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Experimental study on complete stress-deformation curves of larger-size concrete specimens subjected to uniaxial tension

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Abstract: In order to provide parameters for numerical analyses of the huge Three-Gorge concrete dam (2309 m long by 175 m height), complete tensile stress-deformation curves for large-size plain concrete specimens were measured and studied by performing uniaxial tensile tests on large-size unnotched specimens (250 mm×250 mm×1400 mm). The specimens were prepared with the three-graded-aggregate materials provided by the client of the Three-Gorge project. To prevent a failure occurring near the ends of the unnotched specimens, both the ends of each specimen (450 mm in length) were cast using a higher-strength concrete than the middle part (i.e., active part). Tensile tests were completed on a specially-designed tensile testing machine, which can be easily re-assembled to accommodate different-size specimens. To make the specimens fail stably, a cyclic loading scheme was adopted after the peak strength was reached. Four of five tests in this study were successful, and four complete tensile stress-deformation curves were obtained. It was found that the post-peak curve of the large-size specimens used in this study is more gradual than those for the small-size specimens reported in the literature.

Key words: Concrete, Uniaxial tensile tests, Tensile stress, Deformation, Large-size specimens
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INTRODUCTION

Failure of reinforced and pre-stressed concrete structures is initiated in many instances by cracking of plain concrete. The post-cracking softening behavior of concrete subjected to tension has been realized for many years (Li *et al*., 1993). However, the resistance of cracked concrete is generally ignored in conventional design practice. Until recently it has become increasingly evident that it is necessary to account for the post-cracking resistance of concrete when performing nonlinear finite element analyses for reasonable predictions of the cracking width and bond transfer, etc., particularly in a large-size concrete associated with the heat of cement hydration.

The tensile behavior of concrete can be represented by a complete stress-deformation curve measured by a uniaxial tension test. It is well known that the experimental measurement of a complete tensile stress-deformation curve is difficult because of the low resistance and brittle property of concrete subjected to tension. The experimental results are greatly affected by size and shape of specimen, testing machine, measuring gauge length, etc. Literature review indicated most of previous experimental studies were carried out on small-size specimens (Cornelissen *et al*., 1985; Yankelevsky and Reinhardt, 1987; Guo and Zhang, 1998, Hordijk *et al*. 1987; Evans and Marathe, 1968; Li *et al*., 1993). A notched specimen was used by some researchers to ensure the cracking zone develop within the scope of the measuring gauge (Cornelissen *et al*., 1985; Yankelevsky and Reinhardt, 1987; Guo and Zhang, 1998; Evans and Marathe, 1968).

The Three-Gorge concrete gravity dam (2309 m long by 175 m height) currently being built in China is perhaps the largest and most important concrete project in China or even in the world in the 20th century. One of the major problems associated with the project is the cracking of concrete as a result of the heat of cement hydration in this large-size structure. Therefore, a comprehensive study on the tensile behavior of the concrete was required by the client of the Three-Gorge Project.

To meet the requirement of the Three-Gorge concrete project, uniaxial tensile tests were carried out on large-size unnotched plain concrete specimens. The specimen dimension is 250 mm by 250 mm (cross section) by 1400 mm (length), and the maximum aggregate size is 80 mm. The tensile tests were completed on a specially-designed tensile testing machine, which can be easily re-assembled to accommodate different-size specimens.

In this paper, the specially-developed tensile testing machine is first introduced. Then, the preparation of specimens and the related experimental techniques such as the measuring gauge length and loading consequence will be presented. Third, typical test results for the large-size plain concrete specimens will be interpreted and discussed. Some suggestions and conclusions are drawn at last.

