Influence of Joint Dip Angle on Dynamic Mechanical Properties and Crack Propagation Law of Rock-like Materials

Xiaoshuai Li¹, Lianjun Guo² and Wenzhou Gao¹

¹ Faculty of Architecture, Civil and Transportation Engineering, Beijing University of Technology, Beijing, 100124, China
² School of Architecture and Civil Engineering, Shenyang University of Technology, Shenyang, Liaoning, 110870, China

Corresponding author: wxgao@bjut.edu.cn, Wenzhou Gao
First author: 516741249@qq.com, Xiaoshuai Li

Abstract. The main objective of this study is to investigate the dynamic mechanical properties and crack propagation law of rock-like materials with different joint dip angles. The precast cement mortar specimens are impacted by split Hopkinson pressure bar (SHPB). The meso damage of the specimens before and after impact is detected by nuclear magnetic resonance system (NMR), and the crack propagation path is extracted. The influence of joint dip angles on dynamic response characteristics of rock-like materials is analyzed from the aspects of dynamic compressive strength, meso damage and crack propagation path. The analysis indicates that joints make the internal stress distribution of rock-like materials uneven, resulting in the weakening of the dynamic compressive strength of rock-like materials. At the same time, joint characteristics affect the weakening degree of the dynamic compressive strength of rock-like materials. With the increase of joint dip angle, the weakening degree of dynamic compressive strength of rock-like materials first increases and then decreases. The relationship between the damage degree and the dynamic compressive strength of rock-like materials is approximately negative linear. With the increase of joint dip angle, the damage degree changes in an inverted "U" shape. Tensile stress or the combination of tensile stress and shear stress leads to the initiation and propagation of cracks. The intact specimens, the specimens with joint dip angle of 0°, and the specimens with joint dip angle of 90° develop axial tensile cracks. The specimens with joint dip angles of 15°-75° develop tensile cracks and shear cracks at the joint tips.

Keyword. Jointed rock mass, SHPB, dynamic compressive strength, meso damage, crack propagation.

1. Introduction

In the construction of transportation, mining, hydropower and other projects, the relevant design and construction are generally based on rock mass, such as subgrade engineering, roadway engineering, dam foundation of hydropower station, etc. The vast majority of rock mass is composed of rock and
various discontinuities. As a common discontinuity, the joints in rock mass have a significant impact on the mechanical behavior of rock mass. At the same time, rock engineering construction is mainly based on drilling and blasting method. Under the dynamic disturbance, jointed rock mass is prone to rock burst, collapse and other geological disasters. Therefore, it is very important to correctly understand the mechanical properties and crack propagation law of jointed rock mass under dynamic load to ensure the stability and safety of rock mass engineering.

The mechanical behavior of jointed rock mass is closely related to the geometric characteristics of joints. Many scholars have carried out a large number of physical experiments to study the above phenomena [1-5]. Yang et al. [6] carried out the research on the influence of joint thickness on the dynamic characteristics of rock. They found that with the increase of joint thickness, the dynamic compressive strength of jointed rock decreased and the energy dissipation increased. Niktabar et al. [7] believed that the cyclic shear action along the joint plane may occur under the action of dynamic load, which will seriously affect the stability of rock mass structure. Therefore, they conducted shear tests on joint specimens with different rough rolling angles, and found that the shear strength of the specimens is in direct proportion to the rough rolling angle. Wang et al. [8] used SHPB to carry out impact tests on cement mortar specimens with 0-3 horizontal penetrating joints, and obtained the influence law of joint number on energy transfer, compressive strength and failure mode of rock specimens under impact load. Ma et al. [9] deeply studied the dynamic mechanical characteristics of through joint specimens with different dip angles. It was found that the difference of joint dip angles had a significant impact on the dynamic compressive strength and crack propagation law of sandstone.

Due to the difficulty in preparation of non-penetrating joint specimens, the above studies all focus on penetrating joints. However, there are some shortcomings in using penetrating joint specimens to analyze the crack propagation law. Researchers cannot get the influence of joint characteristics on the crack initiation location and propagation path of cracks. At present, there are few studies on the dynamic mechanical properties and crack propagation law of non-penetrating jointed rock.

