Experimental study on the effect of reinforcement ratio on the ultrasonic velocity and modal frequency of concrete members

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Abstract: In order to study the effect of reinforcement ratio on ultrasonic sound velocity and modal frequency of reinforced concrete members, 13 concrete circular cross-section short columns were designed to detect the ultrasonic sound velocity and self-strain of short columns with different cuff ratio and longitudinal reinforcement ratio. Compared with non-reinforcing short columns, the results show that the stirrup reinforcement ratio is from 0.4% to 1.667%, the ultrasonic sound velocity is increased by 3.4%, the modal frequency is increased by 1.8%; the longitudinal reinforcement ratio is from 1.772% to 2.657%, the ultrasonic sound velocity is increased by 3.5%, and the modal frequency is increased 4.1%; the reinforcement can improve the ultrasonic sound velocity and the natural vibration frequency of the concrete to a certain extent, the change of the reinforcement ratio causes the same regular change of the sound velocity and the modal frequency.

1. Introduction

Reinforced concrete is a multi-phase composite material. The steel has certain influence on the physical and mechanical properties of the concrete. Ultrasonic non-destructive testing and structural vibration-based damage identification methods in structural damage problems correspond to the physical and mechanical properties of concrete structures[1]. In actual engineering, different concrete members generally have different reinforcement ratios. How to improve the efficiency and accuracy of detection in testing is the focus of current research[2]. Therefore, it is necessary to consider the reinforcement ratio of steel bars to ensure the accuracy of structural non-destructive testing.

At present, the methods for non-destructive testing of reinforced concrete structures are mainly ultrasonic methods and damage identification methods based on structural vibration[3-4]. Ultrasonic non-destructive testing is mainly affected by the environment and physical properties of concrete components, including temperature, humidity, section, reinforcement, compactness, water-cement ratio and aggregate[5]. Literature[6] mainly deals with the sensitivity of sonic tomography to hole defects in concrete members when the ratio of reinforcement is changed. The literature[7] illustrates the effect of reinforcement on the propagation of ultrasonic waves in concrete specimens by the axial direction of the reinforcement perpendicular to the direction of sound velocity propagation and parallel to the direction of sound velocity propagation. However, the research on the influence of the change of the reinforcement ratio on the ultrasonic sound velocity is limited, and it is valuable to consider the influence of the concrete reinforcement ratio on the sound velocity. The damage identification method based on structural vibration is mainly used to detect the natural vibration frequency of reinforced concrete structures[8]. The literature[9] shows that the reinforcement ratio is an important variable for the mechanical properties of different concrete members, and the influence on the elastic modulus of the members can not be ignored. The literature[10] studied the difference of equivalent modulus of
reinforced concrete members under different stress states, and proposed that the reinforcement ratio increases linearly with the elastic modulus of concrete. Literature\cite{11} studied the effect of reinforcement ratio on the stiffness of concrete frame structure, and found that the greater the reinforcement ratio, the more sensitive it is to the structural stiffness. Combined with the influencing factors of the natural frequency of the structure, it is very important to study the effect of the reinforcement ratio on the natural vibration frequency of the structure.

This paper mainly studies the ultrasonic sound velocity and natural vibration frequency of concrete short columns with different reinforcement ratios, and compares the effects of the hoop ratio and the longitudinal reinforcement ratio on the sound velocity and frequency. The aim is to improve the accuracy of non-destructive testing results for different reinforcement ratios in concrete structures. This study provides a reference for structural damage detection.

2. Experimental overview

13 reinforced concrete short columns are designed in this experiment. The length of short column is 940 mm, the diameter is 340 mm, and the strength grade of concrete is C40. The distribution of test points is shown in Fig 1, Fig 2. The change of reinforcement is shown in Table 1.

