Modeling and Simulation of Three-Point Bending Experiment of H-Beam and Teaching Application in Higher Vocational Colleges

Meiqin Liang[1] and Shang Wang[2](✉)

[1] College of Automation Engineering, Beijing Polytechnic, Beijing, China
liangmeiqin@bpi.edu.cn
[2] School of Automotive Engineering, Beijing Polytechnic, Beijing, China
wangshang@bpi.edu.cn

Abstract. In view of the problem of poor quality of Material Mechanics experiment teaching, this paper puts forward a method of using simulation technology to assist teaching. In order to solve students' learning doubts about bending deformation of H-beam, the research team established a geometric model together with students. Based on the geometric model, a finite element model of three-point bending was established. Bending deformation behavior of beams under different pressures was simulated, and rich digital teaching resources such as Mises stress nephograms and animations were obtained. These nephograms and animations have effectively solved students' learning doubts. The introduction of computational finite element technology into the teaching of Material Mechanics is an innovation of teaching methods. On the one hand, rich digital resources can clearly and intuitively display boring mechanical concepts. On the other hand, the application of simulation technology not only improves students' interest in learning, arouses their enthusiasm in learning, but also expands their knowledge. The application of finite element technique in Material Mechanics should be further explored.

Keywords: modeling · three-point bending · teaching application · vocational colleges · simulation

1 Introduction

Material Mechanics is a very important specialized basic course. This subject is to study the strain, stress, strength, stiffness, stability and limit of damage to various materials under the action of various external forces. Material Mechanics is the basic theoretical knowledge that must be mastered in all kinds of industrial design and is almost a required course for all engineering students [10]. The course content of Material Mechanics is closely connected with subsequent courses to be learned, such as Mechanical Design Principle, Mechanical Manufacturing Engineering and Material Processing Engineering [5].

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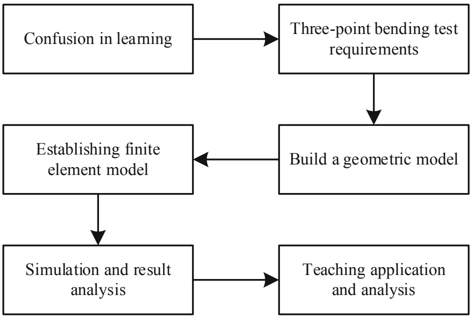


Fig. 1. The research logic diagram of the paper.

Experimental teaching is an important way to further study and consolidate classroom content. Many concepts of Material Mechanics, such as polar moment of inertia (I_p), moment of inertia (I_z) and bending section coefficient (W_z), are esoteric and abstract, and need to be understood and consolidated with the help of experimental teaching. Different from undergraduates, students in higher vocational colleges are less able to learn and understand. Therefore, experimental courses are more important for students in vocational colleges. However, the problem of poor teaching quality of Material Mechanics experiment course in vocational colleges has existed for a long time. For instance, the equipment in many mechanics laboratories is old and small, which is difficult to meet the teaching needs. In many cases, among these vocational colleges, one school has only one device for teaching an experiment and a teacher operates an experimental device around which students of a whole class observe the phenomena of the experiment, so only a few students in front can see the whole experimental process clearly. Even if one school has multiple devices, teachers in most cases do not let students use them for safety reasons [7].

In order to improve the teaching quality, scholars have made various attempts in teaching. Some scholars tried to use MOOC to assist teaching and used data analysis to give feedback on classroom teaching [3, 6], some tried a mixed teaching mode to enhance students' interest in learning [2, 8], and some tried a flipped course to improve students' thinking skills [9, 11]. This paper presents a method of using finite element software for modeling and simulation to assist experimental teaching. Taking the three-point bending experiment of H-beam as an example, the research team carried out modeling and simulation calculation, and applied the materials obtained by simulation to experimental teaching of Material Mechanics, thereby achieving good teaching effect. The research logic of this paper is shown in Fig. 1.