The crack initiation and propagation of non-penetrating joint rock mass is greatly different from that of penetrating joint rock mass, under the action of earthquake, blasting, mechanical vibration and other dynamic forces [10,11]. Therefore, it is necessary to study the dynamic mechanical properties and crack propagation law of rock mass with non-penetrating joints. In order to reveal the influence of joint dip angle on the dynamic response of rock like materials with non-penetrating joints, SHPB tests were carried out on cement mortar specimens with different joint dip angles. Combined with the NMR test results of cement mortar specimens before and after impact, the influence rules of joint dip angle on dynamic compressive strength, meso damage and crack propagation path of rock-like materials were analyzed. The research results can provide reference for the design and construction of related rock engineering.

2. Experimental study

2.1. Preparation of cement mortar specimens with joints

Cement mortar was used to make rock-like material specimens. Referring to the method of preparing brittle rock-like material specimens by Wang et al. [12], the cement with grade P·O 42.5 was selected, fine sand with particle size ≤0.6 mm was used for fine aggregate, and the mix proportion was $m_{\text{cement}}$.
m\text{cement}: m\text{water} = 1:2:0.5. After casting, they were cured in standard environment for 28 days. Generally, in SHPB tests, the ratio of length to diameter of Φ50 mm cylindrical specimen ranges from 0.4 to 1.0 [13], so as to reduce the error caused by inertial effect and end friction effect. In this experiment, the ratio of length to diameter of the specimens in quasi-static compression tests is used for reference, and the ratio of length to diameter of the specimen is adjusted to 2.0, which can better observe the propagation path of cracks, and will not affect the qualitative analysis of the influence of joint dip angle on the dynamic compressive strength of the cement mortar specimens under the same loading conditions.

In this study, intact specimens (as shown in figure 1, No. 1#) and seven kinds of non-penetrating joint specimens with different dip angles (as shown in figure 1, No. 2# - 8#) were designed. The joint parameters of the specimens are shown in figure 1. Two groups of intact specimens with three specimens in each group were prepared. For specimens with joints, the number of specimens with each dip angle is three, a total of twenty-one specimens with single joint. In addition, in order to obtain the basic physical and mechanical parameters of cement mortar material, a batch of standard specimens were prepared. The average elastic modulus, uniaxial compressive strength and Poisson's ratio of the specimens were obtained through uniaxial compression test. At the same time, the average density of the specimens was also measured. Table 1 shows the basic physical and mechanical parameters of cement mortar specimens with this mix proportion.

| Mix proportion | Elastic modulus (GPa) | Uniaxial compressive strength (MPa) | Poisson's ratio | Density (g·cm⁻³) |
|----------------|----------------------|-----------------------------------|----------------|-----------------|
| 1:2:0.5        | 25.27                | 32.47                             | 0.29           | 2.15            |

2.2. Experimental scheme

The experiment is divided into five steps: 1) determining the critical impact pressure to meet the experimental requirements; 2) detecting the initial meso damage of the specimens using NMR system; 3) conducting SHPB tests under the same impact pressure; 4) detecting the meso damage of the specimens after impact; 5) studying the law of crack propagation.

The experimental instruments mainly include a loading system and a damage detection system, as shown in figure 2. The SHPB system was used to carry out impact tests on cement mortar specimens. The length of incident bar, transmitted bar and buffer bar are 1800 mm, 1800 mm and 1000 mm
respectively, and the diameter of the three bars are 50 mm. The size of the cylindrical punch is Φ50 mm×300 mm. The signals of incident wave, reflected wave and transmitted wave were collected by LK2109A ultra dynamic strain gauge. Laser velocimeter was used to record the speed of cylindrical punch. Through the dynamic compressive strength tests of a group of intact specimens under different impact pressures, the critical impact pressure value satisfying the observation of crack propagation path was determined to be 0.11 MPa.

Figure 2. Loading system and damage detection system for testing.

MacroMR12-150H-I NMRI system was used to detect the meso damage of cement mortar specimens. The key to reduce the error of NMR damage detection is to make the specimens fully saturated with water. Therefore, before the initial damage detection and secondary damage detection, the specimens should be immersed in water for 6h and the water level should be over 4 mm above the top of the specimens. Then the specimens were saturated with water in ZYB-II vacuum pressure saturation device, the pressure was controlled at 15 MPa, the saturation time was 12h. After water saturation, the pore structure parameters of the specimens were tested in time.

