete function of the structures produced, however, is often to carry a load. The aim in teaching in this area should be to make the pattern of abstract forces involved both inspiring and readily accessible to the student of design. This allows the structure to be more than simply a functional necessity but to also provide an image of the forces that are present.

Courses in mechanics have the immediate practical goal here of providing both the understanding and the tools needed for the designing of structures. Courses should also be taught in such a way, however, that they become a source of inspiration in matters of design. Although the conceptions of mechanics are abstract, they contribute to an understanding of how a construction comes to form a well-functioning structural system. One of the great strengths of the use of mechanics here is also that both the conception of a structure and the context in which it is placed have a physical shape. Mechanics allows one to experiment with materials and shapes in creating the basis for an intuitive interpretation of the abstract conceptions of the content which is aimed at and to readily understand what is heavy, light, stable, in equilibrium or seemingly out of balance, or when a structure seems to be at the boundaries of what it can withstand in term of exterior forces. The abstract, absolute thinking of science is likewise 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 the preliminary sketches for these which are made.

A software tool for implementing this will be described, one which supports an iterative design process. This tool uses an image based metaphor making it possible to go from a 2D sketch to a complete 2D finite-element model within the space of only a few minutes, enabling students to make mechanics an integral part of their design work.

2. A SKETCH-BASED APPROACH TO TEACHING MECHANICS

In the following, a task students were given is described. Brief accounts of discussions with students are presented to indicate how the processes referred to above influenced them and allowed them to use various elements of mechanics as a source of inspiration. The software employed in conjunction with such tasks is also used in standard classes in mechanics for providing rapid responses to what the student does and allowing the student to experiment with the basic structural mechanics components.

2.1 A Weekly Task – A Tripod

One task given to first-year students of industrial design at Lund University is presented to them basically as follows, although certain details have been added here to facilitate the reader's understanding of it:

"Imagine three points located on a horizontal plane, such that they form a triangle with sides of equal length, each side being 1400 mm long. Imagine a fourth point located 600 mm above the plane, about in the center of an upward projection of the triangle, and imagine that an object weighing five kg or more and having a base 100 X 100 mm in size is to be supported there. Your task is to create a tripod-like structure able to support such an object at that location. The base of each of the three main structural elements in the tripod, to which the part supporting the object is to be joined, is to rest on an area no larger than 100 mm in diameter located in each case within the confines of the triangle but near the respective corner of it. You will be provided with sheets of corrugated cardboard 1000 X 600 mm in size to use for building the structure. After cutting them to the size and the form you decide upon for creating the different parts, you assemble the parts and join them together by gluing, stapling or sewing them in place, selecting one of these three methods and using it throughout. The structure you build is to be judged on the basis of how effectively it expresses the manner in which the load is supported, including how the force of it is transmitted from the loading position where the object itself rests to the support of the structure as a whole near the corners of the triangle. The structure should be as light as possible and a volley ball should be able to be rolled under it."

