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Finite element implementation for computer-aided instruction of structural mechanics

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Abstract

A new approach of computer-aided instruction is proposed for education of structural mechanics and other related subjects. The instructional tools are operated with the user-created modeling data and their ensuing analysis results on the basis of finite element technology. They are devised to promote the understanding, and to stimulate the interest in the subjects by substantiating the conceptual principles and visually exhibiting the complex computational processes with the aid of interactive computer graphics.

1. Introduction

Many commercial finite element analysis programs are available for solving various problems in the fields of engineering and physical science. They are widely adopted also as instructional software by academic courses in many disciplines. However, their role for instruction is limited either to training of their own usage or to their application in practice, but not extended to education of the academic substance itself in the subjects of application. VisualFEA, a finite element analysis program, has the uniqueness in its native instructional capability to assist teaching or learning the fundamental concepts, principles and methods in structural mechanics and other related subjects. The user-friendliness and ease-of-use are the basic requirements of the educational functions (Abel [1], Hilheim [2]). The contents of the tools should possess the ingredients to stimulate the interest in the study of the subjects. VisualFEA pursues the standard with the following features:

- Graphical manipulation and visualization
- Operation with user created analysis model
- Generalized application of finite element processing
- Results adapted to conventional approaches

We expect that the use of these instructional tools will produce the following educational effects,

- Enhancement of the understanding on conceptual subjects through visualization
- Learning by experience through interactive simulation
- Familiarization with computing methods by observing the process and the result with realistic data
- Trial-and-error learning through repeated real-time operations
- Effect of self training and practicing

The instructional functions presently available in VisualFEA can be categorized into two parts, items for education of structural mechanics and others for finite element method (Lee [3],[4]).

2. Instructional aids for structural mechanics

Interactive computer operations and graphical visualizations are extensively employed to aid the instruction of conceptual principles, computing formula and analysis methods in the classical structural mechanics.

2.1 Structural response to applied conditions

Interactive manipulation of input data such as material properties, applied loads and support state, and the consequent real-time analysis and rendering will help the users to build a good sense of presumption about the structural behavior under various conditions. Graphical animation is employed to deliver the dynamic behavior.

2.2 Mathematical relationship of shear force, bending moment and deflection

As shown in Figure 1, the diagrams of shear force, bending moment and deflection of beams are drawn in parallel so that their inter-relationships are indicated conspicuously. The diagram area, slope, curvature, zero crossing points, and mini-max points are dynamically highlighted in response to user's operation. Such graphical visualization will help reasoning and understanding the mathematical relationships between the diagram items.