2 Learning Problems and Geometric Models

The teaching of beam bending involves a lot of concepts and formulas, which is a difficult point in teaching of Material Mechanics. During the teaching involving H-beam, some students proposed two questions to the teacher:

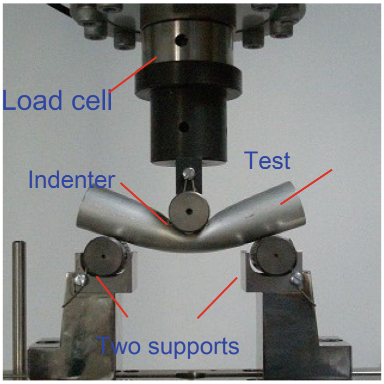


Fig. 2. Three-point bend test equipment.

1. What kind of bending deformation occurs in the H-beam under the action of external force?
2. Where does stress concentration occur in the H-beam?

Students wanted to do an H-beam three-point bending experiment so as to use the results to explain their doubts.

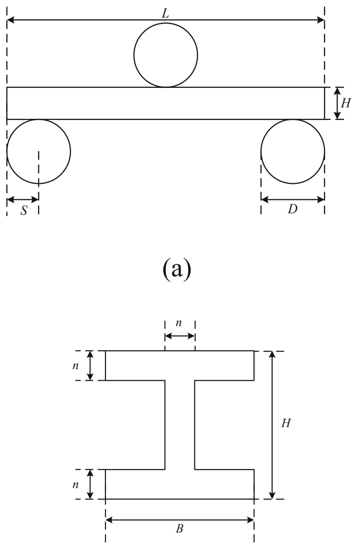
On the one hand, the school does not have corresponding mechanical experimental equipment. On the other hand, after H-beam is purchased, it needs to be cut according to sample size requirements of three-point bending test equipment; but the school has no corresponding cutting device. Therefore, students' idea of doing experiments cannot be realized.

In order to solve students' learning problems and improve their learning enthusiasm, the research team considered using finite element software for modeling and simulation calculation.

At the suggestion of the research team, students who raised doubts combed the experimental data of bending. They searched the pictures of three-point bending test equipment on the Internet (as shown in Fig. 2), and sorted them into a geometric model, as shown in Fig. 3.

The length of H-beam to be simulated is $L = 100$ mm and height $H = 10$ mm. The geometric dimensions of H-beam cross-section are shown in Fig. 3(b), in which wall thickness is $n = 2$ mm and H-beam width is $B = 10$ mm.

The indenter and the two supports have the same structure, with diameter $D = 20$ mm and axial length $z_1 = 10$ mm ($z_1 = B$).The indenter is tangent to the upper surface of the beam at the center of the beam. The two supports are tangent to the upper surface of the beam. The distance between the axis of the two supports and both ends of the beam is $s = 10$ mm (as shown in Fig. 3).



(a)

(b)

Fig. 3. Simplified diagram of bending experimental. Structure: (a) the main view of the model; (b) a cross-section of the H-beam.

3 Finite Element Modeling

According to the above dimensions, the finite element model was established by the research team using ABAQUS software.

The indenter and the two supports are designed to be rigid without regard to the setting of its material properties. The material property of the H-beam are set as follows: density of the material $\rho = 7.9 \times 103\,\text{kg/m}^3$, elastic modulus $E = 210$ GPa, and Poisson's ratio $\lambda = 0.3$. The plastic deformation of the beam are set as: $\sigma_1 = 418$ MPa, $\varepsilon_1 = 0$; $\sigma_2 = 500$ MPa, $\varepsilon_2 = 0.0158$; $\sigma_3 = 606$ MPa, $\varepsilon_3 = 0.0298$; $\sigma_4 = 829$ MPa, $\varepsilon_4 = 0.25$; $\sigma_5 = 932$ MPa, $\varepsilon_5 = 0.55$; $\sigma_6 = 1040$ MPa, $\varepsilon_6 = 0.85$.

In the ABAQUS software, "element type" of each part is selected as C3D8R. "Approximate global size" of the beam was set as 1 mm, and the supports and indenter were set as 2 mm. The finite element model is shown in Fig. 4.

In order to set "load" and "boundary condition" more reasonably, operation points RP-1 (0, 40, 5), RP-2 (−40, −40, 5) and RP-3 (40, −40, 5) were created.

Three special points are defined and bound to three rigid bodies in the model. The indenter was set as a "rigid body" and bound to the point RP-1. Similarly, the left support was set as a "rigid body" and bound to the point RP-2, and the right support was set as a "rigid body" and bound to the point RP-3.