The major question for the student to consider is how the solution arrived at expresses the external load and the path of the internal load, i.e. how the visible structure itself 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 they aim at. 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 rough sketches are shown in Fig.1 below. The drawing (a) to the left represents their first suggestion. The basic idea was to have the loading position encircled by the structure. Since large parts of the structure did not contribute to the load-bearing capacity, one could ask whether it was possible both to let their intention of encircling the load be fulfilled and to let each part contribute then to supporting the load. Allowing the structural parts to meet above the loading position is one possible solution.
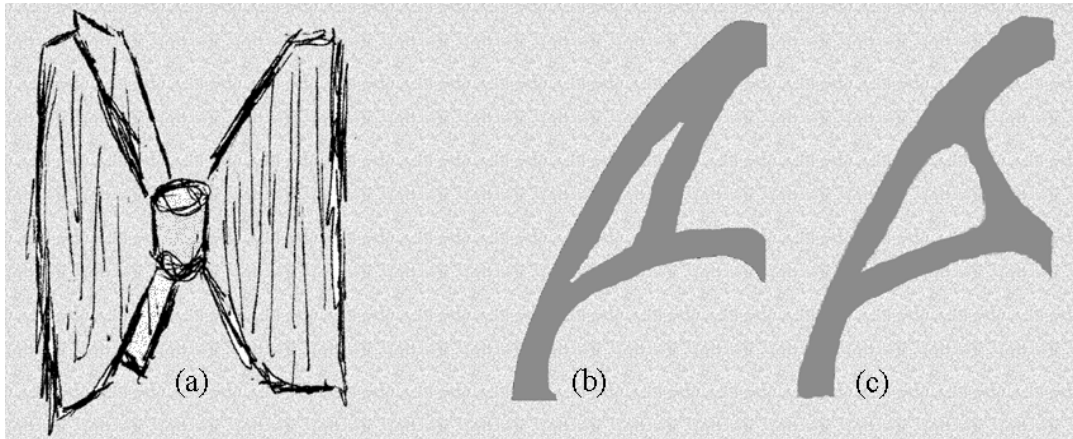
FIG.1: The first suggestion for the tripod, that the structure should encircle the load, (a). Two suggestions for a leg of the tripod, (b)-(c)

(b) Shows their first proposal of this sort, in connection with which they argued for letting all the structural elements have the same visual direction. It was not evident, however, that this was favourable from a structural point of view. Their third proposal is shown in (c) at the right. There, the changes made make the flow of forces within the external load evident, interest being directed at where the load is placed. Quick simulations also indicate the flow of the internal forces here to be different.
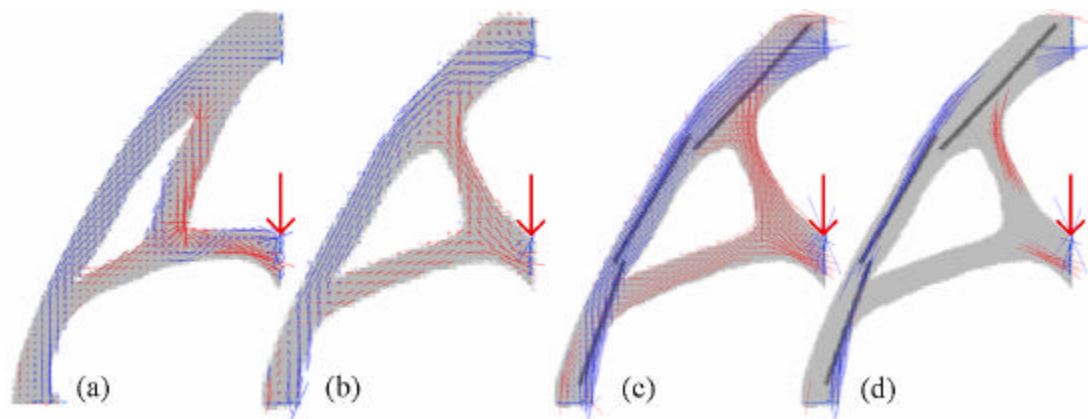

FIG. 2: Stresses in one of the legs of the tripod, blue indicating compression and red indicating tension stresses: (a) the first attempt, (b) the final solution, (c) stiffeners have been attached, and (d) only the particularly high levels of stress are shown.

Whereas proposal (a) at the far left in FIG. produces an unclear and mixed field of stress, both tensile and compressive states being involved, proposal (b) is better coordinated. Two of its parts are exposed to tensile forces, which 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, now ready for testing, is shown in Fig. 3. Loads of increasing size was applied until the structure collapsed. This particular tripod yielded with grace under the ultimate load, rotating downwards as the legs collapsed. Even after its collapse, the solution selected looks interesting, since the failure tells such a clear story, see FIG. .

FIG. 3: Final solution in constructing a load-carrying tripod

FIG. 4: Loading of the structure (left) and the structure as it appeared following failure (right).

As the results taken up briefly here suggest, 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. This is the role which the ForcePAD software plays in this context. While performing a task such as that just described, students are able to use ForcePAD for analysing the forces involved in the structures they design and build.

