Experimental study on tension-compression alternation of fully-graded concrete under cyclic loading

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Abstract. Considering the reciprocating effect of seismic load and the initial compressive stress level of high arch dam, a feasible test procedure is designed by using the 15MN large dynamic material testing machine and special connection devices. The tension-compression alternating test of fully-graded concrete specimens under cyclic loading of about 5MPa compressive stress level is carried out. By means of the VIC-3D non-contact full-field strain measurement system and high-precision axial extensometer, a complete tension-compression alternating stress-strain curve of fully-graded concrete under 5 MPa compressive stress level is obtained. Based on that the tension-compression damage evolution law for this whole process of fully-graded concrete is summarized, which provides data support for studying the damage evolution of arch dams under reciprocating seismic loads.

1. Introduction
China's hydropower resources rank first in the world, and about 80% of the hydropower resources are concentrated in the west. At present, Baihetan, Xiluodu, Xiangjiaba, Jinping, Ertan and Dagangshan are among the highest for the reservoir dams being built in this region.

But the western region is also a seismically active area, where 82% of the strong earthquakes occurred in the mainland of China in modern times. Once the high dam reservoir is destroyed by strong earthquake, the consequences are unimaginable. Seismic safety of high arch dams has become a key technical problem to be highly concerned and urgently solved [1,2]. For seismic safety evaluation of high dams, the result is highly dependent on the structural resistance, especially the dynamic properties of concrete [3,4].

The tension-compression alternating test of fully-graded concrete can reflect to the most the whole process of the material evolution from linear to non-linear tension-compression damage of high reservoir dam under the action of earthquakes. It is of great significance to study the mechanical behavior and deformation mechanism of fully-graded concrete under earthquake loading.

The 15MN large-scale dynamic material testing machine of China Institute of Water Resources and Hydropower Research has advanced performance. Based on the dam projects including Xiluodu, Three Gorges, Shapai and Fengman, a series of mechanical properties tests of fully-graded concrete have been carried out [5-8].

Considering the reciprocating effect of seismic load and the high compressive stress in the high arch dam, by using the 1500 tons large-scale dynamic material testing machine and special connection devices, a feasible test scheme has been designed, and the tension-compression alternating test of fully-graded concrete specimens under cyclic loading and an additional compressive stress of about 5
MPa is carried out. By means of VIC-3D non-contact full-field strain measurement system and high precision axial extensometer, the complete tension-compression alternating stress-strain curves of fully-graded concrete is obtained. On that basis, the evolution law of tension-compression damage of fully-graded concrete is summarized, which provides data support for studying the damage evolution of concrete dams under seismic loads.

2. Tension-compression test scheme of fully-graded concrete under cyclic loading

2.1. Preparation of specimens
Since the maximum aggregate size of fully-graded concrete can reach up to 150 mm and the cross-section size of the specimens should be no less than 3 times that size, the test specimens are cylindrical with a diameter of 450mm and a length of 1470 mm. The middle part of each specimen with a length of 680mm is cast with fully-graded concrete. To ensure that the specimen cracks at that part, reinforced two-graded concrete are used to cast the rest of the specimen according to the standard. A typical specimen is shown in Fig. 1.

![Figure 1. A specimen](image_url)

2.2. Loading and control system
The test is carried out in China Institute of Water Resources and Hydropower Research by using the 15MN large-scale dynamic material testing machine as shown in Fig. 2.
The specific parameters of 15MN large dynamic material testing machine are as follows.

