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EXPERIMENTAL STUDY ON SEISMIC RESISTANCE OF REINFORCED CONCRETE LINING OF SHIELD TUNNELS

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SUMMARY

A series of loading tests on the reinforced concrete shield linings were conducted to investigate longitudinal stability of shield tunnels during earthquakes. Three types of specimens which simulate parts of the reinforced concrete linings were considered, and were subjected to loadings in the direction of tunnel axis. It was understood from the tests that deformation and damage of test specimens concentrated on the joint sections between segment rings, and that stress and deformation of joint section is of great importance to seismic design for shield tunnel linings.

INTRODUCTION

In recent years the great majority of urban tunnels, such as sewer trunk pipes, underground railways, etc., have been constructed by shield tunneling method. As for the pipe-like underground structures, such as oil/gas pipelines and submerged tunnels, dynamic behavior during earthquakes has already been investigated by many researchers and several codes for seismic resistant design method have been presented. On the contrary, behavior of shield tunnels during earthquakes has not yet been sufficiently clarified and neither has been the earthquake resistant design method. It is necessary to examine the response of shield tunnel lining to ground motion from a different point of view from other pipe-like underground structures, due to the fact that shield tunnel linings are assembled with many precast segments and joints as shown in Fig. 1.

This study presents a series of loading test results of reinforced concrete linings of shield tunnels, and examines failure process and mechanical characteristics of the linings subjected to seismic force in the direction of tunnel axis.

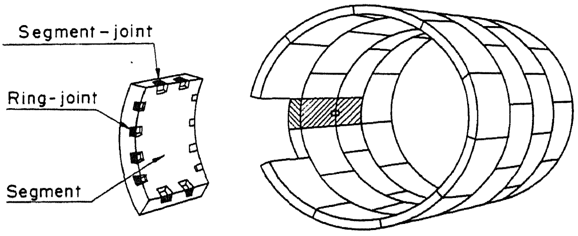
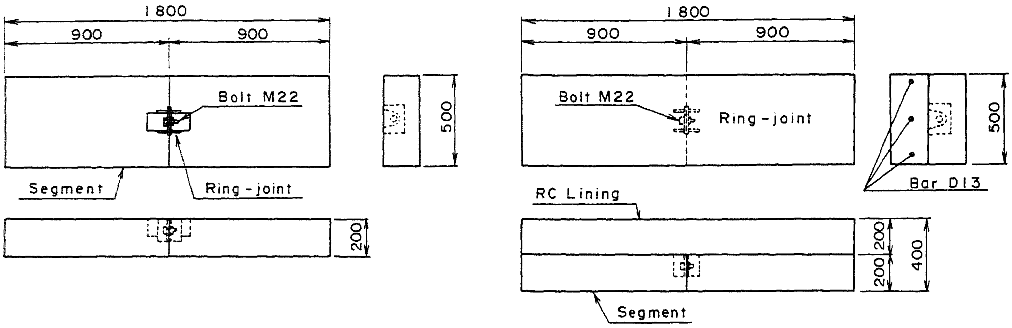


