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Research on Technical Adaptability of Cross-regional Rail Transit: Application and Optimization of Japanese ECC Side Wall Compression Structure in Shanghai Metro

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ABSTRACT
In this study, the application potential, adaptability and localization optimization strategy of ECC (cement-based composite material) side wall compression structure technology used in Japan subway project are systematically discussed. The purpose of the project is to explore the feasibility and optimization strategy of applying Japan's advanced ECC side wall compression structure technology to Shanghai metro system. In view of the similarity between Shanghai and Tokyo in terms of geography, population and economic scale, and the challenge of Shanghai soft soil foundation to the safety of metro structure, the long-term durability of ECC materials in Shanghai metro environment is evaluated by comparing and analyzing the geological environment difference between Tokyo and Shanghai, optimizing the material formula to improve the corrosion resistance, and analyzing the feasibility of application of ECC side wall structure in Shanghai metro station. The research adopts experimental research method, numerical simulation method and case analysis method to improve the stability of ECC under the condition of complex terrain across regions and guarantee the safe operation of Shanghai Metro.

KEYWORDS
ECC; Seismic structure of subway; Soft soil foundation

1 Introduction

1.1 Research Background and Significance

With the continuous evolution of economy and society and the rise of transportation demand, the traditional rail transit structures face more and more serious challenges in carrying capacity, earthquake resistance and life cycle cost. As a country with many earthquakes, Japan has accumulated rich experience in seismic resistance of underground structures. The serious earthquake damage of the subway station during the 1995 Hanshin Earthquake prompted the engineering community to seek higher performance materials and tectonic techniques[1]. Under this background, ECC (engineering cement-based composite material) has been successfully applied to seismic structures such as subway side walls in Japan by virtue of its excellent tensile strain hardening, multi-joint cracking and high energy consumption, which provides an innovative way to improve the ductility of underground structures.

As Asian megacities, Tokyo and Shanghai face similar challenges in terms of high-density commuting demand and land resource constraints in the development of metro systems. However, the soft soil foundation widely distributed in Shanghai has high compressibility, low bearing capacity and rheological characteristics, which poses a special challenge to the long-term safety and durability of subway structures. Therefore, the systematic study on the applicability, adaptation mechanism and optimization strategy of ECC side wall compression structure technology derived from Japan in Shanghai soft land iron environment not only has direct engineering significance for improving the seismic resilience of Shanghai metro structure and guaranteeing the operation safety, but also provides an important reference for promoting the technology transfer and standardization application of high-performance materials under the complex geological conditions across regions.

1.2 Current Research Situation at Home and Abroad

Engineering cement-based composite (Engineered Cementitious Composites) was proposed by V. C. Li[2]in the early 1990s. It is a high-performance fiber-reinforced cement-based material based on micromechanical design. It has the characteristics of tensile strain hardening and multi-joint cracking, and exhibits excellent energy absorption capacity and durability[3].

In terms of engineering application, Japan took the lead in applying PVA-ECC technology to infrastructure anti-seismic repair, for example, the anti-seismic performance of Shinkansen bridge is significantly improved after strengthening; The use of ECC in the repair project of San Francisco Bay Bridge in the United States has proved its superiority in energy dissipation and crack control. In Europe, ECC is also used for seismic reinforcement of historical buildings, and good protection and enhancement effects have been achieved. These practices show that ECC technology has high technical maturity and wide engineering applicability in improving structural seismic toughness and durability.

Domestic scholars have carried out a series of researches on the properties and structure of ECC materials. Gao Shuling and others have effectively improved the anti-crack and deformation ability of members by arranging ECC protective

layer in the tensile area of reinforced concrete beams[4]. Wang Mengfu applied ECC to the frame column of the corridor, and the test shows that ECC can significantly enhance the bearing capacity, ductility and energy dissipation of the structure[5]. These studies provide theoretical basis for further popularization of ECC in China.

However, the existing researches mainly focus on the performance optimization of ECC material itself and its reinforcement application in bridge, building and other superstructure. Especially in the background of cross-regional technology transfer, the evolution law and design adaptation method of durability and seismic performance of ECC materials under the action of soft soil subsidence, long-term deformation and water-soil corrosion coupling are not enough for test verification and theoretical support. Therefore, the research on seismic structural performance of ECC side wall for Shanghai soft soil geological conditions is of great significance to realize the safe, economical and reliable landing of the technology.

