ABSTRACT

Dynamic properties of dam concrete are important in the evaluation of the safety of concrete dams under earthquakes. Considerable researches have been performed in the area of dynamic properties of concrete in laboratory tests with small size specimens. However, few tests were performed with fully-graded aggregates specimens of dam concrete due to the necessity of large specimens and testing machines. In presented paper, direct tensile tests of dam concrete have been performed with cylindrical specimens of 450×1350 mm, made with dam concrete (maximum aggregate size of 120 mm), to measure the dynamic strength as well as the stress-strain curves under either monotonic or cyclic load. The stress-strain curves include both pre peak strength part and post peak strength part, known as soften part also. Standard cylindrical specimens of 150×300 mm made with wet-screened dam concrete (maximum aggregate size of 40 mm) were tested for comparison. In order to capture the stress-strain curves in soften part, the displacement was used as the control command during the tests. The displacement rate was adjusted according to the strain rate expected before the peak strength of the specimen. Very good stress-strain curves were obtained under both monotonic and cyclic loading for fully-graded specimens of dam concrete. It is found from the tests that the fully-graded specimens of dam concrete indicate higher increase in tensile strength compared with static one than the wet-screened specimens under dynamic loading with a strain rate corresponding to the responses of concrete dams to earthquakes.

Keywords: dynamic tensile test; dam concrete; fully-graded; cylinder specimen

1. INTRODUCTION


As the rapid development of modern mechanics and numerical analysis method in recent decades, remarkable progress has been achieved in the dynamic analysis of dams. In the meantime, as the improvement in the dynamic testing facilities and the measuring systems, dynamic model tests with scaled dam structures can be carried out with many important conditions simulated suitably, which influence the seismic responses of dams significantly, that makes the test results of dynamic scaled model closer than ever to the responses of the prototype of dam under investigation (Wang H and Li D. 2007).

Another important aspect that contributes to the strong seismic responses of dams related to potential...
damages is the dynamic mechanical properties of dam concrete. Few researches on it have been reported. The published papers on the dynamic properties of the dam concrete are rather rare (Harris D. 2000, Wang H et al. 2017), especially for tensile tests with the specimens of full-graded dam concrete. Many basic issues related need be investigated more comprehensively. And the lack of cyclic constitutive model (Sima J. 2008) for dam concrete becomes the bottleneck in the seismic design of the dams.

Accompany with the rush developments of many giant concrete dams ranking worldwide in the western region of China with high seismicity, considerable social concerns have been attracted about their safety against extreme potential earthquakes. The research works on the dynamic properties of the fully-graded dam concrete can not only provide more accurate and reliable data for the safety assessment of dams, but also reveal furthermore the ultimate capacity of dams against earthquakes, and give solid convincing to the public concerns about the seismic safety of dams. Since the compressive and tensile strength of the concrete material differ very much, most of damages due to earthquakes are in tension for the structures of massive concrete (Raphael J. 1984). The methods to obtain the tensile strength of concrete include splitting, bending as well as direct tensile test. It is far more complicated to prepare and install a direct tensile specimen of concrete than in either bending or splitting tests, and usually in a low rate of success. It is, however, the only way to obtain the stress-strain relation of material with direct tensile test (Akita H et al. 2003, Cadoni E et al. 2000, Gopalaratnam V and Surendra P. 1985, Lee S et al. 2008, Zheng W et al. 2001).

2. TEST METHOD AND SPECIMEN PREPARATION

The rate of strain of concrete dam structures under earthquakes is about $10^{-4}/s$ to $10^{-2}/s$. It depends on the resonant frequency of dam structure and the properties of seismic motion (Wang H. 2017). For instance, the fundamental resonant frequency of main monoliths of Three Gorges Dam is about 2.0Hz. The corresponding strain rate in tensile damage of the concrete due to vibration is about $800 \mu \varepsilon/s$. The demand in the strain rate requires that the motion of a test system must be precisely controlled for a given speed. The test machine used in this study is a servo controlled machine, as shown in Figure 1, the maximum compressive capacity and tensile capacity of the machine are 15MN and 8MN, respectively, and the stiffness of the mainframe is about 6MN/mm. The system is fully digital-controlled through computer and the system displacement, measured with a digital displacement transducer, was used as the control command for most of the tests. The rate of data acquisition can be as high as 6144Hz.

![Figure 1. The servo controlled test machine](image)

2.1 The Specimen and Measurement

The fully-graded concrete cylinder specimen for the direct tensile test was 450mm in diameter and
1350mm in length, larger than three times of the nominal maximum size of the aggregate, 120mm. The age of concrete specimens were 180 days made with two different grade concrete, C9020 and C9015. At each ends of the specimen, 8 connecting bolts of M24 were embedded when casted, 4 of them with a buried depth of 335mm and another 4 with a buried depth of 285mm. 8 bolts were to be connected with test machine for the tensile loading.