EQUIPMENTS FOR UNIAXIAL TENSION TEST

As a concrete specimen was loaded on a tensile loading machine, elastic energy tended to be accumulated and stored in the testing system. Once the peak tensile stress of the specimen was reached, the specimen failed (or cracked) suddenly and the stored elastic energy released in a short time. This is an unstable failure. In this case, it is difficult to record the post-cracking stress and deformation because they were completed in a short time. How to control the failure process and make the specimen fail progressively is the key problem for the measurement of a complete tensile stress-deformation curve (van Mier and Shi, 2002). This requires the tensile loading machine have the ability: (1) to maintain the stiffness of a tensile loading machine to be high enough, or (2) to control the strain rate. For the latter, it can be implemented with a closed-loop control system (Li *et al.*, 1993). However, the design and production of closed-loop control system is generally expensive. For the former, it requires that the stiffness of a tensile loading machine should be larger than the stiffness of a specimen (Chen, 1999). But the design and production of such a tensile loading machine according to the required stiffness (larger than the stiffness of the specimen) are also believed to be expensive. Therefore some researchers attempted to modify a conventional loading machine. In other words, they tried to enhance the stiffness of the conventional loading machine by adding some load-sharing units parallel to the specimen. However, in general the modified loading machine can only accommodate small-size specimens.

To obtain a balance between performance and economy, a special tensile loading machine was designed and produced (Figs.1 and 2). The working principle of the machine is to use a special-designed framework to produce a reaction tensile force for an attached specimen. As shown in Figs.1 and 2, the

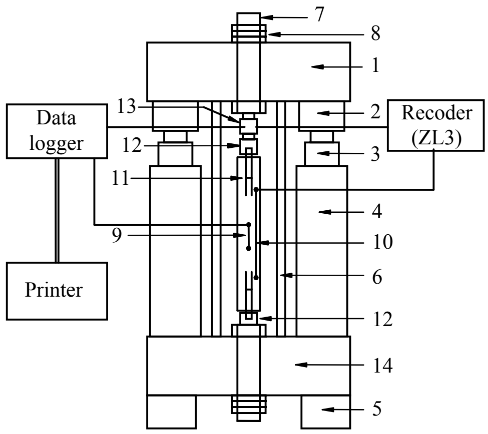

Fig.1 Schematic diagram of the equipment for uniaxial tension test
1: Upper cross beam; 2: Longitudinal beam; 3: Hydraulic jack; 4: Concrete pillar; 5: Footing; 6: Additional stiff bar; 7: Transmission bar; 8: Locking screw cap; 9: Electric micrometer; 10: Displacement transducer; 11: Pre-embedded assembly; 12: Universal-type joints; 13: Load cell; 14: Lower cross beam

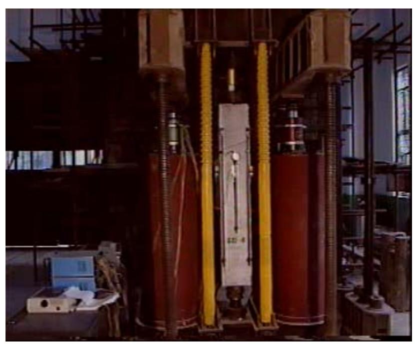

Fig.2 Photograph of the equipments for uniaxial tension test

framework is made up of two cross beams (one upper and one lower), two longitudinal beams and four steel bars. The upper and lower cross beams are main load-supporting units. The two ends of a specimen are attached to the upper and lower cross beams by two transmission bars, respectively. The two longitudinal beams, underlying the upper cross beam, are to improve the stability of the framework. The four steel bars (100 mm in diameter and 2000 mm in length) were installed in the direction parallel to the specimen. The objectives of the four steel bars are: (1) to enhance the stiffness of the loading machine; and (2) to improve the global stability of the loading system. Two hydraulic jacks are installed on concrete pillars (600 mm in diameter) to provide a push force to the two longitudinal beams, and in turn to the upper cross beam. The two hydraulic jacks were controlled by a single oil pump to ensure the same loading applied to the two longitudinal beams. A load cell was directly attached to the specimen to measure the loading transmitted to the specimen. Four electrical micrometers were installed on the four lateral faces respectively to measure the specimen deformations. The load cell and four electrical micrometers were connected to a data logger for automatic data acquisition. The logging frequency was set at 0.3 Hz. To provide a feedback signal for manual control of the strain rate, another four long-distance displacement transducers were installed on the four lateral faces of the specimen. The signals from the load cell and four displacement transducers were transmitted to a recorder (ZL3). The recorder can rapidly plot out a loading-deformation curve for manual feedback.

