Finite Element Analysis of Reinforced Concrete Beams with Holes in the Abdomen, Strengthened with Steel Casing

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Abstract. Through making a comparison between the experimental values of the ultimate bearing capacity of the ordinary beams and the beams with circular holes and the result of the finite element analysis, the value of the shear transfer coefficient between cracks in a reinforced concrete beam with circular holes in its abdomen is put forward in ANSYS finite element simulation, and the circular hole beams strengthened with steel casing are simulated and analyzed by using this coefficient. It is pointed out that steel pipe reinforcement has little effect on improving the bearing capacity of the beams with circular holes.

1. Introduction

In modern buildings, it is often necessary to open holes in the beam due to the need for installation of the ventilation system, the air-conditioning system, the hot water piping, and the upper and lower water pipes. The opening of the holes in the beam has a great effect on the performance of the beam. The main tensile stress and shear stress of the concrete around the opening will be greatly increased, the stress concentration will be presented at the opening, and the local stability of the concrete near the opening will be obviously reduced [1]. Wang Xinling et al[2] have carried out tests on test analysis of simply supported reinforced concrete deep beam with holes made in the middle of the span, which is under a concentrated load, and an analysis has been made, the conclusion that the bearing capacity of the continuous deep beam with holes is related to the area and the position of the holes was obtained, and the restriction condition and design proposal of the opening were also given. Liu Xiaochun[3], Wang Peng[4], Yang Yuhua[6] and Cai Jian[7] have conducted a large number of experiments to study the influence of the following factors which may affect the beam: with regard to a combined beam, its thickness; with regard to a beam which has holes on its abdomen, the size and the location of the holes, the form and quantity of the abdomen supports, the shear span ratio, the spacing of the holes and the strength of the concrete. Liu Shizhong[8], Jiang Jiaohel[9], Wang Dongsheng[10], Li Yiqiang[11], Luo Rudeng[12] et al have used Ansys finite element simulation software to simulate and analyze the concrete beams with simple supports; Solid65 concrete element modeling was used to verify the effectiveness of the Ansys analysis; and the issues were discussed, such as the finite element model, selection of the constitutive relations and the parameters, the convergence of solutions. Zhu Mingqiao[13] et al have carried on the simulation analysis to the concrete beam which have simple supports and square holes on the abdomen. However, there have been less Ansys finite element analysis made on the concrete beams with circular holes on the abdomen. On the one hand, the hexahedral Solid element has eight nodes, so the mesh division of the model is strict and the difference among the element shapes can not be too big; otherwise it is easy to lead to the situation where the
calculations are not accurate, and if round holes are to be made, it will cause more difficulties on this respect. On the other hand, after a hole has been made on the abdomen, the failure characteristics of oblique cracks in a beam will be different from that of oblique cracks in a complete beam which has simple supports, so with regard to the above two kinds of concrete beams, i.e. the concrete beam which has square holes on the abdomen and the concrete beam which has round holes on the abdomen, this may not be applicable in selecting the parameters of the concrete, so it will be necessary to carry out further researches.

2. Analysis finite element analysis

2.1. The unit type and the material properties

In this paper, the separated finite element model is adopted, solid65 element is used for modelling of the concrete material, link80 element is used for modelling of the steel bars, and solid185 element is used for modelling of the protective tubes. All of the elements have the common joints so as to ensure the deformation coordination of the three elements, and the bonding slip between the three elements has not been taken into account.

For the concrete material mode, the concrete+miso model has been adopted, which is a multi-linear isotropic strengthening model. The uniaxial compressive stress-strain relationship is shown in Figure 1 (a). The highest compressive strength is 37.3 MPA, which does not take into consideration the descending section of the concrete. The tensile strength of concrete is 2.07MPA. The elastic modulus is 3.0 × 104 MPA. The willam-warnke five-parameter strength criterion are adopted and the failure surface of the concrete is controlled by the five parameters. The shear transfer coefficients for opening and closing of cracks are studied by using several groups of different values. In this way, the effects of different coefficients on the model is investigated so as to determine the optimal coefficient of a beam with circular holes on it. The crushing switch has been turned off (that is, the uniaxial compressive strength value has been set to -1).

The steel bars have adopted HPB300 grade steel bars. For all the steel bars, the elastic modulus is 2x105 MPA, the yield strength is 300 MPA, and the ultimate strength of 463 Mpa. The steel bar has the bilinear isotropic strengthened material characteristics (curve), i.e., the elasticity is linear and the plasticity is linear, too. The stress-strain curve is shown in Figure 1 (b).

2.2. Setting of the criteria for convergences

In this paper, the modified Newton-Raphson iterative method is used to solve the problem. The biggest difficulty in calculating the reinforced concrete structures with Ansys lies in maintaining the normal convergence; usually because of the poor grid division, the convergence accuracy or different
setting of other parameters, there is not any convergence in the calculations. In order to improve the accuracy of calculation, the following measures are taken in this paper:

- Switch on the geometry large deformation, click open the automatic time step and the linear cord collection option.
- The division of grids should be controlled very well, which has a great impact on the results. In order to divide the grids in a good way, in this paper, the following steps have been carried out: the hole is cut into four parts along the symmetry line of the hole, and then the concrete is divided into the hexahedral elements with similar shapes by using the method of scanning grid division. The element size is about 50mm, the calculation results will be affected in the case where the elements are too large and too small.
- The loading is carried out by increasing the load in a linear manner; for a concentrated load, the input is carried out by uniformly distributing the load within a small area in the middle position on the span.
- The rigid gaskets have been set up at the support positions so as to avoid the problem of concentrated stress.
- The convergence criterion based on force has been adopted and a convergence accuracy of 5% has been obtained.