For comparison, standard cylinder specimens of 150mm in diameter and 300mm in length made with wet-screened dam concrete C9020 (maximum aggregate size of 40 mm) were prepared as well. Rather than embedded connecting bolts in specimen, metal connectors were epoxied to both ends of the standard cylinder specimen for tensile tests (Wang H. 2017).

As to the measurement, four columns of strain gages were equally spaced around the fully-graded specimen surface. Each column includes 4 strain gages of 150mm long to cover a 570mm measuring range at the center of a specimen. The resistance of the strain gage is 350 Ω. Totally 16 strain gages were used for each specimen, as shown in Figure 2. The maximum strain was selected at every data acquisition step during the test and can be used to check preset points of unload for cyclic loading test. The force and displacement were measured with the load cell and Temposonic digital displacement transducer of the test machine system. For comparison and control, four extensometers were installed on the specimen with measuring span same as that covered by the strain gages.

The instrumentation for the wet-screened concrete specimen was the same as for the fully-graded one, except for that 300mm measuring range was covered with 3 strain gages of 120mm long for each column.

![Figure 2. Arrangement of the strain gages on the specimen](image)

The eccentricity $e$ is defined as follows for judgment of the uniform loading on the specimen (The Ministry of Water Resources. 2006).

$$ e = \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2} $$

(1)

where $\varepsilon_1$ and $\varepsilon_2$ are the maximum and minimum ones among the column average strains of four sides, respectively. The eccentricity $e$ should be less than 0.15 to be regarded as a test with effective result.

### 2.2 Loading

The system displacement was used as the control command for all tests except for incremental amplitude cyclic loading tests with the system load as control command. In the tests for strain-stress relationship, the system displacement with a constant speed was used as control command, but the unloading was triggered when the maximum displacement among the four extensometers reached a preset value, and reloading was triggered when the system load reached zero.
In static monotonic tensile tests with fully-graded concrete specimens, the speed of the actuator was 0.0013mm/s, corresponding to a loading rate about 0.4MPa/min on the specimens, the value is determined according to the test code (The Ministry of Water Resources. 2006). In dynamic
monotonic tensile test, the speed was 3.12mm/s, corresponding to a strain rate about 800µε/s on the specimens. In the incremental amplitude cyclic loading tests, 3 cycles were applied for every amplitude steps, and the cycling frequency is 4.0Hz for all amplitudes. The loading amplitude began with 50KN and increased by 50KN each step until the fracture of the specimen, refer to Figure 3. For the tests with wet-screened concrete specimens, the speed of the actuator was adjusted to give the same loading or strain rate on the specimens as for the fully-graded concrete specimens.

3. RESULTS AND DISCUSSIONS

Among 50 fully-graded concrete tensile specimens, 36 tests were succeeded to reach effective results, with a success rate of 72%. Because of their large diameter, the specimens were easy to fall into an eccentric tension state soon after some local cracking occurs, especially for cyclic loading tests. Therefore, only the eccentricity e at the initial loading state was used to judge the uniform loading on the specimen.

In Figure 4 present the photos of a typical fracture position on a fully-graded concrete tensile specimen and its fracture surface. It can be found from the photos that the fracture was dominated by the interface of aggregate and cement, especially by large aggregates. The fracture of the aggregate itself took only a small portion.

![Figure 5](image-url)  
**Figure 5.** Time histories of the average strains along four columns and the eccentricity

![Figure 6](image-url)  
**Figure 6.** Curves of the load against displacement of extensometers and strain
3.1. Results of tensile strength

Figure 5 gives the time histories of the average strains along four columns and the eccentricity calculated for a typical fully-graded concrete tensile specimen under monotonic loading. Figure 6 shows curves of the load against the displacement of extensometer and the load against the strain. The strain in the figure is a section strain where the fracture occurs, calculated from the average value of four strain gages on the same section circle. The displacement of extensometer in the figure is the average value of four extensometers. Both ranges on the abscissas in the figure for the displacement of extensometer and the strain were so adjusted that two curves can coincide with each other prior to the peak load. For most of specimens, the strain increases far more faster than the extensometer on the soften part of the curve post the peak load. This reflects the stress release on the fracture surface, which cause the unloading of whole specimen and the loading frame so that their elastic deformation sprang back. All the deformation of specimen as well as loading frame before cracking transfers to the gape of the fracture, resulting in a rapid increase in the value of strain gages on the fracture. When the crack is in an unstable state, it is very hard to control the loading or unloading rate. The larger the specimen in size, the more rapidly the crack open increasing, the more difficult to control the test. Statistical results from the tests show that the average tensile strengths for Grade C90.20 fully-graded concrete specimens were 1.79MPa, 2.80MPa and 2.36MPa for static loading, monotonic dynamic loading and incremental amplitude cyclic loading, respectively. The dynamic increment factor in tensile strength was 1.56 and 1.32. For Grade C90.15 specimens, the average tensile strengths were 1.70MPa, 2.34MPa and 2.37MPa, respectively. The dynamic increment factor was 1.38 and 1.39. For wet-screened specimens, the corresponding values were 2.68MPa, 3.47MPa and 3.07MPa. And the dynamic increment factor in tensile strength was 1.30 and 1.15. It consists with the common knowledge that the strength of the fully-graded concrete is lower than wet-screened concrete. However, the dynamic increment factor in tensile strength of fully-graded concrete is larger than those of wet-screened concrete.