The structure of the specially designed testing machine is relatively simple, and can be easily re-assembled to accommodate different-size specimens as well as to meet different loading requirements. In addition, the testing setup was made of conventional elements (steel beams, steel bars, concrete pillars and hydraulic jacks), and hence it is relatively cheaper as compared to a large-size commercial tension machine.

PREPARATION OF SPECIMENS

Materials

All the materials for preparing the concrete specimen were provided by the client of the Three-Gorge Project. The mixing proportion for the specimen is listed in Table 1. The weak cross section tends to be affected by many uncertain factors such as on-uniformity of materials and variations in casting and curing conditions. So the location of weak cross section cement was a 42.5 low-hydration-heat one manufactured by Jingmen Cement Company. The fly ash was a first class one produced by Sanxi Shentou power station. The three-graded aggregates and sand were artificially produced from the granite at the site of the Three-Gorge dam.

Size of specimen

The effect of specimen size on the tensile behavior has been studied by Carpinteri and Ingraffea (1998). It was found that cracking of concrete usually developed along the interface between the coarse aggregate and the sand paste. Some aggregates are favorable for resisting the development of cracking. It can be imagined that the experimental results will be influenced by the size and shape of aggregates used in the specimens. Therefore, the specimen for a uniaxial tension test should be prepared with the actual aggregates used in the construction, and the specimen size should be so large as to be compatible with the adopted aggregates.

According to "Standard for Concrete Testing in Hydro-Electric Engineering" (SD105-82), the cross-sectional dimension of the specimen for a tensile test should be 3 times larger than the maximum particle size of aggregates. So the cross-sectional dimension of the specimen was adopted as 250 mm×250 mm. The length of a specimen was adopted as 1400 mm by accounting for the requirement for the measurement of deformation and the length of the embedded assembly.

Table 1 Mixing proportion of the concrete tested (kg/m^3)

Component	Water	Cement	Fly ash	Sand	Aggregates			Water reducer	Air entraining agent
					5~20 mm	20~40 mm	40~80 mm		
Quantity	101	172	33	694	437	291	729	1.41	0.012

Treatment on the ends of specimen

Concrete specimen subjected to uniaxial tension generally fails along a major cracking. The major cracking is most likely to occur at a relatively weak cross section. The location of a weak cross section (i.e., the location of potential major cracking) is usually uncertain. The location of major cracking is one of the major difficulties associated with the tensile testing. A notched specimen was used by some researchers to ensure the major cracking face develop within the scope of measuring gauge. However, the notch created in the specimen may result in a reduction in the peak tensile strength because of the stress concentration near the notch. On the other hand, the stochastic characteristic associated with the development of cracking cannot be simulated with a notched specimen. Therefore, it is more reasonable to perform a uniaxial tensile test on an unnotched specimen.

For testing of concrete materials in direct tension, there are generally two attaching methods at the ends of a specimen to transmit the loading. One is to use grips to clip a specimen, the other is to use a pre-embedded assembly for attaching. However, both these two methods are likely to result in a stress concentration near the ends of a specimen. Hence, the specimen is most likely to fail at or near the grips or the embedded assembly (i.e., outside the scope of measuring gauges). In the present experimental study, the specimens were attached to the load-supporting frame using a pre-embedded ribbed bar assembly. The bar assembly consists of four bars (each 10 mm in diameter). The embedded length at both ends of each specimen is 225 mm in length. Some trial tests prior to the formal tests showed that most of the specimens cracked near the pre-embedded steel assembly. Therefore, a new treatment method was proposed to solve this problem. Both ends of each specimen were cast using a higher-strength concrete (i.e., a strength grade of 52.5) than that used for the middle part (i.e., a strength grade of 42.5). The length of the stronger part is 450 mm at both ends. The bar assembly mentioned above was embedded in the stronger ends during casting. It was found that about 80% of the specimens treated by this method failed within the scope of gauges as anticipated. In this experimental study, four of five tests were successful. Therefore, the treatment for specimens was demonstrated to be effective.