2.2 Utilization in other courses and disciplines

ForcePAD has also been used successfully in the basic mechanics courses given to civil engineering students. Most such courses focus on teaching students the basic theories of mechanics. This involves considerable amounts of mathematics and hand calculations. Student often concentrate a great deal on theory but fail to see the larger context in which a theory can be applied. ForcePAD is used here as a tool for enhancing the students understanding of theory by providing experimentation and visualisation in a fast and effective way.

3. DESIGN AND IMPLEMENTATION OF FORCEPAD

In designing and in design education, much emphasis is placed on the idea of sketching. A design is never accepted automatically, but rather is iterated over time until a satisfactory solution is found, sketching being used extensively in this process. ForcePAD, see FIG. , was developed as a tool both for enhancing the user's

understanding of mechanical concepts and for its concrete use in the sketching process, particularly in an educational setting.
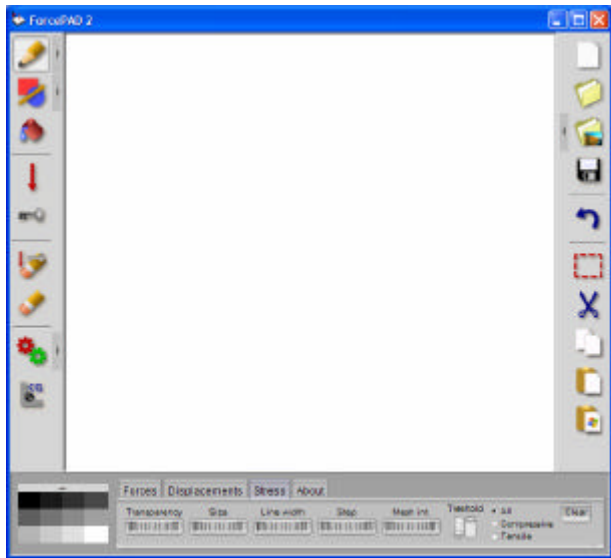

FIG. 5: ForcePAD

The ForcePAD application employs a metaphor similar to the metaphors found in such image editing applications as Adobe Photoshop and Jasc PaintShop Pro. The underlying implementation of ForcePAD is that of a 2D finite element model based on simple triangular plane stress elements, having 2 degrees of freedom at each node. Users don not create elements directly, but first "paint" stiffness onto a screen image. The painting is done, however, not in colour but with use of a grey scale in which white represents zero stiffness and black maximal stiffness. This approach enables ForcePAD to handle different structural properties of materials by allowing variations in stiffness to be utilised in drawing. When calculations are made, the image is transferred to an element grid, which is then solved. The stiffness value for each element in the grid is determined by calculating the number of pixels the element contains, as illustrated in FIG..
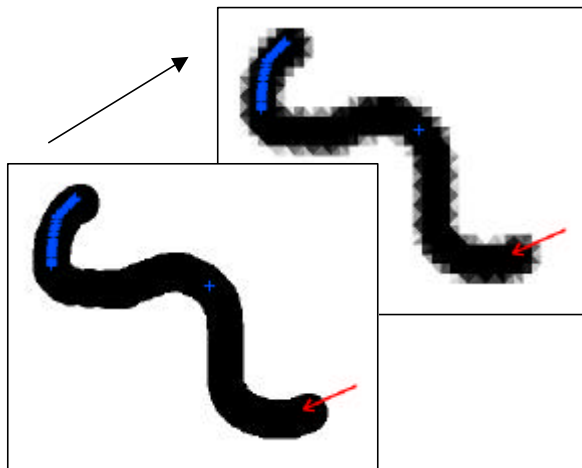