1.3 Research Purpose

Based on the theme of "Research on Technical Adaptability of Trans-regional Rail Transit-Application and Optimization of Japanese ECC Side Wall Compression Structure in Shanghai Metro," the performance of ECC materials can be evaluated, such as long-term durability of ECC in Shanghai Metro environment, and the material formula can be optimized to improve corrosion resistance. Design of side wall structure: The feasibility of application of ECC side wall structure (prefabricated ECC slab) in Shanghai metro station is analyzed, and the thickness, reinforcement ratio and connection mode of side wall are optimized in combination with Shanghai geological conditions (such as soft soil foundation). In addition, numerical simulation method (stress-strain analysis, seismic analysis), case analysis method (comparison-case reference possibility) and other methods are adopted. Through the above means and methods, the feasibility of ECC side wall compression structure in Shanghai Metro is explored and analyzed.

2 Experimental process

Performance Test of 2 ECC Material in Shanghai Soft Ground Environment.

2.1 Test Piece Design and Preparation

In order to systematically evaluate the seismic performance of engineering cement-based composite materials (ECC) in subway side wall structures, and compare it with traditional concrete structures, in this chapter, three full-scale shear wall specimens are designed and fabricated to simulate the stress state of subway side walls under vertical and horizontal reciprocating loads. The specimen number and material type are as follows:

Q-1: The reference test piece poured with ordinary C40 concrete represents the side wall materials commonly used in the current metro structure.

Q-2: The material cost of the test piece poured with the economical ECC material is the same as that of the ordinary concrete.

Q-3: Specimens cast from high performance ECC materials with standard mix design to verify structural performance under optimum material performance.

The design dimensions, reinforcement ratio and loading boundary conditions of all specimens shall be consistent to eliminate the influence of non-material factors. ECC is prepared in strict accordance with Technical Code for Application of High Ductility Fiber Reinforced Cement Matrix Composite, PVA fiber is used, and its tensile strain hardening and multi-joint cracking characteristics meet the design requirements are ensured through trial blending.

2.2 Loading Scheme and Test Method

Test loading shall be in strict accordance with Code for Seismic Test Methods of Buildings (JGJ/T 101-2015), and quasi-static low-cycle reciprocating loading system shall be adopted to simulate the force response of structures under seismic action.

2.2.1 Loading System

Force-displacement hybrid control mode is adopted in the loading process, and the specific steps are as follows:

(1) Vertical load application: Firstly, axial pressure is applied to the top of test piece to simulate the constant overburden earth pressure and superstructure load of subway structure. The load is applied to the design value in three stages and kept constant.

(2) Horizontal reciprocating load application: After the vertical load is stabilized, apply low-cycle repeated horizontal load on the top of the test piece to simulate seismic action. The loading is divided into two stages:

Force control stage: Load in increments of ±20kN and ±40kN, until the test piece shows obvious yield signs.

Displacement control stage: Multiple of yield displacement (Δy) of test piece (±2Δy, ±3Δy, ±4Δy⋯)The controlled loading shall be carried out, and the displacement of each stage shall be cycled for 2 times until the horizontal bearing capacity of the test piece drops to 85% of the peak load or serious failure occurs, and the test shall be terminated. See Figure 1 (or Table 1) for specific loading system.

Table 1 Loading System

First stage loading (KN)	First stage loading (KN)	Third-level loading(KN)	Determine yield displacement and begin to control with displacement	Fourth stage loading (Mm)	Level 5 loading (Mm)	Sixth stage loading (Mm)	Gradually increase until failure conditions are reached
±20	±40	Until yielding		±2Δ*y*	±3Δ*y*	±4Δ*y*	

Yield displacement, downward loading is positive, upward loading is negative Δ*y*.

2.2.2 Measurement Content

During the test, the following data are collected by the sensor system arranged at the critical part of the test piece:

Load and displacement: The horizontal load output from the actuator and the horizontal displacement at the top of the specimen are collected in real time by force sensors and displacement meters.

Strain: Paste strain pads at the root of the wall and main stressed parts of the reinforcement to monitor the strain development of materials and reinforcement.

Crack development: Crack observer and high-definition camera are used to monitor and record crack initiation, development width and distribution mode throughout the process.