Casting and curing

The materials were mixed using a mixing machine fully. Then the mixture was placed in a mould and disturbed with a vibrator into shape. Lastly, each specimen was left in a curing room (with temperature of (20±3) °C, and relative humidity of more than 90%). The curing period was 28 d. For the materials listed in Table 1, totally five specimens were prepared, namely *S*1, *S*2, *S*3, *S*4 and *S*5.

EXPERIMENTAL TECHNIQUES

Measuring gage length

Generally, the failure of a concrete specimen subjected to tension is associated with the development of cracking in a narrow zone. When the loading reaches the tensile limit of the concrete, the crack was formed and developed. Thereafter, as the resistance of the specimen decreases, the deformation in the cracking zone keeps increasing, whereas a recovery of elastic deformation occurs to the other parts of the specimen away from the cracking zone because of the decreasing stress. Therefore, the measured deformation value depends greatly on the measuring gage length. Generally speaking, the smaller the measuring gage length, the larger the measured deformation value, and hence the more gradual the post-cracking stress-deformation curve. Ideally, the measuring gage length should be as small as possible to register the true deformation within the cracking zone. However, the probability for the measuring gage length covering the cracking zone decreases greatly with a reduction of the measuring gage length because of the uncertainty of the cracking zone location. Therefore the selection of the measuring gage length is very important, and a balance should be made between the feasibility and reasonability of the deformation measurement. According to the SD105-82 Standard, the measuring gage length for uniaxial tension tests should be not smaller than three times the maximum particle size of the aggregates. The measuring gage length for this experimental study was determined by this standard and selected as 250 mm, i.e., equivalent to three times the maximum particle size of the aggregates (i.e., 80 mm).

Loading scheme

There are generally two kinds of loading schemes for a uniaxial tensile test, namely monotonic loading and cyclic loading. Fig.3 shows a comparison of the elastic energy stored in a specimen subjected to a monotonic loading and a cyclic loading, respectively.

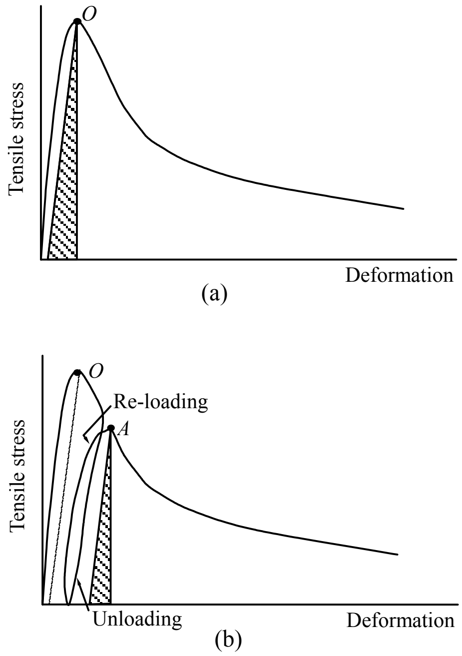

Fig.3 A complete stress-deformation curve associated with a monotonic loading (a) and a cyclic loading (b)

If a monotonic loading scheme is adopted, the elastic energy stored in the specimen is accumulated with the loading process. When the applied load reaches the peak tensile strength, a large elastic energy is stored. After the peak, cracking occurs to a local zone of the specimen. The deformation within this cracking area continues increasing, whereas the deformation in the non-cracked zone is partially recovered. As a result, part of the elastic energy stored in the non-cracked zone will be released. The released elastic energy, if large enough, will cause a sudden failure at the cracked zone. In other words, the large elastic energy stored in the specimen is unfavorable to the measurement of post-cracking stress-deformation curve. The shadowed area in Fig.3a shows the elastic energy stored in the specimen subjected to a monotonic loading.