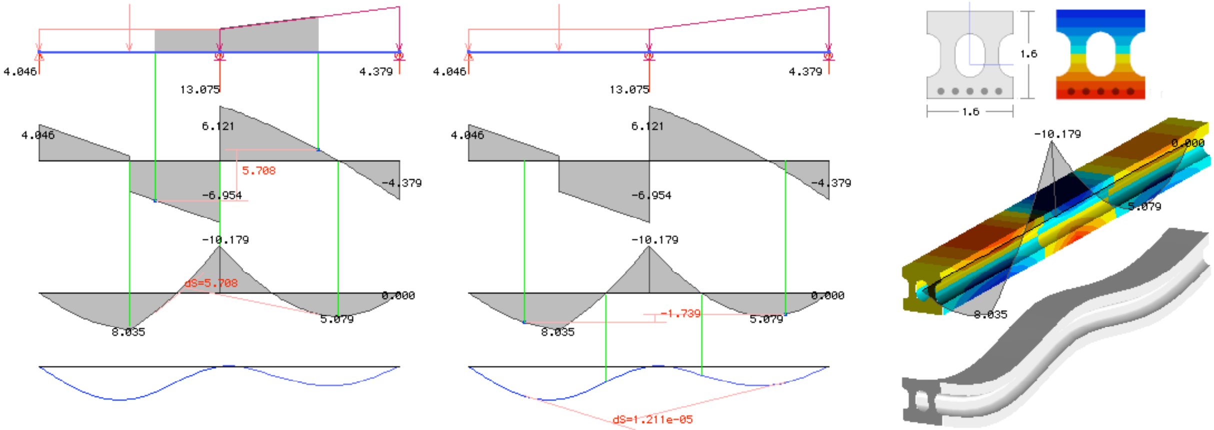


Figure 1: Inter-relationship of stresses, forces and deflection

2.3 Stresses on the frame member section

The cross sections of frame members can be defined either in freeform or in preset geometric shape. The sectional constants, stresses, internal forces and moments are instantly computed and displayed as soon as the necessary data are supplied or modified. The stress images suggestive of the computational aspects are rendered along the span and over the cross section, and updated instantly following any data change so as to give the insight on the structural behavior. The user may add sectional reinforcements and examine the resulting effects.

2.4 Influence line

The influence line is a conventional but still useful concept in structural mechanics. VisualFEA constructs the influence lines of a statically determinate or indeterminate frame by combining a series of finite element solutions with multiple loading cases. This function helps the user to emulate the drawing of influence lines for various conditions, and thus to understand the variation of the internal forces due to the changing load position.

2.5 Moving load

The minimum and maximum stress resultant envelopes of interconnected moving loads are useful as practical information for structural designs. In VisualFEA, this function is implemented for educational use as well as for practical application. While the position of the loads is being moved interactively, the consequently changing diagrams of bending moment or shear force are overlaid with the envelope diagrams. This interactive and dynamic display provides various information explanatory of moving load concept and its significance.

2.6 Mohr circle

VisualFEA draws the Mohr circle for the solution data sampled at the mouse-clicked point of an actual finite element model, instead of arbitrarily assumed data. Such an approach is more plausible in getting the sense of the real and also in understanding the context and the usage of Mohr circle. While the user is setting or changing the direction of the stress plane, the Mohr circle is refreshed on the σ_n-τ plane. At the same time, an inclined rectangle is drawn with stress components on the sampling point as shown in Figure 2. The principal stresses, the maximum shear stresses and their directions are instantly drawn on the σ_n-τ plane and on the stress point in response to the user actions. In case of a 3-D solid model, the Mohr circle is represented by threesome circles on σ_n-τ plane, and the direction of stress planes are rendered by a cube at the sampling point.

2.7 Elasto-plastic yielding

The representation of failure envelope on the σ_n-τ plane or the mean-deviatoric stress plane will be very effective in delivering the concept of the elasto-plastic failure theories. As exemplified in Figure 2, the Mohr-

Coulomb theory of plastic yielding due to load increment is clearly revealed by a series of Mohr circles bounded by the line of failure envelope.