- The total height of the rack is about 8200 mm, and the horizontal test space is 2500 mm.
- Rated load capacity: 15MN compressive force (actuator extension), 8MN tension force; stroke: +300mm (total 600mm);
- 15MN and 2.5MN sensors are used for load measurement and control; 15MN differential pressure sensor is between 2.5MN and 15MN, the measurement error is less than (+0.5%) and the indication variation is less than (+0.1%); 2.5MN load sensor is within the range of 10%-100%, the measurement error is less than (+0.5%) and the indication variation is less than (+0.1%).
- 249.51 articulated seat assemblies, rated force (+1000kN), rotation angle (+90 degrees or -30 degrees), inclination angle (+8 degrees), can be used for static and cyclic testing, weighing about 510kg.
- The working frequency range is 0.001Hz to 10.0Hz, in which range there is no resonance between the frame and the actuator.
- The ultimate tension of the fully-graded concrete axle-tension specimen is about 500 kN by estimation, so to ensure the measurement and control accuracy, 2.5 MN sensor and (+1000 kN) hinged seat assembly are selected in the experiment.
- Full digital closed-loop control is adopted, and all control channels have 32-bit digital arbitrary waveform generator. Load, displacement and strain control modes can be provided, and the three control modes can be switched arbitrarily. The sampling and feedback frequencies of the data are higher than 5kHz, and the update frequencies of the closed-loop control of the controller are higher than 5kHz.

2.3. Measuring system of axial tension-compression test

In the uniaxial tension test of fully-graded concrete specimens, high precision extensometers are used to measure the deformation of the specimen in the tension-compression zone. The accuracy can reach 0.0003 mm. Even tiny change in the deformation of the specimen can be accurately obtained in real time. Therefore, deformation measured by the high precision extensometer is used as the key point control signal. Considering the inhomogeneity of concrete cracking, four high precision extensometers are arranged in the pure tension zone of fully-graded tension-compression specimens.

The VIC-3D non-contact full-field strain measurement system is adopted (Fig. 3). By printing hundreds of thousands of data acquisition points on the surface of the specimen, the spatial position changes of all the points can be observed at the same time, and the three-dimensional displacement
field and deformation field can be obtained by the difference. Moreover, from the collected massive raw data the hot spots from the previously acquired images can be extracted and data mining and analysis can be conducted again without re-testing. What’s more, since VIC-3D is non-contact measurement, it has no effect on the specimen itself.

VIC-3D non-contact full-field strain measurement system can synchronously collect the load signal of the testing machine as input signal, and can study the stress-strain relationship of non-linear damage of the concrete based on the strain field.

2.4. Tension-compression test scheme

For an arch dam with a height of 200-300 meter, the compressive stress in the dam due to self-weight is about 5-7 MPa. Considering the rated force value of the articulated seat assembly used in this test (+1000kN), the cyclic load of this test is set at 800KN, and the compressive stress of the corresponding specimen is about 5 MPa.

Because the ultimate tensile stress of specimens is unknown, step-by-step loading method is adopted. In order to obtain the stable tensile failure process of fully-graded concrete, the cyclic loading is realized by means of systematic displacement control.

When using displacement loading mode, the selection of key control parameters of tension-compression conversion is crucial to the success of the test. The longitudinal deformation of the specimen obtained by high precision extensometer is used as the key control parameter in the tension stage of the cyclic load. Under this control mode, when the deformation of the whole specimen reaches a certain set value, the displacement of the system begins to reverse load.

For the compression stage, because the compressive stress of the specimen is much smaller than its ultimate compressive stress, a fixed value for the pressure is adopted. In other words, under displacement control, when the system load reaches 800KN, the system displacement begins to reverse load.

3. Tension-compression test of fully-graded concrete under cyclic loading

3.1. Post-failure photographs of full-scale concrete tension-compression specimens under cyclic loading
Tension-compression alternating tests of fully-graded concrete under cyclic loading were carried out and the damaged specimens are shown in Fig. 4.

![Post-failure photographs of specimens under cyclic loading](image)

**Figure 4.** Post-failure photographs of specimens under cyclic loading

### 3.2. System displacement control curve

The displacement curve of fully-graded concrete under cyclic loading is shown in Fig. 5.

![Displacement curve](image)

**Figure 5.** The displacement curve of fully-graded concrete under cyclic loading

### 3.3. System Load Curve

The system load curve of fully-graded concrete under cyclic loading in tension-compression test is shown in Fig. 6.
3.4. **Longitudinal deformation curve of specimen**

In the tension-compression test of fully-graded concrete under cyclic loading, the longitudinal deformation of the specimens measured by four high-precision displacement meters in the range of 515 mm is shown in Fig. 7.