FIG.6: Converting a pixel based image to a finite element grid

Using this approach, a student can take a paper sketch and easily import it into ForcePAD to create a finite element model, no more than a few minutes being required. FIG. illustrates the process of going from a scanned image to a full finite element model. With use of conventional finite element modelling, this process would usually take several hours, which places strong limits on the possibilities of an iterative design process.
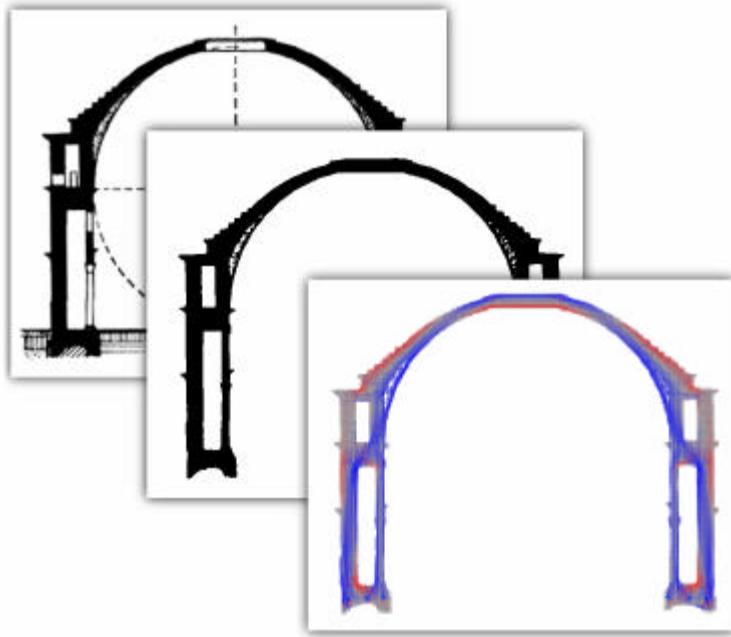
FIG. 7: An example of a design process in ForcePAD

3.1 User interface

The ForcePAD system is designed as a direct manipulation system, which according to (Preece, 1994) has the following properties: visibility of the objects of interest, rapid and reversible, incremental actions, and the replacement of complex command language syntax by direct manipulation of the object of interest.
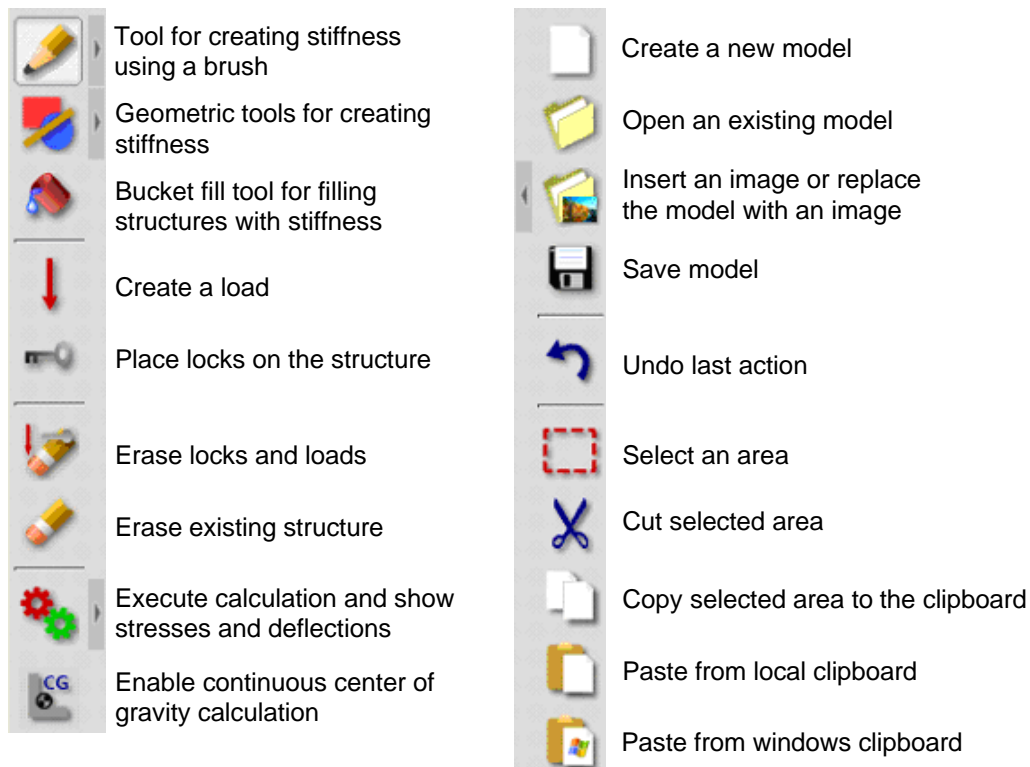
✏️	Tool for creating stiffness using a brush	📄	Create a new model
🟥	Geometric tools for creating stiffness	📁	Open an existing model
🪣	Bucket fill tool for filling structures with stiffness	🖼️	Insert an image or replace the model with an image
↓	Create a load	💾	Save model
🔑	Place locks on the structure	↩️	Undo last action
	Erase locks and loads	⬜	Select an area
✏️	Erase existing structure	✂️	Cut selected area
⚙️	Execute calculation and show stresses and deflections	📄	Copy selected area to the clipboard
CG	Enable continuous center of gravity calculation	📄	Paste from local clipboard
		📄	Paste from windows clipboard