If a cyclic loading scheme is adopted, the case will be different from the mono-loading scheme discussed above. It can be seen from Fig.3b that an unloading just after the peak results in a release of elastic energy in the specimen. When the specimen is subjected to re-loading, the re-loading stress-deformation curve will follow a new curve until the loading approaches the new peak (i.e., point *A*). At point *A*, the elastic energy stored in the specimen (represented by the shadowed area in Fig.3b) is significantly less than the accumulated elastic energy during the monotonic loading. This is because the large elastic energy is artificially released during the unloading process, and less energy is accumulated when re-loading. Therefore, a cyclic loading scheme is favorable to the progressive cracking process.

Cornelissen *et al.*(1985) demonstrated that the complete stress-deformation envelope measured by cyclic loading was essentially close to the one measured by monotonic loading. In other words, the cyclic loading during the uniaxial tension tests has negligible effect on the experimental results.

On the base of the discussion above, a combined loading scheme was adopted for this experimental study, i.e., monotonic loading prior to the peak tensile resistance of the specimen and cyclic loading after the peak. The loading procedures are detailed as follows: The specimen was loaded to the peak tensile strength according to the SD105-82 Standard. Afterwards, the specimen is subjected to a deformation-control cyclic loading. For each step of the cyclic loading, the specimen was loaded to a prescribed deformation increment and then unloaded immediately. In order to eliminate the effect of loading rate on the experimental results, the loading rate was controlled within the range 0.2~0.6 MPa/min.

Measures taken for eccentric tension

Eccentric tension is another difficulty confronted with a uniaxial tension test. For a uniaxial tension test, it is expected that the tension stress could be uniformly distributed on any cross section of a specimen. This requires that the central axial of loading should be always made to pass through the physical centroid of the specimen. However, it is found to be considerably difficult. First of all, the non-uniform distribution of aggregates in a specimen may make the physical centroid of the specimen deviate from the geometric central axis of the specimen. On the other hand, after the peak tensile resistance of the specimen is reached, a local cracking may first occur to the specimen, and hence the cracked part loses resistance to tension. Thus, the cross section of the resisting zone becomes irregular in shape (or a change in the geometric centroid). Moreover, the geometric centroid of a specimen tends to keep changing with further development of cracking. Therefore, it is believed to be impossible to eliminate eccentric tension completely. Regardless of this, the following measures were taken to minimize the eccentric tension in this experimental study: (1) During the preparation of a specimen, the pre-embedded steel assembly was placed centrically; (2) Two universal-type joints were installed at both ends of a specimen to provide an automatic adjustment on the central axis of loading; (3) Prior to formal loading, a small loading was first applied to bring the specimen in a proper place by doing a careful adjustment manually; (4) As mentioned before, deformation was measured at all the four lateral faces of a specimen, so that the effect of an eccentric loading can be counteracted to some extent by taking the average of the two stress-deformation curves measured on the two opposite lateral faces. This will be discussed in more detail later.

Fig.4 Crack after a stable failure

Fig.5 Crack after an unstable failure

TYPICAL TEST RESULTS AND DISCUSSIONS

The improvements on the loading machine, specimens and experimental techniques led to success in uniaxial tension tests on a large-size unnotched specimen. In this experimental study, all specimens were tested for a complete tensile curve. Four tests (i.e., specimens *S*1, *S*2, *S*3 and *S*4) were successful. The other specimen (i.e., *S*5) failed outside the gage scope. Fig.4 shows the crack of a failed specimen after a successful test. It can be seen from the figure that the crack width is small, and that the upper and lower parts of the failed specimens inosculate well with each other. During the cracking process, only a slight sound from the tearing of materials was heard. All these indicated the specimen failed progressively and stably. On the contrary, Fig.5 shows a specimen failed under an unstable condition. The specimen failed with a significant crack and a large sound, and the upper and lower parts of the specimen could not inosculate well.