2.3. Building of the model

With reference to the test parameters of Yang Yuhua[6] of South China University of Technology, with respect to the common beams with no holes on them and the beams with holes with a diameter of 80 mm and 100 mm respectively, three groups have been selected and comparisons were made. The detailed dimensions are as shown in Figure2, and the thickness of the protective layer of the concrete is 25 mm.

![Figure 2 A schematic diagram of the test pieces.](image)

3. Comparison and Analysis of the Calculation Results and the Test Results

The linear loading method was used in the simulation process until there were no any converges occurred in the calculation and then exited the program. Because the shear transfer coefficient for the crack, $C_1$ and the shear transfer coefficient for closed crack, $C_2$, have great influence on the simulation results, several representative values have been selected and compared with the experimental results. In the comparisons, it is found that for ordinary beams, the group $C_1=0.40$ and $C_2=0.90$ and the group $C_1=0.40$ and $C_2=1.0$, the values of their ultimate baring capacities are close to the values of the actually measured ultimate bearing capacity, which is consistent with the results of Luo Ruden[12]. For the beam ① and beam ②, the values of the group $C_1=0.30$ and $C_2=1.0$ and the group $C_1=0.35$, $C_2=1.0$ are close to the values of the actually measured ultimate bearing capacity. The reason for this phenomenon lies in that, for the ordinary beams, the crack width is relatively small, the crack development is relatively slow, the binding force between the concrete materials basically has not disappeared, and the shear resistance is more ideal. For a beam with round holes on it, due to the concentrated stress at the edge of the hole, oblique cracks tend to appear at a earlier stage. The cracks are relatively concentrated and the crack width is relatively large, so it is easier for a oblique tensile
failure to occur. Therefore, for the shear force transfer coefficient of the opening crack, $C_1$, a relatively smaller value should be taken.

Table 1. A comparison between the simulation values and the experimental results (in kN).

| Test          | $C_1$=0.45 | $C_1$=0.40 | $C_1$=0.35 | $C_1$=0.30 | $C_1$=0.40 | $C_1$=0.35 | Measured limit value |
|---------------|------------|------------|------------|------------|------------|------------|---------------------|
| Ordinary beam | 380.0      | 399.3      | 331.1      | 265.0      | 400.4      | 220.9      | 395                 |
| Beam ①       | 343.7      | 263.4      | 296.5      | 296.5      | 255.5      | 273.7      | 312                 |
| Beam ②       | 297.3      | 372.1      | 269.7      | 266.0      | 376.8      | 235.1      | 250                 |

Note: An ordinary beam refers to a beam on which no holes have been made, beam ① is a beam on which a circular hole with a diameter of 80mm has been made, and beam ② is a beam on which a circular hole with a diameter of 100mm has been made.

In the current engineering applications, especially for a fire-fighting pipeline, after any holes have been made on the beam, the pipe is usually provided with a tube (for a round hole, it is often reinforced with a steel sleeve), and the pipeline and the concrete are effectively bonded together. In order to study the effect caused by the interaction between the steel tube and the beam, a steel sleeve with a thickness of 6 mm is provided at the hole position, and its influence has also been studied. The relevant calculation results are shown in Table 2, where the average analog value for the beam is the simulation result of the group $C_1=0.40$ and $C_2=1.0$, and the simulation results of the beam ① and beam ② are simulation values of the group $C_1=0.40$ and $C_2=1.0$.

Table 2 A comparison between the simulation values and the experimental results (in kN).

| Ordinary beam | Test piece | Beam ① | Beam ② | Reinforcement ① | Reinforcement ② |
|---------------|------------|---------|---------|------------------|------------------|
| The opening load of a normal crack | 91 (90)    | 88 (80) | 85 (80) | 89 (80)          | 88 (80)          |
| The opening load of a normal crack | 190 (190)  | 70 (120)| 76 (110)| 139 (110)        | 161 (110)        |
| The load during a failure | 399 (395)  | 296 (312)| 266 (250)| 328 (250)        | 326 (250)        |
| Deflection    | 5 (4)      | 4 (5)   | 3 (3)   | 4 (3)            | 4 (3)            |

Note: The values in the parentheses are the experimental results; the reinforcement ① refers to a beam which has a round hole with a diameter of 80mm on it and which is strengthened with a steel tube, and the reinforcement ② refers to a beam which has a round hole with a diameter of 100mm on it and which is strengthened with a steel tube.

From the simulation results, it can be seen that, for a beam which has a round hole on it and which is strengthened with a steel tube, the opening load of a normal crack is similar to that of an ordinary beam, and the opening load as well as the ultimate bearing capacity of a diagonal crack are larger than those of a beam on which a hole has been made but smaller than those of an ordinary beam. This indicates that the steel sleeve can strengthen a beam on which a hole has been made and can work to a certain extent. However, the effect is not significant.

Figures

4. Conclusion

- With respect to a beam on which a round hole has been made, $C_1=0.30$ and $C_2=1.0$ are taken for the shear transfer coefficient for the open crack, $C_1$, and the shear transfer coefficient for the closed crack, $C_2$, respectively, these two values are close to the actually measured values of the ultimate bearing capacity and can be used for simulating and analyzing a beam on which a round hole has been made.
• For a beam on which a round hole has been made, the reinforcement of a steel sleep has a certain effect. However, this effect is not significant.

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