FIG. 8: ForcePAD User interface

ForcePAD's user interface is divided up into three main areas as shown in FIG. 8: drawing area, toolbars and the property palette. The drawing area is used to paint the structures to be studied and to visualise the displacements

and stresses. Modeling tools are found in the toolbar to the left. The toolbar to the right contains functions for archiving, as well as undo and functions for copy and paste. Visualisation controls are found in the property palette.

A problem of many computer applications in this area today is that most functions and features are available in a variety of different toolbars and menus, making the user interface very complex. According to (Norman, 1998) there are two ways of overcoming this "featurism". One is that of avoidance or restraint in the designing of applications. This is not always possible, however, because many features are essential parts of an application and cannot be removed without the functionality of the application suffering. The other way is that of organisation or modularisation. Here, the functions an application contains are divided up into a number of separate modules, each with a limited number of functions. In this way, all the features are intact but are represented in different sections of the application, each of which is readily comprehensible.

To make ForcePAD easy to use and yet provide a wide variety of features for experienced users, the more advanced features have been "hidden" through the use of property buttons and "flip-out" toolbars. A property buttons is located beside a normal button. When it is pressed, a small window providing more advanced features appears alongside it, as illustrated in Fig. 9. Geometric painting functions are also hidden by placing them on a "flip-out" toolbar, which appears when the button for geometric painting functions is pressed.
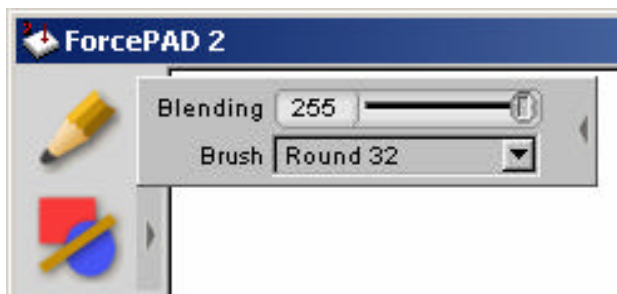

FIG. 9: Property button flip-outs

The design of the ForcePAD icons is influenced by the guidelines presented in chapter 6.4 (Shneidermann, 1998). Since the ForcePAD icons have 36x36 pixels and a high colour depth, they can provide a three-dimensional representation. Each of the icons also has a drop-shadow to make the image more clearly identifiable.

3.1.1 Painting with stiffness characteristics

Creating structures in ForcePAD is done by painting with stiffness characteristics. Black represents maximum stiffness and white no stiffness at all. The degree of stiffness desired is chosen by use of the stiffness palette. This corresponds to selecting a different colour in a normal image editing application.

Painting is done by use of any of the three different painting tools available, a brush, geometric shapes and filling. These correspond to tools commonly found in image-editing applications.