An important basis for measuring seismic performance of structural members is their bearing capacity. The corresponding load when the shear wall is cracked is called the cracking load, the load value when the wall reaches the maximum bearing capacity is called the ultimate load, and the corresponding value when the load value drops to 85% of the ultimate load after the maximum bearing capacity of the test piece is called the failure load. The operating point of longitudinal bar can be defined as yield load, and it is difficult to obtain the yield point of test piece directly during test. Geometric plotting method and isoarea method based on skeleton curve are two commonly used methods to determine yield point in low cycle test. In this paper, equal area method[6]is used to determine yield point.

Figure 1 is a method for determining an equivalent yield point, that is, an isoarea method, based on an equal area surrounded by a curve. Firstly, the secant line passing through the original point O of the curve intersects with the horizontal line passing through the ultimate load point A at the point B. The intersection curve intersects with the point D. The inclination angle of the secant line is continuously adjusted so that the area of ODO is equal to the area of ABD. Then the point C crossing the transverse axis perpendicular to the skeleton curve is the approximate yield point.

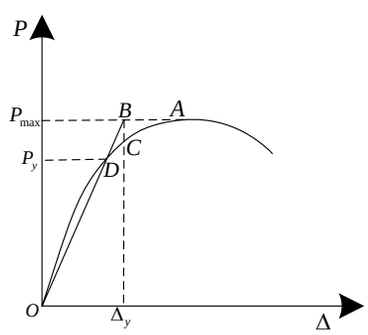

Figure 1 Calculation Of Yield Point By Equal Area Method

Ductility is one of the important indexes to measure the seismic performance, and the displacement ductility coefficient is generally used as the evaluation index. The results show that when the ductility coefficient is between 3-5, the structure has higher curvature and ductility, which is beneficial to seismic resistance of the structure. The mathematical expression for the displacement ductility coefficient is:μ

$$\mu = \frac{\Delta_u}{\Delta_y}$$

Where: ---displacement ductility coefficient;μ

Δ_u---failure displacement/mm, the displacement corresponding to the beam end when the load drops to 85% of the ultimate load;

Δ_y---yield displacement/mm, the displacement corresponding to the beam end when the member is yielded.

The corresponding position of each parameter in the load-displacement skeleton curve is shown in Figure 2.

2.3 Restoration Force Characteristics

2.3.1 Hysteresis curve

The seismic performance of the structure can be evaluated by hysteresis curve, which is a load-displacement ($P-\Delta$) curve obtained by cyclic loading. Figure 2 shows several typical forms of hysteresis loop, and the shape of hysteresis loop can intuitively show the hysteresis characteristics of test piece under low-cycle reciprocating load.