3.5. **Stress-deformation curve**

Taking the average values measured by four high-precision displacement meters as the deformation of the specimen body within the range of 515 mm, the tension-compression stress-deformation curves of fully-graded concrete under cyclic loading are obtained, as shown in Fig. 8.
3.6. Measurement results of VIC-3D non-contact full-field strain field
The results of VIC-3D non-contact full-field strain measurement of fully-graded concrete under cyclic loading are shown in Fig. 9.

4. Analysis of test data

4.1. The complete stress-deformation curve of full-graded concrete
As can be seen from Fig. 8, the area of hysteretic curve of tension-compression stress and deformation of fully-graded concrete is very small in the linear elastic stage. After the stress in the fully-graded concrete reaches the ultimate tensile strength, the tensile modulus of the specimens decreases gradually. However, when using large distance measurement, the crack development is still in the initial stage, and the crack development is slow. At this time, the residual bearing capacity of the specimen decreases rapidly, and the elastic deformation reduction in the distance measurement is greater than the crack development displacement. In Fig. 11, it is shown that the tensile deformation of fully-graded concrete is slightly smaller than that of the specimen after reaching the ultimate tensile stress. When the residual tensile stress decreases to about half of the ultimate tensile stress, the cracks begin to develop rapidly. At this time, the residual tensile stress decreases slowly, while the specimen...
deformation increases sharply, and the area of hysteretic curve of tension-compression stress-deformation curve increases gradually.

For the convenience of research, the analysis is carried out from the selected part of the post-peak stage of stress and deformation of the specimen, as shown in Figure 10.

![Figure 10. Partial stress-deformation curve of specimen body](image)

According to the commonly used tension-compression damage constitutive model, the theoretical damage evolution process of concrete specimens as denoted by the blue line passing through points A, B, C, B and D in Fig. 10. But the actual damage evolution process of concrete specimens is the red line passing through points A, B, E, F and D. Line FB is a part of residual deformation recovered after compressive stress. It can be clearly seen from Fig. 3 that the current constitutive model of tension-compression damage does not consider the recovery effect of compressive stress on tension damage under reciprocating loads, which is quite different from the real damage evolution process and needs to be further studied.

4.2. VIC-3D non-contact full-field strain measurement data analysis

In order to study the deformation at different parts of the specimen during the whole process of elastic response to crack initiation and propagation, the deformation and strain data of long virtual rod E1 and short virtual rod E5 at crack location are extracted and compared, as shown in Figure 11.

![Figure 11. Deformation and strain data comparison between long virtual rod E1 and short virtual rod E5 at crack location](image)
As can be seen from Fig. 14, the strain of E1 is consistent with that of E5 during the elastic stage, and the strain tested by E5 is smaller than that of E1 due to different span. After the crack initiates and with its continuous propagation, the deformation growth rate of E5 exceeds that of E1, and the two gradually approaches and ultimately basically coincides. The strain of E5 begins to exceed the strain of E1 until the specimen fails.

5. Conclusion

The tension-compression alternating test of fully-graded concrete under cyclic loading can reflect the whole process of damage evolution from linear to non-linear tension-compression of dam materials under cyclic seismic loading, which is of great significance to the study of mechanical behaviour and deformation mechanism of fully-graded concrete under seismic loading.

By using the 15MN large-scale dynamic material testing machine and special connection devices, a feasible test scheme is designed. The tension-compression alternating test of fully-graded concrete specimens under cyclic loading and an additional compressive stress of about 5MPa, which is the first one to be reported for the tension-compression alternating test of fully-graded concrete.

By means of VIC-3D non-contact full-field strain measurement system and high precision axial extensometer, the complete tension-compression alternating stress-strain curve of fully graded concrete under 5 MPa compressive stress is obtained. The test data show that there exists an obvious transition zone from compression to tension after fully-graded concrete is damaged by tension under reciprocating load. Higher compressive stress can restore the residual deformation of tensile damage under cyclic loading.

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