3.1.2 Creating loads and boundary conditions

Loads are represented in ForcePAD by red arrows. The user creates a load by selecting the load tool and clicking on the point where the load is to be applied. The Direction of the load is set by moving the mouse in the appropriate direction next to the application point. When the mouse is released the force involved is added to the model.

The term "boundary condition" is not used in ForcePAD, the term locking being used instead. This is to make it easier for novice users to understand the basic concept that the term "boundary conditions" denotes. Three kinds of locks are used, a vertical blue line (|) indicating locking in the x direction, a horisontal blue line (-) indicating locking in the y direction and a blue cross (+) indicating locking in the x and y direction. The line directions employed emulate a frictionless surface on which the structure is free to move.

3.2 Visualisation

For a design tool to be effective, visualisation of the results of a finite element simulation needs to be an integral part of the design process. To facilitate this, the user here can control the visualisation parameters by use of the property palette, see FIG..

FIG.10: Tweakable visualisation controls

Visualising stresses in ForcePAD is done by use of coloured arrows to represent the principal stresses. An arrow is coloured red if the principal stress is positive and blue if it is negative. Important parameters for controlling stress visualisation are those of transparency, size and the width of the stress arrows. An examples of a stress visualisation is shown in FIG. .
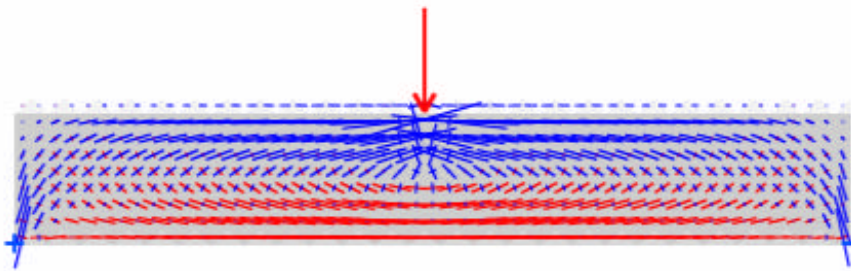

FIG. 11: Stress visualisation

Displacements too can be visualised in ForcePAD. The deflection scale factor can be scaled in real-time using the slider found in the displacements tab on the property palette. FIG. shows a beam being deflected by a single force.
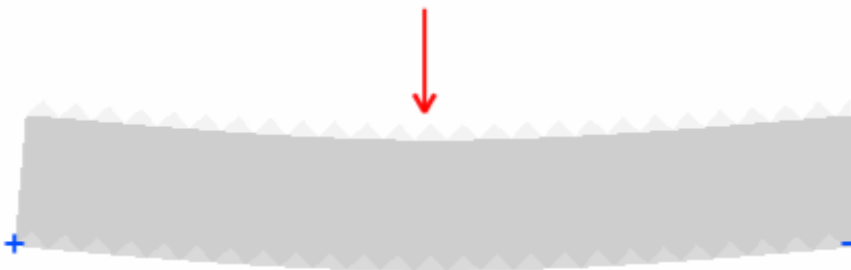

FIG.12: Deflected beam structure subjected to a single load

3.3 Software implementation

ForcePAD is implemented in C++. The user interface is created using the Fast Light Toolkit (Spitzak, 2003). This is a lightweight user interface toolkit written in C++. Good performance can be achieved with toolkit on Windows 95/98/NT and on most UNIX-type operating systems with good performance.

The solver is implemented by use of the newmat09 (Davies, 2002) matrix library, which allows a finite element solver to be implemented employing a notation similar to MATLAB (The MathWorks, Inc, 2003).

Visualisation of the element grid, the stress distribution and displacements was implemented by use of OpenGL (OpenGL, 2003), which allowed good performance to be achieved for 2D graphics of both the software-emulated and the hardware supported type.

ForcePAD is implemented in such a way that when it is installed no changes or modifications of any of the settings in the computer are required. This enables it to be installed and executed from any folder, making it

easier to install on network shares. The ForcePAD install package is also small, only about 1.3Mb being needed for downloading it over slow Internet connections.