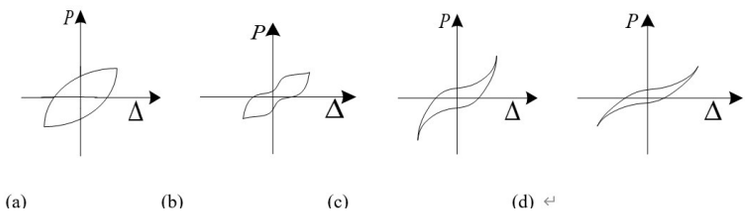

Figure 2 Typical Hysteresis Loop

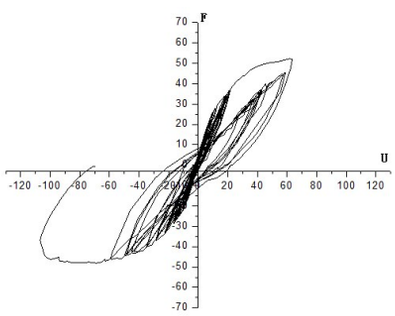

Figure 3 Q-1 Test hysteresis curve

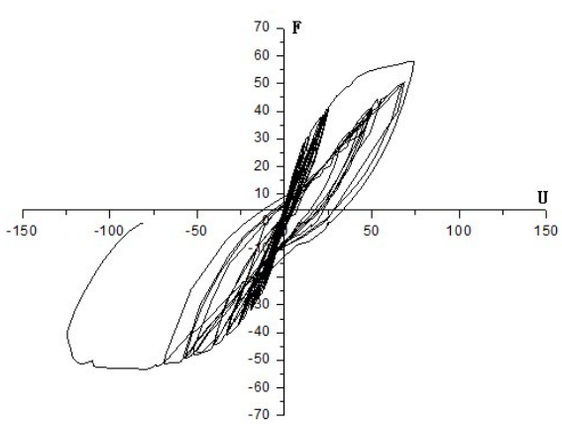

Figure 4 Q-2 test hysteresis curve

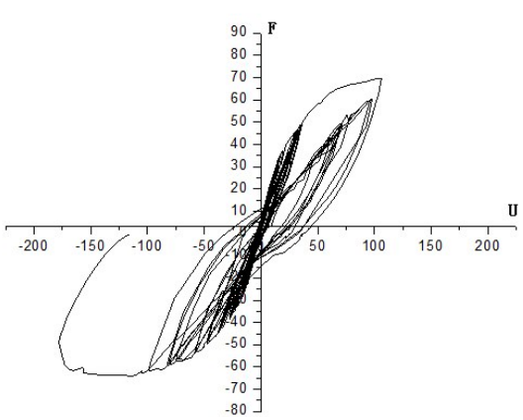

Figure 5 Q-3 test hysteresis curve

2.3.2 Skeleton Curve (Also Known as Bearing Capacity Degradation Analysis)

The skeleton curve is the trajectory of the maximum peak value of the horizontal force reached by each cyclic loading in the reciprocating load test, that is, the peak point of the hysteresis curve is connected in turn to obtain the envelope

curve, which reflects the bearing capacity and ductility of the member.

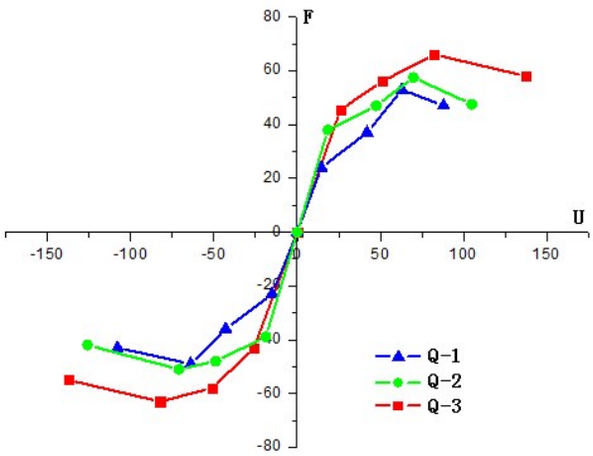

Figure 6 Skeleton Curve

2.3.3 Stiffness Degradation Curve

One of the important characteristics of structural nonlinearity is the change of structural stiffness, which is also an important index for structural nonlinearity analysis. The force characteristics and seismic performance of the structure can also be directly reflected by the variation of the rigidity of the structure.

In the low cycle test, the stiffness decreases with the cyclic loading of load and displacement[7]. In order to eliminate the effect of asymmetry of different batches of materials and forward and reverse loading on the equivalent stiffness calculation, the stiffness residual rate is used to express the stiffness degradation of the member. The formula of stiffness residual rate is:

$$\omega = \frac{K_i}{K_0}$$

Where: - stiffness residual rate;ω

K_i- equivalent stiffness under condition i;

K_0- equivalent stiffness of the first cycle;

The equivalent stiffness residual rate curves of members Q-1, Q-2 and Q-3 are shown in Figure 7:

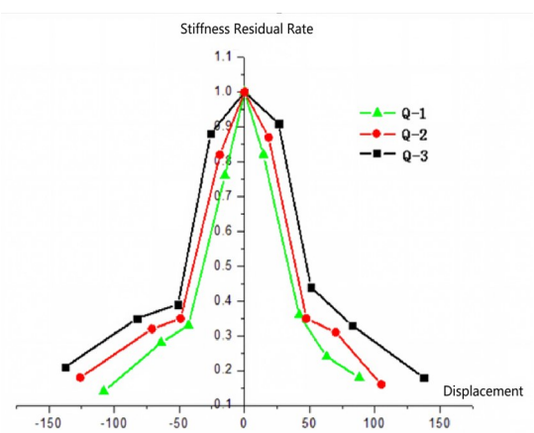

Figure 7 Stiffness Degradation Curve

3 Energy Consumption Capacity

The seismic performance of a structure or component mainly depends on the energy absorbed and dissipated in the inelastic phase. Under the action of reciprocating load, the energy of structure or member is converted into heat energy by internal damage such as material internal friction resistance, crack development and plastic hinge rotation. If the component can fully dissipate the seismic input energy without losing the bearing capacity and stability, the seismic performance of the component is better.