![Figure 7. The curves of load against strain and load against displacement of extensometer](image)

3.2. Results of stress-strain relationships

If the purpose is to measure the tensile stress-strain relationship of concrete, not only the part prior to peak strength but also the soften part, post peak strength, must be caught under cyclic loading. The system displacement was used as control command for the tests, the loading process continued until a preset maximum displacement of the extensometer was reached, and then after, the unloading process continued until the system tensile load was close to zero to start next reloading process. For the first 6
specimens, the same speed for loading and unloading was adopted in the test, unfortunately no satisfied stress-strain curve on the soften part was obtained, see an example in Figure 7. After carefully examining the test data recorded, it is found that the crack was in an unstable state post the peak strength of the specimen, the crack may extend suddenly even the load was decreasing slowly soon after turned to unloading process. Based on the judgement above, faster speed of unloading was set in subsequent tests while the speed of loading or reloading was kept no change. Figure 8 shows the time histories of the displacements of extensometers as well as the system load in a pseudo static test. The different speeds in loading and unloading can be identified easily.

Figure 8. Time histories of the displacement of extensometers and system load

Figure 9. The curves of load against strain and load against displacement of extensometer

As shown in the Figure 9, satisfied results were achieved for the tensile tests of the fully-graded dam concrete under cyclic load, and the complete stress-strain relationship in tension can be calculated from them. As in the monotonic tensile loading, the envelope strain increases faster than the envelope displacement of extensometer in the soften part of the curve, due to the transformation of elastic deformation to the crack accompanied with the stress release on the fracture surface.

For the tensile stress-strain relationship in dynamic tests, 8 specimens of Grade C9020 were tested. All fractures on them fell in the instrumented part, a typical time histories of load and displacement were
shown in Figure 10 and the curves of load to strain in Figure 11. The eccentricity of 2 specimens was bigger than 0.15 at the first loading cycle, and that of other specimens increased after some cracks occurred. In the dynamic tests, the speed of loading and unloading was set to 0.4mm/s and 0.8mm/s, respectively, corresponding to the strain rate on the specimen of 100\(\mu\varepsilon/s\) and 200\(\mu\varepsilon/s\). Although in the monotonic dynamic tensile tests, the strain rate was 800\(\mu\varepsilon/s\), the dynamic response of the test machine system limited the strain rate to get a satisfied result under cyclic loading test. Further improvement on the test machine is essential.

From the effective results of 6 fully-graded concrete specimens, the average tensile strength under dynamic cyclic loading was 1.78MPa, dynamic increment factor is 1.15 only, because of lower strain rate of loading than monotonic dynamic loading tests.

![Figure 10. Time histories of the displacement of extensometers and system load](image)

![Figure 11. The curves of load against strain and load against displacement of extensometer](image)

The same tests with 4 specimens of Grade C\(_{90}\)15 were completed. All fractures on them fell in the instrumented region. Since the deficiency on one specimen, its result with obvious low tensile strength was eliminated. The average tensile strength from 3 specimens under pseudo static cyclic loading was 1.84MPa. It seems higher than static tensile strength of 1.70MPa in monotonic loading tests. In fact, one result among three was 25.5% higher than the average value. And its small eccentricity during the whole test presented the reason of its high tensile strength in whole.
4. CONCLUSIONS

Direct tensile tests of dam concrete have been performed with fully-graded dam concrete cylinder specimens 450mm in diameter and 1350mm in length, and wet-screened dam concrete cylinder specimens 150mm in diameter and 300mm in length. Both static and dynamic tensile strength as well as the tensile stress-strain curves of the concrete under either monotonic or cyclic load were measured. The stress-strain curves include both pre peak part and soften part. The test results reveal the larger dynamic increment factor for fully-graded concrete specimens than wet-screened concrete specimens. Almost perfect tensile stress-strain curves achieved with fully-graded concrete specimens under static and dynamic cyclic loading will provide fundamental information for the establishment of its tensile constitutive relation in an analytical form and improvement of the evaluation of concrete dam safety under destructive earthquakes finally.

5. ACKNOWLEDGMENTS

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