As discussed before, for a uniaxial tension test, the development of cracking after the peak strength of concrete is generally localized in a narrow zone. With a decrease in the resistance of the specimen, the deformation within the cracking zone keeps increasing, whereas a recovery of elastic strain occurs to the zone beyond the influence of cracking. Therefore, it is believed that a stress-deformation relationship can represent the tensile characteristic of concrete more than a stress-strain relationship.

Fig.6 shows one typical experimental result (specimen *S*1). The four different stress-deformation curves in Fig.6 were deduced from the different deformations measured on the four lateral faces of the specimen (i.e., faces *A*, *B*, *C* and *D*), respectively. It should be noted here that face *A* is opposite to face *D*, and that face *B* is opposite to face *C*. It can be seen that the four stress-deformation curves prior to the peak strength are essentially close to one another. The consistency indicates a centric loading prior to the peak of the curve. After the peak, the two softening stress-deformation curves measured on the two opposite faces (i.e., faces *B* and *C*) are satisfactorily close to each other. However, the softening curve measured on face *D* deviated significantly from the curve measured on face *A*. The negative values of deformation on face *D* obviously indicate not tension but compression occurred to the concrete near face *D*. This inconsistent performance observed on face *A* and face *D* is believed to be attributable to the eccentric loading in the direction.

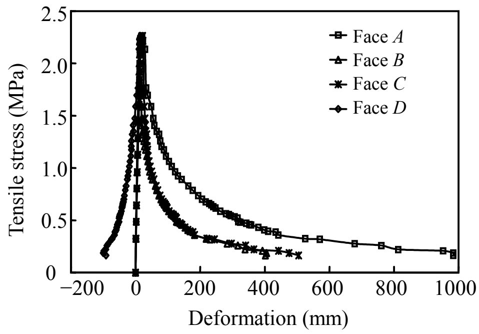

Fig.6 Complete stress-deforamtion curves measured on the four lateral faces

As discussed before, it is considerably difficult to eliminate the eccentric loading existing in a uni-axial tension test, particularly for a large-size specimen. So experimental results are inevitably affected by an eccentric loading. However, it was noticed that the effect of an eccentric loading on the two opposite lateral faces (e.g., face *A* and face *D*) appeared to be contrary. It is suggested that the contrary effect of an eccentric loading may be counteracted by taking average of the two stress-deformation curves measured on the two opposite lateral faces. Fig.7 shows two stress- deformation curves deduced from the four curves shown in Fig.6 with this treatment method. The solid line was obtained by taking the average of the two curves measured on face *A* and face *D*, and the dashed line by taking the average of the two curves measured on face *B* and face *C*. It can be seen that the solid line is satisfactorily close to the dashed line. The same case was observed for most of the tests conducted in this experimental study (Yankelevsky and Reinhardt, 1987). This indicated the suggested treatment method is of significance. Fig.8 shows the final complete stress-deformation curve obtained by taking the average of all the curves measured on the four lateral faces. Fig.9 shows results from all the four successful tests in this study. It can be seen that *S*1, *S*2 and *S*3 curves are essentially close to one another. However, the curve for *S*4 is different from the former three curves in both the peak and the softening curve.

Fig.10 shows a comparison of the complete tensile curves between the large-size specimens used in

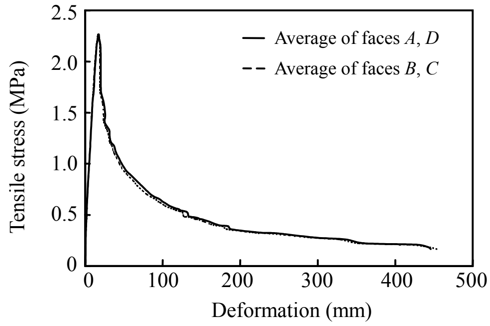

Fig.7 Complete stress-deforamtion curves obtained by taking the average of the two opposite lateral faces