Fig 1. Ultrasound measuring point

Fig 2. Measurements of natural frequencies

Sound velocity of measuring points is measured by concrete ultrasonic detector. There are 70 measuring points in each column, which are divided into 14 rows and 5 rows. The location of steel bar is detected by steel bar detector. Longitudinal bars are distributed inside the first, third and fifth rows. At the same time, the natural frequencies of short columns are measured by modal testing instrument. Each column is equipped with three measuring points, and the first order natural frequencies of short columns are excited by force hammer.

3. Experimental results and analysis

3.1 Data Processing and Analysis of Ultrasound

The ultrasonic data of 13 concrete short columns are processed and analyzed. The sound velocity is selected as the research object. The M1 column was analyzed separately, and the ultrasonic sound velocity of some rows and columns was plotted into Figure 3 below using the graphic data processing software OriginPro.
A single concrete short column, the longitudinal reinforcement is symmetrically distributed. The main research is on the change of sound velocity caused by the position of the ultrasonic wave through the steel bar. The figure A selects 5 rows of data to observe the influence of the longitudinal reinforcement on the ultrasonic sound velocity, among which the first, third and fifth columns. The speed of sound is generally higher than the sound velocity of the 2nd and 4th columns in the same row. It shows that the longitudinal bar has an effect on the speed of sound in its propagation path, and the longitudinal bar can increase the speed of sound in its propagation path. The figure B mainly investigates the influence of stirrups on the ultrasonic sound velocity propagation. Three columns are selected as the research objects, and there is no obvious rule compared with the A chart. The main reason is that the diameter of stirrups is smaller. Although the propagation speed of ultrasonic wave in steel bar is faster than that in concrete, concrete can be regarded as one medium and steel bar as another medium because of the little difference in the composition of concrete matrix. When sound waves pass from one medium to another, refraction and reflection occur, and the transmission sound pressure is smaller than the diffraction sound pressure, thus affecting the propagation of sound velocity. From the diagram, it can be seen that the sound velocity of each column increases from left to right. The main reason is that the concrete compactness increases gradually from top to bottom, and the sound velocity in concrete is much faster than that in air, so the higher the compactness, the faster the sound velocity. As a result, for a single component, the larger the proportion of steel bar diameter in the sound speed propagation path, the faster the ultrasonic wave propagation speed.

The effect of reinforcement ratio on the ultrasonic sound velocity of concrete is studied below. The average sound velocity of each short column is listed in Table 1.

| Specimen number | Longitudinal reinforcement ratio % | Stirrups HPB300 | Volume ratio of stirrups % | Average velocity km/s | standard deviation |
|-----------------|-----------------------------------|-----------------|----------------------------|----------------------|-------------------|
| M1              | 2.215                             | φ 6@40          | 0.600                      | 4.042                | 0.142             |
| M2              | 2.215                             | φ 6@50          | 0.480                      | 4.041                | 0.057             |
| M3              | 2.215                             | φ 6@50          | 0.400                      | 4.022                | 0.086             |
| M4              | 2.215                             | φ 8@40          | 1.077                      | 4.095                | 0.095             |
| M5              | 2.215                             | φ 8@50          | 0.853                      | 4.045                | 0.084             |
| M6              | 2.215                             | φ 8@60          | 0.711                      | 4.091                | 0.084             |
| M7              | 2.215                             | φ 8@100         | 0.437                      | 4.087                | 0.069             |
| M8              | 2.215                             | φ 10@40         | 1.677                      | 4.161                | 0.101             |
| M9              | 2.215                             | φ 10@50         | 1.333                      | 4.228                | 0.121             |
| M10             | 2.215                             | φ 10@60         | 1.111                      | 4.200                | 0.254             |
| M11             | 1.772                             | φ 8@50          | 0.853                      | 4.039                | 0.276             |
| M12             | 2.657                             | φ 8@50          | 0.853                      | 4.179                | 0.053             |
| M13             | 0                                 | 0               | 3.851                      | 0.177                |
Since the reinforced concrete member is a composite material, it is impossible to fully reflect the influence of the reinforcement on the ultrasonic sound velocity by considering whether the ultrasonic propagation path has the participation of the steel reinforcement. The following is a comprehensive consideration of the variation of the ultrasonic sound velocity of the short column under different reinforcement ratios.