4. FORCEPAD ON THE WEB

A special web page, see FIG. , has been set up to support ForcePAD in its use in an educational setting. (http://www.byggmek.lth.se → Resources → ForcePAD). Those using ForcePAD, both students and professionals, can download the latest version of it from this web page, look at video tutorials there and ask questions or discuss the problems that are encountered in an electronic web forum. The availability of the software and documentation on the Internet makes it easy to support.
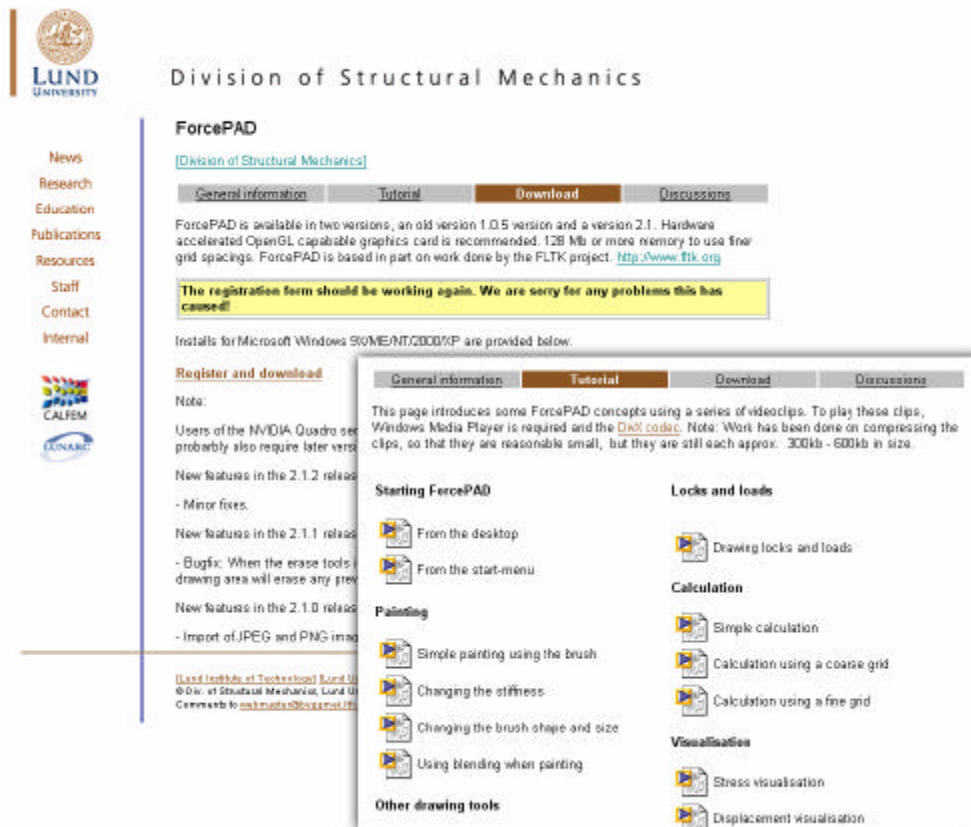

FIG. 13: ForcePAD web page

5. CONCLUDING REMARKS

ForcePAD is an educational software tool 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 that its unique features make it useful for other categories of students as well. 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 the tool is its simple interface, which clearly mirrors the physical constituents involved. The interface mimics the conditions found when one sketches on a sheet of paper. The simplicity of working with it is enhanced by the immediate consequences that adding material or a line or removing material by scratching has in terms of changes in form. This facilitates ForcePAD's becoming an intimate part of design sketching in an educational context. Our experience with it indicates it to support in a very genuine way a reflective process on the part of the user, providing insight in to the forming of material into shapes for creative and constructive purposes as well as inspiration for doing so. The tool supports an iterative process of reflective optimisation that the user is guided through, rather than it's being used simply for an automatic optimisation of shapes. Despite the software only supporting 2D modelling and its not being designed for advanced mechanical analysis, hidden

within it are in fact certain advanced finite element tools having optimising characteristics in computationally terms.

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