In "interaction", the friction coefficient was set to $\mu = 0.2$. In "boundary condition", all six degrees of freedom on the RP-2 and RP-3 were constrained. RP-1 was constrained to move only in the Y-axis to realize the pressure on the normal direction of the beam.

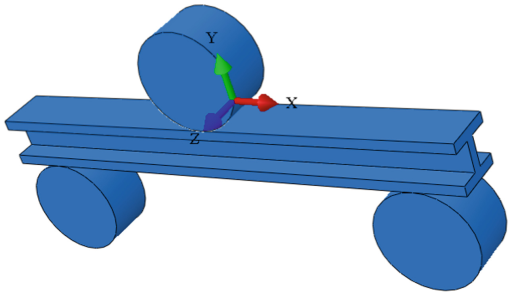


Fig. 4. Finite element models and the coordinate system.

In order to ensure the convergence of the model calculation, the left surface of the beam (surface $x = -50$ mm) was constrained to move only in the X-axis and Y-axis, and the other four degrees of freedom are constrained. The time of the "step" command was set to $t = 1$ s, and the "H-output" command is set to $T = 10$ times.

4 Simulation Calculation and Analysis

The pressure of indenter at point RP-1 of the model was set along the negative Y-axis direction. The pressure value is 3–10 kN and step factor is 1 kN. The deformation behavior of the beam under different pressures was simulated.

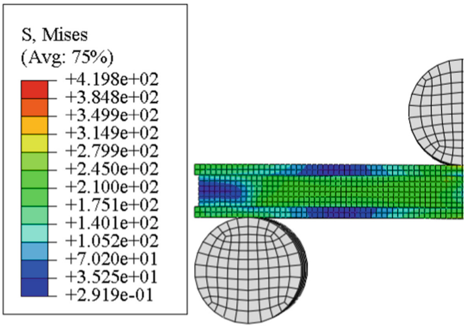
When the pressure is low, the Mises stress nephogram calculated by the model is shown in Fig. 5. Figure 5(a) and Fig. 5(b) show the simulation results when pressure $F_1 = 3$ kN and pressure $F_3 = 5$ kN respectively.

As can be seen from Fig. 5, when the pressure is small, the overall bending deformation of H-beam is not obvious. The Mises stress is not large as a whole, but it is concentrated and its maximum value is not small. The maximum Mises stresses are 419.8 MPa and 450.8 MPa respectively when pressure $F_1 = 3$ kN and pressure $F_3 = 5$ kN. In order to better study the stress concentration, the cross-section (plane with $x = 0$) of the model with pressure $F_1 = 3$ kN was observed.

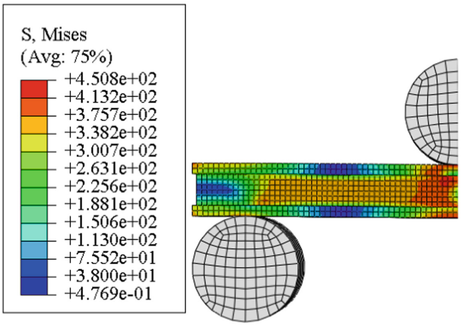
It can be seen from Fig. 6 that the stress concentration appears directly below the indenter. Due to no support below both sides of H-beam flange, the stress is released (as shown in the purple box area).

Correspondingly, the maximum Mises stress (as shown in the blue box area) occurs at the junction of H-beam web and the H-beam flange.When the pressure is large, the Mises stress nephogram calculated by the model is shown in Fig. 7. Figure 7(a) and Fig. 7(b) show the simulation results under pressure $F_6 = 8$ kN and pressure $F_8 = 10$ kN respectively.

Compared with Fig. 5, the overall bending deformation of H-beam in Fig. 7 has been obvious. Mises stress concentration appears directly below the indenter. The maximum Mises stresses of the model are 761.8 MPa and 849.7 MPa respectively when pressure $F_6 = 8$ kN and pressure $F_8 = 10$ kN. As can be seen from Fig. 5 and Fig. 7, the bending degree of the beam increases with the increase of pressure, so does the Mises stress at



(a)



(b)

Fig. 5. Mises stress nephograms of the finite element model at different pressures: (a) 3 kN; (b) 5 kN.