The equivalent viscosity coefficient, work ratio index and energy dissipation coefficient are usually used to quantify the energy dissipation capacity of the component[8-9]. The energy dissipation capacity of the component mainly depends on the magnitude of the load, the limit displacement, the number of cycles of the failure delay loop and the plumpness of

the hysteresis curve. On the hysteresis curve, the energy absorbed by the member, i.e., the area of the hysteresis loop, can be expressed by the difference between the energy absorbed during loading and the energy released during unloading. The hysteresis loop area can measure the energy dissipation capacity of structural members, which represents the maximum energy input that the structural members can bear under seismic action. The fuller the hysteresis loop is, the more the number of hysteresis loops is, the stronger the total energy consumption of structural members is. The equivalent viscous damping coefficient is generally used h_e to measure the energy dissipation capacity of the structure or member, and the equivalent viscous damping coefficient is calculated according to the formula.

$$h_e = \frac{1}{2\pi} \frac{S_{ABCD}}{S_{OCE} + S_{OAF}}$$

Where: S_{ABCD}indicates the hysteresis loop area of the component passing through a loading period; $S_{OCE}$and S_{OAF}respectively represents the triangle area corresponding to the maximum load and displacement of hysteresis loop forward and reverse loading, see Figure 8.

It can be seen that the larger h_e the energy absorbed by the member is not the more the energy absorbed by the member, but the stronger h_e the energy absorption ability of the member, that is, the greater the energy consumption ability of the member.

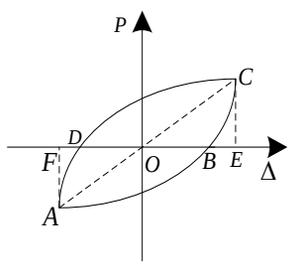

Figure 8 Hysteresis Loop Diagram

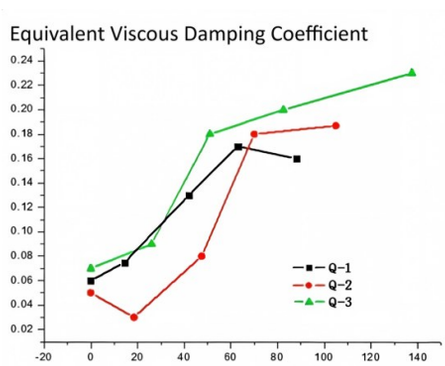

Figure 9 Equivalent Viscous Damping Coefficient

The energy dissipated by the component is composed of elastic deformation energy and inelastic deformation energy. According to the variation trend of the equivalent viscous damping coefficient (hereinafter referred to as h_e) in Figure 9, the coefficient continuously increases with the increase of displacement after a brief decrease in the initial loading stage, and presents a significant growth rate in the member yield stage, and tends to be gentle or slightly fluctuating after yield. This phenomenon can be explained from the energy dissipation mechanism: In the elastic phase, the crack development and material internal friction and other damage mechanisms develop slowly and slowly, $h_e$shows a gentle upward trend; After entering the yield stage, the crack of concrete is accelerated, the plastic deformation of reinforcement is intensified and the plastic hinge area is formed, jointly promoting a significant increase in the energy dissipation of structural rotation and internal friction, thus rapidly enhancing h_e. When the limit state is reached, the breaking and peeling of concrete and the accumulation of residual deformation become dominant, and the energy dissipation mechanism tends to be stable and the change of h_e tends to be slow.

By comparing the curves of the test pieces of h_e in Figure 9, it can be seen that the curves of the test pieces after reinforcement are developed more stably, which indicates that the reinforcement measures effectively improve the stability of energy consumption of the members. The results show that the energy dissipation capacity of the component can be significantly improved by strengthening with high toughness concrete. It is especially noteworthy that the curve of the double-sided reinforcement specimen of h_e (Q-3) is higher than that of the single-sided reinforcement specimen (Q-2), which indicates that the double-sided reinforcement has better improvement effect in lifting the wall energy

dissipation performance.