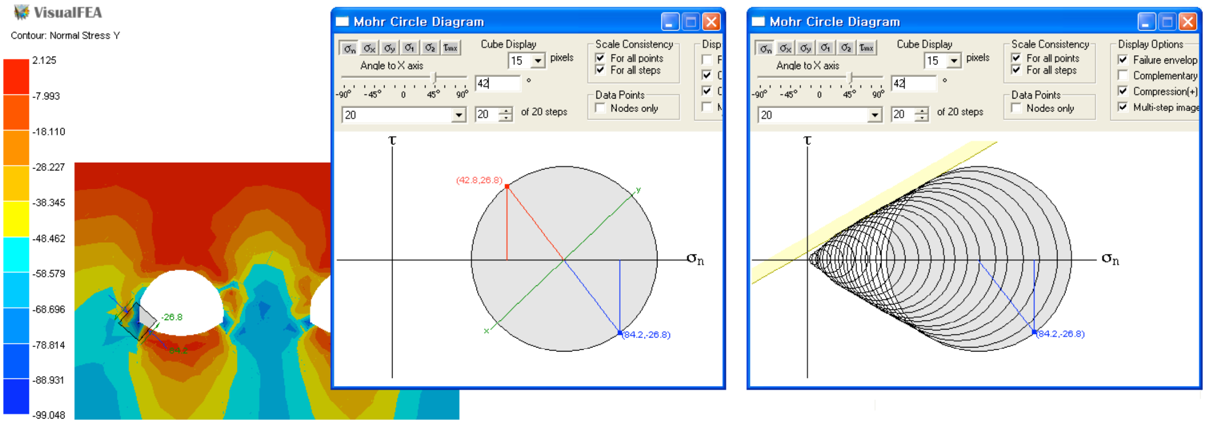


Figure 2: Mohr circle and failure envelope

2.8 Stress path on the yield surface

VisualFEA has the function of visualizing the yield surface and the stress path in the principal stress space defined by σ_1-σ_2-σ_3 axes. The progress of yielding is expressed by the graphical image of the stress path creeping over the yield surface. Such visualization is the most effective method of describing the concept of the yielding process that may look ambiguous otherwise to the students. The axes of the space may represent other parameters. For example, the yielding of CamClay models may be visualized using the stable state boundary surface in the space of mean stress (σ_m), deviatoric stress (σ_d) and void ratio (e) as shown in Figure 3.

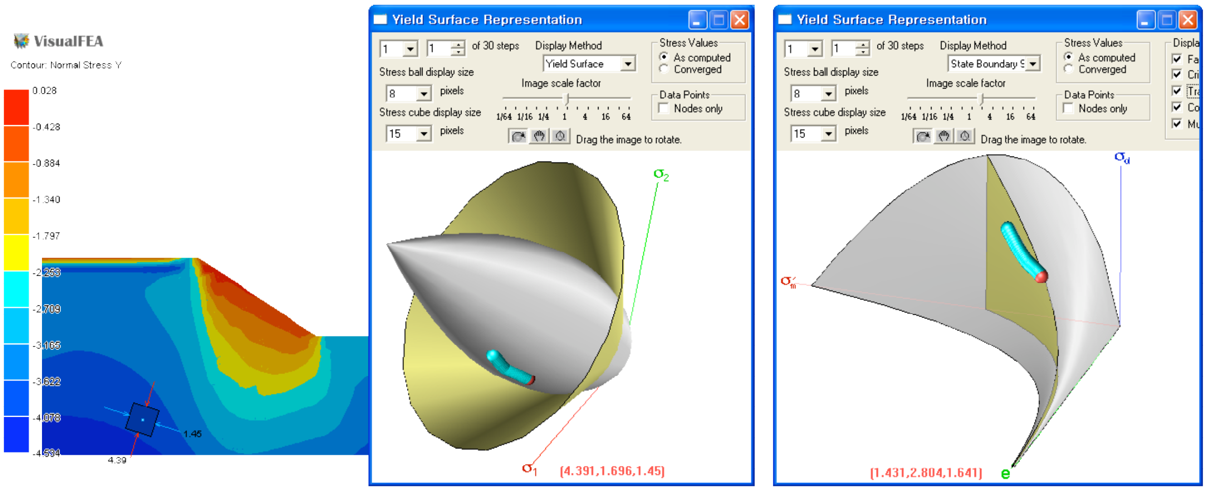


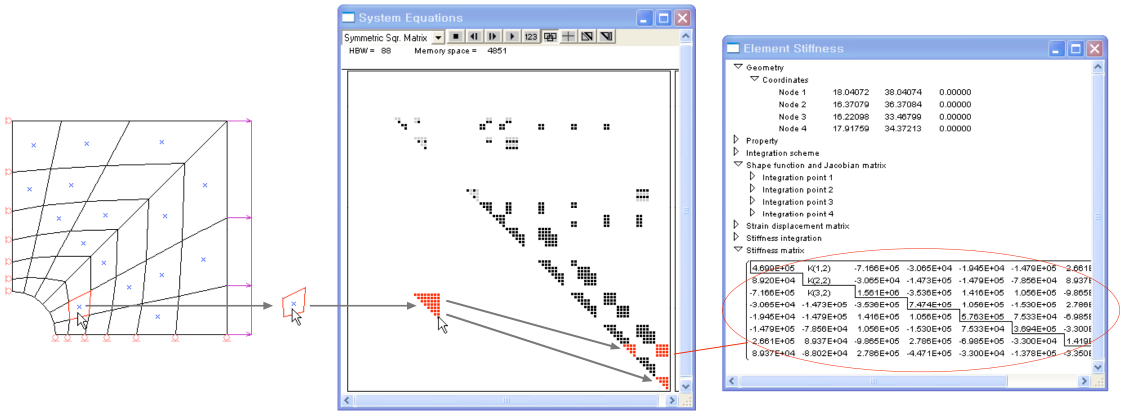
Figure 3: Stress path on the yield surface and the stable state boundary surface of a CamClay model