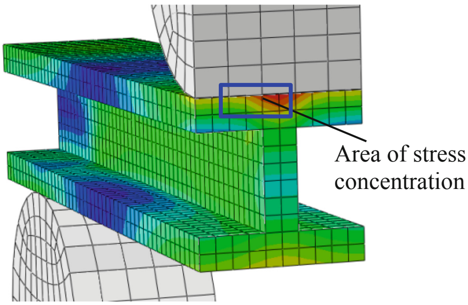
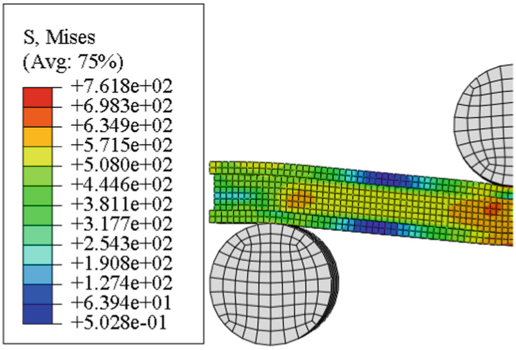


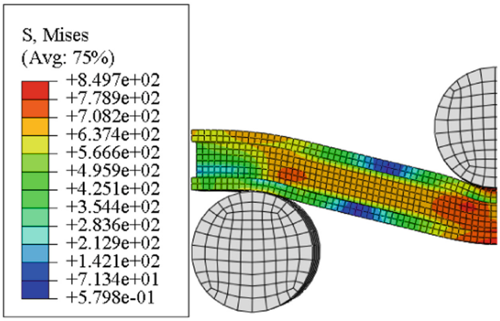
Fig. 6. Mises stress distribution on the H-beam cross-section.

the same part of the beam. The stress concentration in the two figures appears directly below the indenter.

It can be seen from Fig. 8 that the maximum Mises stress value of the finite element model increases with the increase of pressure. When the pressure is less than 5 kN, the



(a)



(b)

Fig. 7. Mises stress nephograms of the finite element model at different pressures: (a) 8 kN; (b) 10 kN.

Mises stress increases slowly. When the pressure is greater than 5 kN, the Mises stress increases sharply.

In order to better study the bending deformation of the beam, the bending condition with pressure $F_8 = 10$ kN was observed microscopically. As shown in Fig. 9, the beam has undergone significant bending deformation under great pressure. Just below the indenter, the stress is concentrated and the deformation is the most obvious. According to the stress data shown in Fig. 8, large-scale plastic deformation has occurred at this time. The H-beam flange below and away from the indenter also has a very big stress.

The maximum Mises stress value based on simulation calculation of the finite element model under all pressures was counted, and the statistical results are shown in Fig. 8.

The stress at the cross-section of the beam directly below the indenter is the most concentrated. Similar to Fig. 6, the cross-section of Fig. 9 was observed, as shown in Fig. 10.

By comparing Fig. 6 and Fig. 10, the effect of increased pressure on H-beam bending was more clearly observed. As can be seen in Fig. 10, the upper and lower H-beam flanges

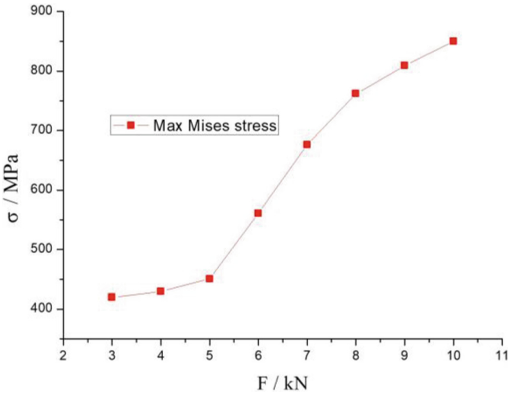


Fig. 8. Maximum Mises stress statistics at different pressures.