Firstly, the relationship between stirrup spacing and sound velocity is grouped. In the first group, M13, M3, M2 and M1, of which M13 is a column without reinforcement, and the stirrup diameter of the latter three columns is \( \phi 6 \), and the spacing is 60mm, 50mm and 40mm, respectively. The average sound velocities collected from 70 ultrasonic measuring points of each column are 3.851 km/s, 4.022 km/s, 4.041 km/s and 4.042 km/s, respectively; In the second group, M13, M7, M6, M5 and M4, the diameter of the rear four-column stirrups was \( \phi 8 \), and the spacing was 100 mm, 60 mm, 50 mm and 40 mm; In the third group, M13, M10, M9 and M8, the diameter of the rear three-column stirrups is \( \phi 10 \), the spacing is 60 mm, 50 mm and 40 mm. Fig 4 is drawn as follows.

Fig 4. Relation Diagram of Stirrup Spacing Change Reinforcement Ratio and Sound Velocity

The three groups of specimens studied the influence of stirrup spacing on ultrasonic velocity when the stirrup diameter was fixed. From the three groups of diagrams, it can be seen that with the decrease of stirrup spacing, the stirrup ratio increased, the increase of ultrasonic velocity was not obvious, but the overall rule increased with the increase of stirrup ratio.

Then, the relationship between stirrup diameter and sound velocity is grouped. In the first group, M13, M1, M4 and M8, of which M13 is a column without reinforcement, and the stirrup spacing of the latter three columns is 40mm, with diameters of \( \phi 6 \), \( \phi 8 \) and \( \phi 10 \), respectively; In the second group, M13, M2, M5 and M9, the spacing of the stirrups of the rear three columns is 60mm, and the diameters of stirrups are \( \phi 6 \), \( \phi 8 \) and \( \phi 10 \), respectively; In the third group, M13, M3, M6 and M10, the stirrup spacing of the latter three columns is 80mm, and the diameters of stirrups are \( \phi 6 \), \( \phi 8 \) and \( \phi 10 \), respectively. Draw Figure 5.

Fig 5. The relationship between stirrup diameter change reinforcement ratio and sound velocity

The effect of stirrup diameter on the ultrasonic velocity of the three groups of specimens is studied under the condition of a certain stirrup spacing. From the above three groups of diagrams, it can be seen that the diameter of stirrups increases, the reinforcement ratio increases, and the effect of ultrasonic lifting is relatively obvious.
Finally, the influence of longitudinal reinforcement ratio on ultrasonic velocity is analyzed. The stirrups of the rear three columns M13, M11, M5 and M12 are \( \phi 8@50 \). Longitudinal bars are \( 8\Phi 6 \), \( 10\Phi 16 \) and \( 12\Phi 16 \), respectively. The average sound velocity is 4.036 km/s, 4.045 km/s and 4.179 km/s. The change range of sound velocity increases with the increase of diameter, and the change range is 3.5%, which is relatively small. The relationship between longitudinal reinforcement ratio and sound velocity is shown in Fig. 6.

Fig. 6. Relation Diagram of Reinforcement Ratio and Sound Velocity of Longitudinal Bars.

In conclusion, the reinforcement affects the propagation of ultrasonic velocity in concrete, and the reinforcement of concrete members can obviously increase the propagation speed of acoustic wave, but the increase of reinforcement ratio has little effect on the propagation of ultrasonic velocity. Among them, the effect of stirrup spacing on ultrasonic velocity of concrete is small, and the ultrasonic velocity increases with the increase of stirrup diameter and longitudinal reinforcement ratio, and the increase is relatively large. To study the effect of reinforced short columns and unreinforced short columns on ultrasonic velocity, the maximum sound velocity M9, 4.228 km/s, M13 and 3.851 km/s of unreinforced short columns are selected. Compared with unreinforced short columns, the maximum sound velocity of reinforced short columns is 8.9%.