3. Computer-based education of finite element method

Numerical exercise and computer programming are the best ways of understanding and mastering the concepts and procedures of the finite element method, but demand considerably rigorous efforts. The difficulty may be relieved by the function of simulating the finite element procedures as provided in VisualFEA.

3.1 Stiffness matrix assembly and solution process

VisualFEA has the function of simulating and visualizing the stiffness computation, assembly and solution processes. Various contents of computation at the element stiffness level are displayed either numerically or symbolically in tree-view expansion style. Assembly of the global system equations can be simulated by drag-and-drop or step-by-step operations. Users may get indirect experience of assembling and solving the system equations for finite element analysis through such interactive operations as shown in Figure 4.



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HBW =  88        Memory space =   4851
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```
Node 1      18.04072    38.04074    0.00000
Node 2      16.37079    36.37084    0.00000
Node 3      16.22098    33.46799    0.00000
Node 4      17.91759    34.37213    0.00000
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```
 4.699E+05   K(1,2)     -7.166E+05  -3.065E+04  -1.945E+04  -1.479E+05   2.661E
 8.920E+04   K(2,2)     -3.065E+04  -1.473E+05  -1.479E+05  -7.856E+04   8.937E
-7.166E+05   K(3,2)      1.561E+06  -3.536E+05   1.416E+05   1.056E+05  -9.865E
-3.065E+04  -1.473E+05  -3.536E+05   7.474E+05   1.056E+05  -1.530E+05   2.786E
-1.945E+04  -1.479E+05   1.416E+05   1.056E+05   5.763E+05   7.533E+04  -6.985E
-1.479E+05  -7.856E+04   1.056E+05  -1.530E+05   7.533E+04   3.694E+05  -3.300E
 2.661E+05   8.937E+04  -9.865E+05   2.786E+05  -6.985E+05  -3.300E+04   1.419E
 8.937E+04  -8.802E+04   2.786E+05  -4.471E+05  -3.300E+04  -1.378E+05  -3.350E
```

Figure 4: Computation and assembly of stiffness matrix

3.2 Shape function and interpolation

The shape functions and their derivatives can be visualized as 2-D or 3-D graphic images, which help understanding the nature and the variation of shape functions. The order of continuity such as C^0, C^1 and C^2, within an element and across adjacent element boundaries can be demonstrated easily by this function.

3.3 Eigenmodes

Eigenvalues and corresponding eigenvectors are extracted from the stiffness equations of a static or a dynamic analysis, and visualized as displacements or vibrations. They are arranged so as to give insight into the system characteristics such as rigid body modes, spurious zero energy modes, dynamic modes, etc. The physical interpretation of the eigenmodes can also be reviewed in conjunction with element types and integration orders.

3.4 Stress smoothing

The stress recovery and smoothing procedure can be experimented and inspected by interactive simulation. The computational aspects and characteristics are recapitulated and understood easily using this educational function. Different methods of recovery and smoothing can be compared with each other.

3.5 Process of adaptive analysis

VisualFEA has the capability of reproducing the multi-step mesh refinement, error evaluation, and adaptation process for step-by-step examination under user control. The function is devised to help understanding the principles and the methods of adaptive solution procedure.

4. Conclusion

Computer-aided instructional tools for structural mechanics and other related subjects were implemented on the basis of finite element technology. They have been experimented in actual education, and proved to be very effective as teaching and learning devices. New items of instructional functions are continuously being added to VisualFEA so that most of the topics in this field of study are covered eventually by the computer-aided instruction. This work will proceed forward to set a new paradigm of education in engineering.

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