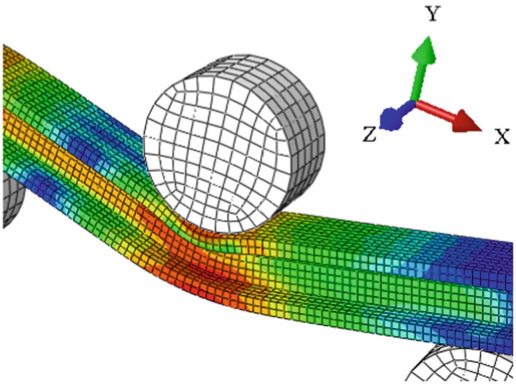


Fig. 9. Bending deformation with F8 = 10 kN.

are both bent in the Z-axis direction. And both ends of the upper H-beam flange are no longer in contact with the indenter.

In order to better study the bending deformation, some nodes of the beam were marked. As shown in Fig. 11, the node directly below the indenter was marked as Node 1 (as shown in the blue wireframe in the figure). Along the negative X-axis direction, the adjacent nodes were marked as Node 2, Node 3· · · Node 16 in turn (as shown in the yellow wireframe in the figure).

Considering that the bending changes when $F_1 = 3$ kN and $F_2 = 4$ kN were very small, only the simulation results under other pressures were studied. Displacements of the 16 nodes marked above in the Y-axis direction were counted, and the statistical diagram shown in Fig. 12 was obtained.

It can be seen from Fig. 12 that under the same pressure, the closer the node to the Y-axis (the smaller the number marked in Fig. 11), the greater the displacement. With the increase of pressure, the displacement of the same node increases. When the pressure is small, the displacement of each node is close, that is, the bending degree of the beam

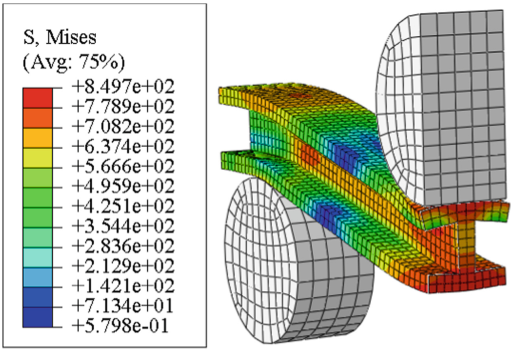


Fig. 10. Mises stress nephograms was observed on the H-beam cross-section with F8 = 10 kN.

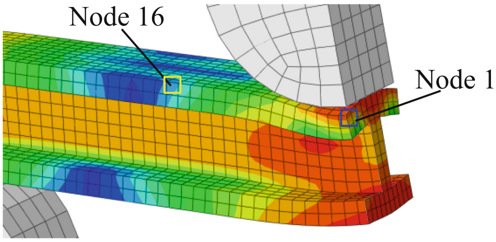


Fig. 11. Several nodes of the H-beam were marked.

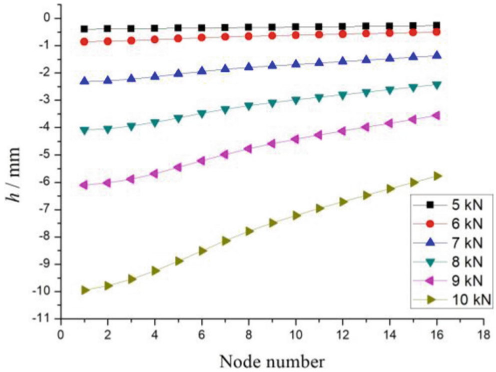


Fig. 12. Displacement of nodes in Y-axis direction.

is small. With the increase of pressure, the displacement difference between the nodes becomes larger and larger, that is, the bending degree of the beam becomes more and more obvious. Under the pressure of $F_8 = 10$ kN, the displacement of Node 1 is $h_1 = -9.943$ mm, while the displacement of Node 16 is $h_{16} = -5.764$ mm, the former being 1.725 times of the latter.

The finite element simulation results mentioned above have solved the students' learning doubts. A large number of Mises stress nephograms and data provided students with a deeper understanding of the H-beam bending deformation. The students gained a preliminary understanding of finite element theory and ABAQUS software. One student is particularly interested in simulation technology, and he plans to study ABAQUS software seriously after he graduates and enters the undergraduate program. These are the words every educator wants to hear. This also fully shows that the teaching application of finite element simulation technology in this paper is successful. These digital materials have also been applied to the teaching of Material Mechanics and achieved good teaching results.