### 3.2 Data Processing and Analysis of Natural Vibration Frequency

Firstly, the modal data of 13 concrete short columns are processed and analyzed, and the natural frequency is selected as the research object. The natural frequencies of different measuring points of each column are listed in Table 2 below.

| Specimen number | Natural frequency |
|-----------------|------------------|
| M1              | 26.152 (P1)      |
|                 | 26.109 (P2)      |
|                 | 26.087 (P3)      |
|                 | 26.116 (average) |
| M2              | 26.106 (P1)      |
|                 | 26.098 (P2)      |
|                 | 26.098 (P3)      |
|                 | 26.101 (average) |
| M3              | 25.781 (P1)      |
|                 | 25.781 (P2)      |
|                 | 25.918 (P3)      |
|                 | 25.826 (average) |
| M4              | 26.201 (P1)      |
|                 | 26.212 (P2)      |
|                 | 26.178 (P3)      |
|                 | 26.197 (average) |
| M5              | 26.172 (P1)      |
|                 | 26.153 (P2)      |
|                 | 26.164 (P3)      |
|                 | 26.163 (average) |
| M6              | 26.071 (P1)      |
|                 | 26.056 (P2)      |
|                 | 26.047 (P3)      |
|                 | 26.058 (average) |
| M7              | 25.902 (P1)      |
|                 | 25.927 (P2)      |
|                 | 25.878 (P3)      |
|                 | 25.902 (average) |
| M8              | 26.315 (P1)      |
|                 | 26.315 (P2)      |
|                 | 26.306 (P3)      |
|                 | 26.312 (average) |
| M9              | 26.202 (P1)      |
|                 | 26.202 (P2)      |
|                 | 26.217 (P3)      |
|                 | 26.207 (average) |
| M10             | 26.159 (P1)      |
|                 | 26.173 (P2)      |
|                 | 26.173 (P3)      |
|                 | 26.168 (average) |
| M11             | 25.429 (P1)      |
|                 | 25.473 (P2)      |
|                 | 25.473 (P3)      |
|                 | 25.458 (average) |
| M12             | 26.509 (P1)      |
|                 | 26.509 (P2)      |
|                 | 26.509 (P3)      |
|                 | 26.509 (average) |
| M13             | 24.918 (P1)      |
|                 | 24.942 (P2)      |
|                 | 24.942 (P3)      |
|                 | 24.934 (average) |

With the above ultrasonic grouping, first consider the influence of the stirrup spacing. The first group of M13, M3, M2, and M1 have frequency values of 24.934 Hz, 25.826 Hz, 26.101 Hz, and 26.116 Hz, respectively. The spacing of the stirrups is increased, the reinforcement ratio of the stirrups is reduced, the elastic modulus of the concrete members is reduced, and the stiffness of the members is
reduced, thereby affecting the natural vibration frequency of the members, and the natural frequency of the short columns decreases with the reinforcement ratio. The decline was 0.8%. The second group of M13, M7, M6, M5, M4, the frequency values are 24.934Hz, 25.902Hz, 26.058Hz, 26.163Hz, 26.197Hz, the reinforcement ratio increases, the natural vibration frequency also increases, the variation range is 1%. The third group M13, M10, M9, M8, the frequencies are 24.934Hz, 26.168Hz, 26.207Hz, 26.312Hz, respectively, with the second group of variation rule, the variation range is 0.55%. The relationship between the stirrup spacing change and the self-vibration frequency is shown in Fig 7.