4 Accumulated Damage

The cumulative damage model reflects the energy dissipation and stiffness degradation of concrete structure under low cycle reciprocating load. Cumulative damage degree can be expressed by cumulative damage index D_{ey}. The cumulative damage index D_{ey} can reflect the process of damage accumulation of concrete structural members under reciprocating load, and the cumulative damage index of structural members can be calculated according to the formula.

$$D_{ey}=\frac{K_0\Delta_i^{\,2}-\left(\int_{\Delta_{i0}}^{\Delta_i} f_1(\Delta_i)d\Delta_i+\int_{\Delta_{j1}}^{-\Delta_i} f_2(-\Delta_i)d\Delta_i\right)}{K_0\Delta_i^{\,2}}$$

Where: ---initial stiffness of structural member;K_0

$f_1(\Delta_{ni})f_2(-\Delta_{ni})$---the shear function of the base of the structure under forward and reverse loading of the *i*-cycle,

$\pm\Delta_{ni}$---Absolute displacement of the top layer of the structure under the *i*-cyclic positive and reverse peak load.

The meaning of symbols in the formula is shown in Figure 10.

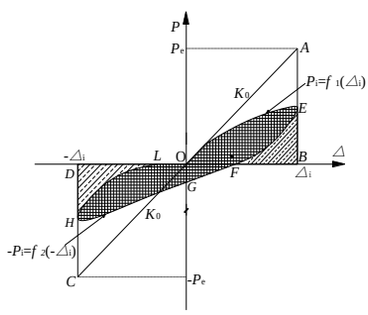

Figure 10 Stress State Of The *i*-Circulation Of Test Piece

According to the external force work and energy conservation law, the cumulative damage index D_{ey} can be calculated according to the following formula.

$$D_{ey}=\frac{(S_{OAB}+S_{OCD})-(S_{OEFGHL}+S_{BEF}+S_{DHL})}{S_{OAB}+S_{OCD}}$$

5 Experimental Conclusion

5.1 Results of Bearing Capacity, Deformation Capacity and Ductility

The corresponding positions of the parameters in the load-displacement skeleton curve are shown in Figure 11.

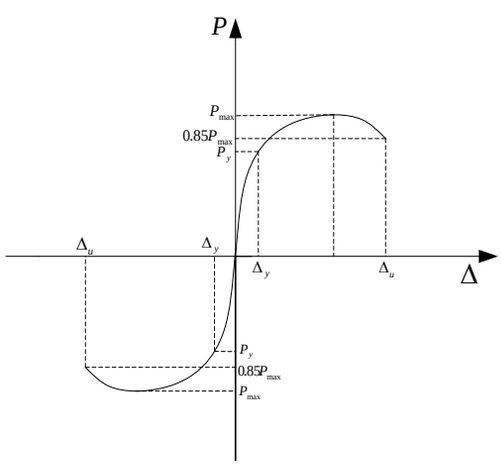

Figure 11 Load-Displacement Skeleton Curve

According to the test results, the displacement ductility coefficient of shear wall calculated by the formula is shown in Table 1. Generally, in the process of reciprocating loading, due to the Bauschinger effect, the values obtained from each loading will be different. In order to eliminate this error, the positive and negative data of the left and right end beam ends are averaged during the analysis. As shown in Table 2, the cracking loads of test pieces Q-3 and Q-2 were increased by 58.3% and 89.5%, respectively, compared with test piece Q-1; The yield load of the test pieces Q-3 and Q-2 was increased by 27.2% and 51.4% compared with that of the test piece Q-1; The ultimate load increased by 8.5% and 24.5%,

respectively, and the failure load increased by 1.1% and 24.2%, respectively. The cracking displacement increased 27.6% and 72.3% respectively. Yield displacement increased by 13.1% and 21.4%, respectively; The limit displacement increased by 11.1% and 30.9%, respectively. The failure displacement increased by 19.3% and 56.2% respectively. The ductility coefficients increased by 21.2% and 36.4%, respectively. Through comparison, the bearing capacity, deformation capacity and ductility of the test piece can be obviously improved by strengthening, especially the shear wall reinforced on both sides.