3. Experimental results and discussion

3.1. Stress-strain curve analysis

The impact tests were carried out on the intact specimens and seven kinds of non-penetrating joint specimens with 0.11 MPa air pressure, and three groups of repeated tests were conducted for each dip angle. After processing SHPB test data, the stress-strain curves of cement mortar specimens were obtained. Representative stress-strain curves were selected from three groups of experiments for dynamic mechanical properties analysis, as shown in figure 3. Through the analysis, it can be seen that: at the initial stage of loading (OA segment of curves), the specimens have elastic deformation under compression, and at this stage, all the curves rise approximately in a straight line. From the slope of curves, it can be seen that the elastic modulus of the intact specimen is the largest, and that of specimen with joint dip angle of 45° is the smallest. From inflection point A to vertex B, the elastic potential energy stored in the specimens is released, which leads to the initiation and expansion of microcracks, and finally leads to the plastic deformation of the specimens. From the slope of the
curves at this stage, it can be seen that the plastic deformation of specimens with joint dip angle of 45° and 60° is the fastest, followed by 30°, 75°, 0°, 90°, 15°, and the deformation of the intact specimen is the slowest. The analysis shows that the specimens with joint dip angle of 45° and 60° are greatly affected by the shear stress, and these specimens are prone to sliding failure along the preset joint, so they are more prone to deformation.

When the stress reaches the peak value, the cement mortar specimens begin to soften (BC segment of curves), and the stress-strain curves of all kinds of specimens begin to decrease, but there are obvious differences in the shape of the curves. The stress-strain curves of the intact specimen and the specimens with joint dip angle of 45° and 60° decrease approximately vertically, which indicates that brittle failure occurs in these three types of specimens. When the joint dip angle is 15°, 45° and 75°, the stress-strain curves first decrease slowly and then decrease rapidly, indicating that the specimens still have the ability to resist external load at the initial softening stage, and then the resistance disappears and the stress decreases rapidly. When the joint dip angle is 60°, the specimen is affected by the sliding of the joint surface, so that it has the ability to resist the load in the softening stage, and there is no sudden drop of stress.

![Stress-strain curves of specimens.](image)

**Figure 3. Stress-strain curves of specimens.**

3.2. **Dynamic compressive strength analysis**

Figure 4 shows the curve of dynamic compressive strength changing with joint dip angle. Under the similar impact load, the joint dip angle has a significant effect on the dynamic compressive strength of cement mortar. The dynamic compressive strength of cement mortar first decreases and then increases with the increase of joint dip angle, showing a "U" type change. The average dynamic compressive strength of the intact specimens is 89 Mpa, and the average dynamic compressive strength of specimens with the joint dip angle of 0°-90° is 77 MPa, 66 MPa, 62 MPa, 52 MPa, 54 MPa, 69 MPa and 83 MPa, respectively, accounting for 86.52%, 74.16%, 69.66%, 58.43%, 60.67%, 77.53% and 93.26% of the average dynamic compressive strength of the intact specimens. Therefore, when the joint dip angle is 0° and 90°, the joints have the least influence on the dynamic compressive strength of cement mortar, and when the joint dip angle is 45° and 60°, the joints have the greatest influence on
the dynamic compressive strength of cement mortar.
Based on the analysis of the above results, it is considered that the joint is the cause of the decrease of the dynamic compressive strength of cement mortar, and the dip angle of the joint affects the decrease degree of the dynamic compressive strength. The existence of joints makes the internal stress concentration of cement mortar specimens occur, which leads to uneven internal stress distribution and local high stress at joints, resulting in the decrease of overall dynamic compressive strength. When the joint dip angle increases from 0° to 45°, the sliding failure of specimens along the joint surface intensifies, which leads to the weakening of the ability of specimens to bear the load. Therefore, the dynamic compressive strength of specimens gradually decreases. The optimal failure angle range of 45°-60° is more prone to failure than other angles, so the dynamic compressive strength of the specimens within this dip angle range is the lowest. With the further increase of the dip angle, the sliding failure along the joint surface decreases and the dynamic compressive strength increases.