Then the influence of stirrup diameter changing reinforcement ratio on the natural frequencies of members is studied. The frequencies of M13, M1, M4 and M8 in the first group were 24.934 Hz, 26.116 Hz, 26.197 Hz and 26.312 Hz, respectively. With the increase of stirrup diameter, the reinforcement ratio increases, and the natural frequency of concrete short columns increases, with a variation of 0.6%; The frequencies of M13, M2, M5 and M9 in the second group were 24.934 Hz, 26.101 Hz, 26.163 Hz and 26.207 Hz, respectively. With the increase of stirrup diameter, the reinforcement ratio increases, and the natural frequency of concrete short columns increases, with a change of 0.4%; The frequencies of M13, M3, M6 and M10 in the third group are 24.934 Hz, 25.826 Hz, 26.058 Hz, 26.168 Hz, respectively. With the increase of stirrup diameter, the reinforcement ratio increases, and the natural vibration frequency of short concrete columns increases accordingly, with a variation of 0.98%. The relationship between stirrup spacing and natural frequencies is shown in Fig 8.

Finally, the effects of longitudinal reinforcement ratio on the natural frequencies of components M13, M11, M5 and M12 are studied. The frequencies are 24.934 Hz, 25.458 Hz, 26.163 Hz and 26.509 Hz, respectively. With the increase of longitudinal reinforcement ratio, the natural frequencies increase, and the variation range is 4.1%. Draw in Fig 9. Fig 10 shows the first-order mode shapes of column 3.
To sum up, the natural frequency of concrete members is the inherent property of the structure. With the increase of reinforcement ratio, the elastic modulus of concrete members will increase accordingly. Therefore, through the reinforcement ratio, the elastic modulus of concrete will be affected, and then the stiffness of components will be affected, so that the natural frequency of components will change. With the increase of reinforcement ratio, the natural frequencies of components will also be increased. For the comparison of short columns without reinforcement and short columns with reinforcement, the maximum natural frequencies of short columns M12 and short columns M13 without reinforcement are 26.509 Hz and 24.934 Hz, respectively, with a variation of 6.3%. Reinforcement can significantly increase the natural frequencies of concrete members.

4. conclusions and Prospects

In this paper, the effect of reinforcement ratio on ultrasonic velocity and modal frequency is studied and the following conclusions are drawn.

1. The speed of sound will increase, but not significantly, when the location of reinforcing steel bar is detected by ultrasonic wave. The larger the proportion of reinforcing steel bar diameter in the path of sound speed propagation, the faster the speed of ultrasonic wave propagation.

2. The stirrup ratio and longitudinal reinforcement ratio of concrete members will affect the transmission of ultrasound, but the effect of stirrup spacing on the ultrasonic velocity is not obvious, the maximum increase is 1.6%. The change of stirrup diameter can increase the ultrasonic velocity by 4.6%. The change of longitudinal reinforcement ratio will also cause the increase of ultrasonic velocity, with the maximum variation of 3.5%. The maximum increase of sound velocity is 8.9% with the increase of reinforcement ratio in this experiment.

3. The natural vibration frequency of concrete members is directly affected by the stiffness of the members. The elastic modulus of concrete is a variable of stiffness. The reinforcement can change the elastic modulus of concrete members. Therefore, the reinforcement ratio is also an indirect variable of the natural vibration frequency of the members. From this experiment, the reinforcement can significantly increase the natural vibration frequency of the concrete circular section short column, the maximum increase is 6.3%. The increase of the reinforcement ratio causes the natural vibration frequency of the member to change regularly. The maximum increase of the natural reinforcement frequency of the stirrup reinforcement ratio is 1.8%, and the maximum increase of the longitudinal reinforcement reinforcement ratio to the natural vibration frequency is 4.1%.

4. In this paper, the influence of the reinforcement ratio on the ultrasonic sound velocity and the vibration frequency of the component is detected. The non-destructive testing is a very practical method for the detection of concrete damage. However, the relative error of non-destructive testing is relatively large, and the influencing factors are relatively complex and effective. Improving the measurement accuracy of non-destructive testing of concrete structures is of great significance for the protection of concrete structures.

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