Table 2 Bearing Capacity, Displacement And Ductility Coefficient Of Members

Test piece No.		Load/kN				Displacement/mm				μ
		Crack	Yield	Limit	Broken	Crack	Yield	Limit	Broken	
Q-1	Positive	25	38	57	51	14	41	62	68	3.03
	Inverse	23	36	49	43	15	43	64	108	3.18
	Mean	24	37	53	47	14.5	42	63	88	3.105
Q-2	Positive	37	46	64	53	18	46	69	84	3.66
	Inverse	39	48	51	42	19	49	71	126	3.88
	Mean	38	47	57.5	47.5	18.5	47.5	70	105	3.77
Q-3	Positive	48	54	69	61	24	49	81	102	4.08
	Inverse	43	58	63	55	28	53	84	173	4.39
	Mean	45.5	56	66	58	26	51	82.5	137.5	4.235

5.2 Seismic Performance Analysis of Specimens

5.2.1 Recovery Force-hysteresis Curve Results

The results showed that the hysteresis curve of specimen Q-1 remained similar to that of shuttle shape with the increase of cycle times, and the kneading phenomenon was not as obvious as that of specimen Q-2 and Q-3. When the test pieces Q-2 and Q-3 are loaded to the limit displacement and failure displacement of the test piece Q-1, the hysteresis curve also presents a shuttle-shaped state. The yield displacement, yield load, ultimate displacement and ultimate load of the test pieces Q-2 and Q-3 are all improved compared with those of the test piece Q-1. This phenomenon can be seen from the hysteresis curves of the three members. Specimens Q-2 and Q-3 require greater forces and displacements in case of stiffness degradation, indicating greater seismic capacity. The hysteresis curve of the shear wall Q-3 with double-sided reinforcement is fuller, indicating that the hysteresis performance is better.

5.2.2 Results of Restoring Force-skeleton Curve

Obvious reverse bending points appear on the skeleton curves of the test pieces Q-2 and Q-3, indicating that the kneading phenomenon of the hysteresis curve of the test piece is more obvious, and the curve is similar to the bow shape. The main reason for this phenomenon is that the ultimate loading displacement of the test pieces Q-2 and Q-3 is larger than that of the test piece Q-1. It is known from Fig.7 that the curve of the test pieces Q-2 and Q-3 is more gentle than that of the test piece JD-1, and the curve of the descending section is more gentle than that of the curve of the test piece JD-1, and the failure occurs after the curve platform with a long displacement span appears, which indicates that the ductility performance of the member is effectively improved by using the high-toughness concrete material, the deformation of the member is more gentle at the later stage, the deformation capacity is better.

5.2.3 The Resumption Force-Stiffness Degradation Curve Results

It can be seen from Figure 7 that the curve trends of the three groups of test pieces are basically similar. Compared with the test piece Q-1, the displacement span corresponding to the descending section of the test pieces Q-2 and Q-3 is larger, and the curve is more gentle. It is shown that the rigidity degradation can be gentle when the structure enters the ductile working stage by adopting the reinforcement, so as to prevent the members from sudden failure due to sudden descending of the rigidity at this stage, which is beneficial to the structure seismic resistance. The curve of specimen Q-3 has smaller curvature and slower stiffness degradation in the later period of loading, which indicates that the stiffness degradation performance of shear wall reinforced by both sides has better improvement effect.

5.3 Accumulated Damage Results

The related literatures[10]point out that the cumulative damage of structure is divided into 5 grades, corresponding to different cumulative damage indexes. The cumulative damage index of test specimen is shown in Table 3.

Table 3 Accumulated Damage Index

Test piece No.	Primary crack	Crack 0.2 mm	Yield	Limit	Sabotage
Q-1	0.07	0.43	0.56	0.82	0.97
Q-2	0.04	0.53	0.51	0.79	0.85
Q-3	0.02	0.51	0.47	0.75	0.82

It can be seen from the accumulated damage index data in Table 14 that the damage development law of each test piece in the key stress stage is generally consistent with the five-level damage division of the shear wall. However, the comparative analysis shows that the cumulative damage index value corresponding to the final failure state of the reinforced specimens Q-2 and Q-3 is significantly lower than that of the unreinforced specimens Q-1, indicating that the actual damage degree is reduced by about one grade as a whole. The results show that the reinforcement with high ductility materials, especially the double-sided reinforcement strategy, can effectively inhibit the damage accumulation process of specimens in the limit state and significantly improve the damage tolerance under the failure mode.

It is further found that the cumulative damage index of the reinforced specimens exceeds the corresponding value of the yield phase when the crack width reaches the typical crack threshold of 0.2 mm. This phenomenon indicates that the reinforcement measures delay the formation and spread of concrete cracks, and the crack width gradually develops to 0.2 mm level after the specimen enters the yielding state. In addition, the cumulative damage index of the reinforced specimen was systematically lower than that of the control specimen Q-1 at each loading stage after yield, especially the double-sided reinforced specimen Q-3. From the point of view of damage evolution, it is proved that the reinforcement of shear walls with high toughness materials, especially the double-sided reinforcement structure, can effectively alleviate the damage accumulation rate and final damage degree of the structure under the cyclic load, thus improving its overall seismic toughness and recoverability.