3.3. Meso damage analysis
According to the pore radius distribution curves (as shown in figure 5) and T2 spectral area variation characteristics (as shown in table 2), the meso damage of specimens with different joint dip angles under similar impact load was analyzed. Based on the research of Shear D L [14] and Liu et al. [15], the porosity of cement mortar specimens is divided into four grades: 0-0.1 μm belongs to micropore, 0.1-1 μm belongs to mesopore, 1-10 μm belongs to macropore, larger than 10 μm is fracture pore.
After analyzing figure 5, it is found that before impact, the microstructure of all specimens is dominated by micropores, accompanied by a small number of mesopore and macropores, almost no fracture pores. After impact, the pore radius distribution curves of all specimens become obvious three peaks structure, and the internal microstructure of the specimens change. In the range of 0-0.1 μm, the...
pore radius distribution curve of the intact specimen decreases but do not move to the right, indicating that the micropores in the intact specimen are compacted under the external load, while the pore radius distribution curves of the other kinds of specimens decrease and move to the right, indicating that the micropores in these specimens develop into micropores with larger diameter under the external load. In the range of 0.1-100 μm, the number of mesopores, macropores and fracture pores in all specimens increased. Further quantitative analysis of the microstructure change of the specimens was carried out through figure 6. After impact, the proportion of micropores decreases by 8.15%-12.31%, the proportion of mesopores increases by 2.51%-3.96%, the proportion of macropores increases by 4.48%-6.66%, and the proportion of fracture pores in the range of 10-100 μm increases by 0.54%-2.90%. The growth rate of macropores in all kinds of specimens is the fastest, followed by mesopores and fracture pores. There are two main reasons for the decrease of the proportion of micropores. On the one hand, the growth of mesopores and macropores is greater than that of micropores, which leads to the decrease of the proportion of micropores. On the other hand, some micropores develop into mesopores and macropores, and some micropores are compacted by external force. It can also be found from figure 6 that for the specimens with joint dip angle of 0°-75°, the proportion of mesopores and macropores increases first and then decreases. For the specimens with joint dip angle of 30°, the proportion of mesopores increases the most, while for the specimens with joint dip angle of 45°, the proportion of macropores increases the most. The results show that the specimens with different joint dip angles have different ability to absorb the energy of stress wave. The more absorbed the energy, the easier the internal pores are activated and expanded, which will lead to more mesopores, macropores and fractured pores. For the intact specimens and the specimens with joint dip angle of 90°, because the micropores are compacted and the amount of new micropores is very small, the proportion of micropores decreases greatly, and the proportion of mesopores, macropores and fracture pores is relatively high.

![Figure 6. Dynamic compressive strength of specimens.](image)

The T₂ spectral area of specimens before and after impact is shown in table 2. After impact, the spectral area of intact specimens increases by 14.56%, and the spectral area of specimens with joint dip angle of 0°-90° increases by 14.21%, 23.48%, 31.44%, 35.00%, 31.84%, 25.48% and 21.09% respectively. From the change rate of T₂ spectral area, the internal damage of specimens increases in different degrees after impact. Generally, the joint dip angle increases from 0° to 45°, and the damage gradually increases, while the joint dip angle increases from 45° to 90°, and the damage gradually decreases. The specimens with joint dip angle in the range of 30°-60° have larger damage, and the pore growth rate is more than 30%. The damage of specimens with joint dip angle of 0° and intact
specimens is the smallest, and the pore growth rate is about 14%. By comparing the curve of dynamic compressive strength changing with joint dip angle and damage curve, as shown in figure 7, it can be found that under the action of similar dynamic load, the dynamic compressive strength of specimens with different joint dip angle has a negative linear relationship with damage, and the lower dynamic compressive strength of the specimens with the greater damage.