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5 Teaching Application

Students in vocational colleges are poor in learning and understanding. Bending deformation of H-beam is actually a further study of inertia moment and coefficient of bending strength. These topics are dull, abstract and involve complex mathematical reasoning, which leads to a lack of interest among students [1, 4]. The College of Automation Engineering of Beijing Polytechnic has carried out teaching and discussion of Material Mechanics for many times. The teachers at the front-line all said that the pressure of teaching is increasing from the bending of beams. Pictures, animations and other materials that can intuitively show beam stress/strain are urgently needed for the courses.

The digital resources obtained in this paper were applied to teaching practice. After the teaching application, a simple questionnaire survey was conducted among students and teachers, among which there are 55 students. The questions involved in the questionnaire are as follows:

Q1: have the digital materials obtained by simulation enhanced your interest in learning?
Q2: have the digital materials obtained by simulation more clearly shown the stress distribution law of the H-beam?
Q3: have the digital materials obtained by simulation helped you grasp knowledge points more solidly?
Q4: have the digital materials obtained by simulation helped you get higher grades?

The students' votes were sorted and counted. The statistical results are shown in Fig. 13. As can be seen from Fig. 13, Q1get 55 votes. All of the students who participated in the questionnaire believe that the application of these materials improves their

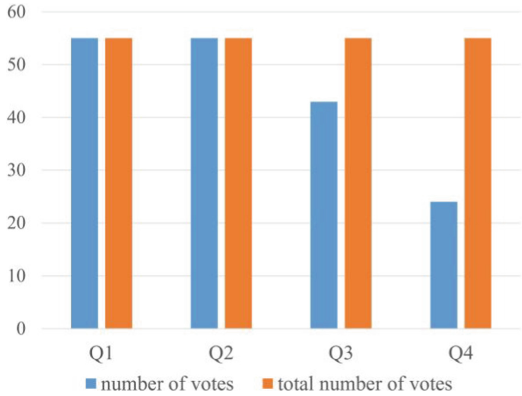

Fig. 13. Statistics of questionnaire survey.

interest in learning. Similarly, the vote rate of Q2 was 100%. All students believe that the application of these digital materials clearly shows the stress distribution law. In addition, some students recognized the introduction of finite element theory and software and opened up their own horizons.

However, the number of students who voted for Q3 was 43 (accounted for 78.2%), and Q4 was 24 (accounted for 43.6%). In order to further improve teaching quality, the research team communicated with the students. They believe that these digital materials can help them more intuitively understand the laws of bending; however, an objective fact is that there are too many knowledge points are abstract and cryptic. Meanwhile, it takes a lot of time and energy to acquire this knowledge, such as reading notes and doing homework. Students' opinions should be taken into account. To improve students' learning efficiency and interest, teachers at vocational schools should work in more fields. In addition to simulation technology, more new technologies should be considered in the teaching. Only through continuous attempts and improvements can the teaching quality of Material Mechanics be improved.

In a word, the application of finite element modeling and simulation improves students' interest in learning and the quality of teaching. In addition, the simulation and demonstration are completed on a computer, which not only has no danger, but also saves the experimental cost. The application of finite element technique in Material Mechanics should be further explored.

6 Conclusions

Finite element technology is a kind of technology that integrates Mechanics, Mathematics, Physics, Computer and other disciplines, takes solving mechanical problems as the goal, and uses graphical interfaces to display calculation results. The research team put forward a method of using finite element modeling and simulation calculation to obtain materials, such as pictures, animations, so as to enrich course resources and improve teaching quality. The materials obtained from finite element simulation have been applied to teaching practice and achieved good teaching results.

On the one hand, the stress nephogram shows the stress distribution in color (the redder the color, the greater the stress). This method of presentation is more clear and intuitive than the textbook. With easy access to complex and abstract knowledge, students' interest in learning naturally increases. On the other hand, the model simulation and the animation demonstration are done on a computer, which not only has no danger, but also saves the experimental cost. The introduction of computational finite element technology into the teaching of Material Mechanics is an innovation of teaching methods. The research idea of this paper should be applied in more courses of vocational education.

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