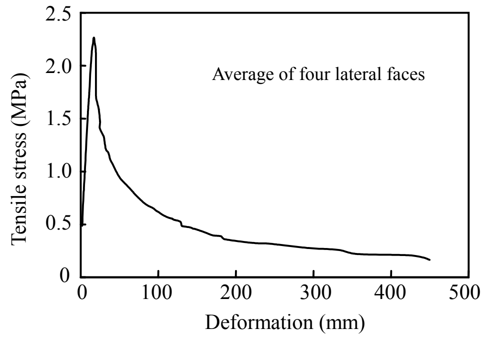

Fig.8 Final complete stress-deforamtion curves obtained by taking the average of four lateral faces

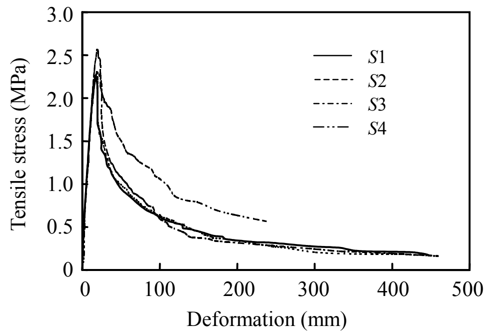

Fig.9 Tensile test results of the specimens *S*1, *S*2, *S*3, *S*4

this study and the small-size specimens reported in (Guo and Zhang, 1998; Gopalaratnam and Shah, 1985; Yankelevsky and Reinhardt, 1987). The mixing properties of the specimens are listed in Table 2. It is known that the shape of a complete tensile curve could be significantly affected by materials, mixing proportion and specimen shape, particularly by the measuring gage length. A comparison in Fig.10 indicates that the post-peak curve for the large-size specimens used in this study is more gradual than those for the small-size specimens.

Table 2 Details of the tests

No.	Reference	Specimen size: width×thickness×length (mm^3)	Size of aggregate	Gage length (mm)	Notched or not
1	In this study	250×250×1400	80	250	unnotched
2	(Guo and Zhang, 1998)	70×70×210	–	155	unnotched
3	(Gopalaratnam and Shah, 1985)	76×19×305; 76×38×305	10	83	notched
4	(Yankelevsky and Reinhardt, 1987)	50×40×150	8	35	notched

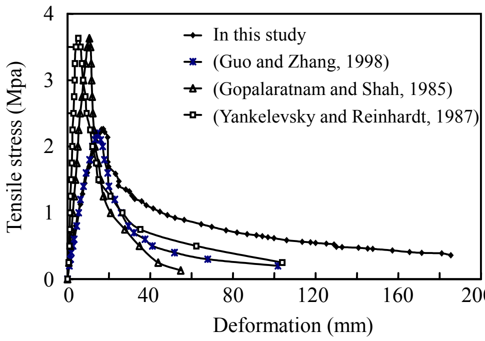

Fig.10 Comparison of tensile test results between large-size specimen in this study and small-size specimens in other literature

CONCLUSION AND SUGGESTIONS

Complete tensile stress-deformation curves for large-sized plain concrete specimens (250 mm×250 mm×1400 mm) were successfully measured by performing uniaxial tensile tests on a specially-developed and simple tensile loading machine. Some conclusions and suggestion can be drawn as follows:

(1) The specially developed tensile loading machine can be easily re-assembled to accommodate different-size specimens and to meet different loading requirements, it takes advantage of simplicity and economy.

(2) A treatment method is proposed to prevent an unnotched specimen from failing and cracking near the ends of the specimen. The main principle of the treatment is that the parts near the ends of a specimen were cast using a higher-strength concrete than the middle part (i.e., active part). The treatment was demonstrated to be effective.

(3) The combined loading scheme adopted for this experimental study, i.e., monotonic loading prior to the peak tensile strength of the specimen and cyclic loading after the peak resistance, was found to be effective in reducing the elastic strain energy accumulated in the specimen, and hence resulting in a stable cracking (or failure). This is favorable for successful measurement of the softening stress-deformation curves.

(4) The effect of an eccentric loading on experimental results can be essentially counteracted by taking the average of the two stress-deformation curves measured on the two opposite lateral faces, respectively.

(5) It was found that the post-peak curve for the large-size specimens used in this study is more gradual than those for the small-size specimens.

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