Table 2. Variation of T2 spectral area of specimens before and after impact.

| Group | T2 spectral area before impact S_B | T2 spectral area after impact S_A | ΔS | ΔS/S_B |
|-------|-----------------------------------|----------------------------------|-----|--------|
| Intact | 80451                             | 92164                            | 11713 | 14.56% |
| 0°     | 120180                            | 137252                           | 17072 | 14.21% |
| 15°    | 112339                            | 138717                           | 26378 | 23.48% |
| 30°    | 102451                            | 134666                           | 32215 | 31.44% |
| 45°    | 99538                             | 134376                           | 34838 | 35.00% |
| 60°    | 99010                             | 130532                           | 31522 | 31.84% |
| 75°    | 109294                            | 137137                           | 27843 | 25.48% |
| 90°    | 110615                            | 133947                           | 23332 | 21.09% |

3.4. Analysis of crack propagation path
The crack propagation path of cement mortar specimens with different joint dip angles after impact is shown in figure 8. When the intact specimen (figure 8a) and the specimen with joint dip angle of 90° (figure 8h) are subjected to impact load, a large tensile stress is generated along the radial direction of the specimens, so a tensile crack parallel to the loading direction occurs in the middle of the specimens. It can be seen from the crack propagation path of the upper and lower end faces of the specimens that there is obvious difference. The tensile crack of the specimen with joint dip angle of 90° has stronger directionality and is almost a straight line, while the tensile crack of the intact specimen has multiple
turns and branches.

When the joint dip angle is 0° (figure 8b), there is a large tensile stress in the middle of the prefabricated joint. Although there is stress concentration at both ends of the joint, the stress at both ends of the joint is released with the propagation of the wing cracks in the middle of the joint, so only the wing cracks parallel to the loading direction appear. When the joint dip angle is 15° (figure 8c), the crack initiation position of the wing cracks moves from the middle of the joint to the two ends of the joint. The crack initiation direction of the wing cracks is approximately perpendicular to the prefabricated joint, and the final propagation direction of the wing cracks is parallel to the loading direction. Meanwhile, the anti-wing cracks appear at the right end of the prefabricated joint under the influence of shear stress. When the joint dip angle is 30° (figure 8d), wing cracks and anti-wing cracks appear at both ends of joint. In addition, there is a coplanar crack at the left end of joint, which is caused by shear stress. When the joint dip angle is in the range of 45°-75° (figure 8e-g), the anti-wing cracks at both ends of the joint disappear, only wing cracks and coplanar cracks develop, and the coplanar cracks of the specimens with joint dip angles of 45° and 60° expand fully, forming large fan-shaped shear failure zones, which indicates that the specimens are most affected by shear stress when the joint dip angle is 45°-60°.

By analyzing the crack propagation path of the specimens, it can be found that the angle between the joint and the compressive stress changes due to the different dip angles of the joint, thus forming different stress fields, and finally making the specimens appear different forms of cracks, which is consistent with the conclusion of Zhang [16]. The intact specimens and the specimens with joint dip angle of 0° and 90° are mainly affected by tensile stress, and the tensile failure occurs. The specimens with joint dip angle of 15°-75° are mainly subjected to the combined action of tensile stress and shear stress, resulting in tension-shear compound failure, and the shear stress intensity first increases and then decreases with the increase of joint dip angle. In addition, the crack initiation location of wing cracks is not always located at both ends of the joint. When the dip angle of the joint is less than 15°, the initiation location of wing cracks is very likely to be near the joint center.

4. Conclusion
In this paper, we analyzed the influence of joint dip angle on dynamic compressive strength, meso damage and crack propagation path of cement mortar specimens in detail by means of SHPB impact tests and NMR tests. The conclusions are summarized follows:

(1) Under the similar impact load, the dynamic compressive strength of the specimens with different joint dip angles changes in a "U" shape with the increase of joint dip angle. When the joint dip angle is in the range of 45°-60°, the dynamic compressive strength of the specimens reaches the lowest value. When the joint dip angle is 90°, the dynamic compressive strength of the specimens is closer to the compressive strength of the intact specimens than the specimens with other dip angles.

(2) The meso damage of specimens with different joint dip angles is approximately linearly correlated with dynamic compressive strength. With the increase of joint dip angle, the meso damage of specimens increases first and then decreases, showing an inverted "U" shape. The specimens with the joint dip angle in the range of 30°-60° are most seriously damaged.

(3) Prefabricated joints with different dip angles affect the propagation law of cracks. When the dip angle of the joint is less than 15°, the tensile stress extremum area appears in the middle of the joint, forming tensile cracks. When the joint dip angle in the range of 15°-75°, tensile and shear stress concentration areas appear at both ends of the joint, and tensile and shear cracks form at both ends of the joint. When the joint dip angle is 90°, the tensile stress concentration area appears at both ends of the joint, and only tensile cracks form at both ends of the joint.

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