6 Practical Migration of 6 ECC Technology

6.1 From Microstructure to Macrotoughness: The Core Mechanism of ECC for Soft Soil Deformation

The brittleness of ordinary concrete results from the weak interface transition area between the aggregate and cement matrix, and the cracks are easy to erupt and penetrate here, resulting in the sudden failure of materials. In contrast, engineered cement-based composites fundamentally reshaped the microstructure by removing coarse aggregates and introducing fine fibers. The strong interface formed between the fiber and the matrix enables the material to "disperse" the single concentrated wide crack into hundreds of micron-sized dense fine cracks during tension, thus realizing the multi-crack cracking mode. The large deformation capacity of Q-2 and Q-3 specimens in this test is the direct embodiment of this micro-mechanism in macro-mechanical behavior.

ECC's design philosophy transcends the traditional material idea of "avoiding damage" and turns to "controllable damage." Its peculiar tensile strain hardening characteristics make the material's bearing capacity increase slowly with the deformation after cracking. This characteristic corresponds to the core challenge of Shanghai Metro in soft ground: Long-term, uneven and slow deformation. The high ductility and slow stiffness degradation of ECC structure confer excellent deformation following ability and damage tolerance. In case of local base rheology or slight earthquake damage, ECC side wall can "digest" the stress through a large amount of micro-deformation to control the damage within the range of many micro-cracks and repairable, so as to avoid the occurrence of catastrophic cracks, thus significantly improving the operation safety and maintenance convenience.

6.2 Economic Analysis of ECC Full Life Cycle for Shanghai Soft Soil Foundation

The economic rationality of applying engineering cement-based composite materials to Shanghai metro side wall must be based on the deep understanding of Shanghai's unique engineering geological conditions and evaluated from the perspective of life cycle cost.

6.2.1 Cost-benefit Revaluation for Long-term Deformation of Soft Soil

The thick muddy soft soil in Shanghai area has obvious characteristics of high compressibility, rheology (creep) and secondary consolidation settlement. This means that the subway tunnel structure will endure slow and uneven long-term deformation throughout the service life of 100 years. The traditional concrete structure has poor adaptability to this problem, and it is easy to cause harmful cracks due to deformation constraints, resulting in water leakage, thus speeding up steel rust and causing high operation and maintenance problems, such as continuous plugging, dehumidification operation and final outage overhaul.

The high ductility, strain hardening characteristics and multi-joint cracking mode of ECC materials can effectively coordinate and follow the slow deformation of foundation like "flexible structure skin," disperse the local concentrated stress evenly, and greatly reduce the risk of cracking and leakage from the source. Therefore, it is higher than the initial material input of ordinary concrete, in essence, it is the "toughness consideration" paid to meet the specific challenge of Shanghai soft soil, which directly translates into the saving of long-term operation and maintenance cost.

6.2.2 Risk Cost Discount and Social Benefit Internalization

In super-large cities such as Shanghai, the safety and continuous operation of metro systems is of great socio-economic value. The direct economic loss and indirect social impact of any outage caused by structural damage are enormous.

Firstly, the excellent damage tolerance and self-healing ability of ECC structure can fundamentally reduce unplanned maintenance and medium-term overhaul caused by chronic leakage and performance degradation, thus ensuring continuity and predictability of operation. Secondly, in the face of extreme working conditions such as earthquakes, the excellent energy dissipation capacity (the energy dissipation capacity of Q-3 test piece is more than 1.3 times that of ordinary concrete) and deformation capacity, especially adapting to the characteristics that the soft soil foundation may amplify the long-term components of seismic motion, can effectively reduce the structural damage, thus greatly reducing the "catastrophic risk cost" caused by long-term shutdown after the disaster.

Therefore, in the special scene of Shanghai soft soil foundation, the choice of ECC is not only a technical optimization, but also a "strategic structure insurance" with high cost performance. The additional initial cost is a strategic investment for operation safety, maintenance cost controllability and social benefit guarantee in the coming decades, showing remarkable economic and technical rationality in the whole life cycle scale.

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