Fig. 1 Segment and Ring-joint of Shield Tunnel Lining

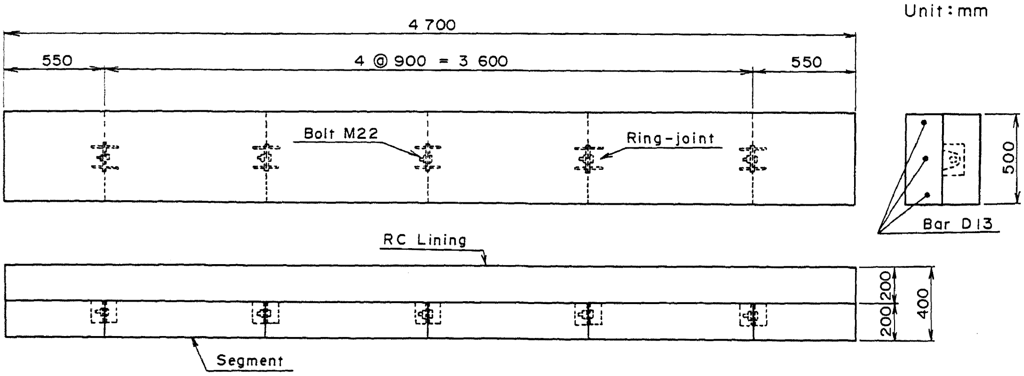
TEST SPECIMENS AND EXPERIMENTAL SET-UP

Three types of specimens as shown in Fig. 2 were used for the tests. Specimen type A (hatched area in Fig. 1), simulates a part of the tunnel lining which is a standard type for sewer trunk pipe with outer diameter of 4-5 m and thickness of 20 cm. A ring-joint is used to connect the parts of segments in the longitudinal direction. Specimen type B has an additional concrete lining with a thickness of 20 cm on the type A to simulate a part of tunnel lining which has inner lining. The additional lining is reinforced in the longitudinal direction with 3 SD30 bars with diameter of 13 mm. Specimen type C is the successive structure of type B and has an additional lining which is continuously placed on 6 segments being connected in series, i.e., the specimen has 5 joint-sections in the longitudinal direction. The loading tests on type C were aimed to investigate the failure process of lining in the actual case where segments are successively connected in the direction of tunnel axis. Strength of concrete used for each specimen is shown in Table 1. Yield point and tensile strength of SD30 bars were 36.7 kgf/mm^2 and 51.9 kgf/mm^2, respectively.

Fig. 3 shows the details of a ring-joint commonly used over the 3 types of specimens. It was made to be built up with 9 mm thick metal plate. Two SD30 bars with diameter of 13 mm and length of 30 cm were used to anchor the joint to segment. Bolts with diameter of 22 mm and tensile strength of 80 kgf/mm^2 were used to connect ring-joints, and were tightened with axial force of 6000 kgf.



(a) Type - A (b) Type - B



(c) Type - C

Fig. 2 Test Specimens

Table 1 Cases of Loading and Concrete Strength of Specimens

Type of specimen		Type A		Type B			Type C	
Name of specimen		A-1	A-2	B-1	B-2	B-3	C-1	C-2
Loading pattern		Monotonic tensile loading	Reversed cyclic loading	Monotonic tensile loading	Reversed cyclic loading	Monotonic tensile loading	Monotonic tensile loading	Reversed cyclic loading
Segment (kgf/cm^2)	Compressive strength	475	571	482	492	507	525	520
	Tensile strength	37.3	46.0	38.4	38.2	37.8	43.8	43.5
Inner lining (kgf/cm^2)	Compressive strength	---	---	256	310	315	315	323
	Tensile strength	---	---	22.0	24.1	33.2	33.2	29.4

It should be noted here that effective cross section of the bolts was reduced to about 70% of the original one for the purpose of measuring strain developed in the bolts.

Fig. 4 shows outline of experimental set-up. The specimens with one end being fixed to a reaction frame and the other end connected to an electro-hydraulic actuator were subjected to loadings in the longitudinal direction.

Two loading conditions, i.e., monotonically increasing tensile loading and step-wise monotonically increasing reversed cyclic loading, were employed on each type of specimen. Loadings were statically applied. Test cases are shown in Table 1. The specimens were subjected to the loading up to failure except the case of reversed cyclic loading on type C (case No. C-2) due to the trouble in loading device.

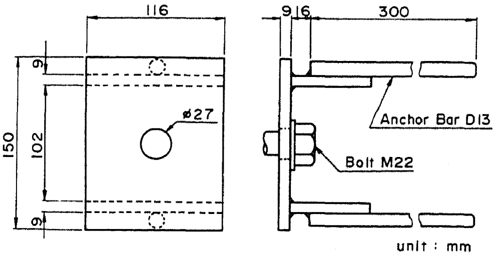


Fig. 3 Ring-joint

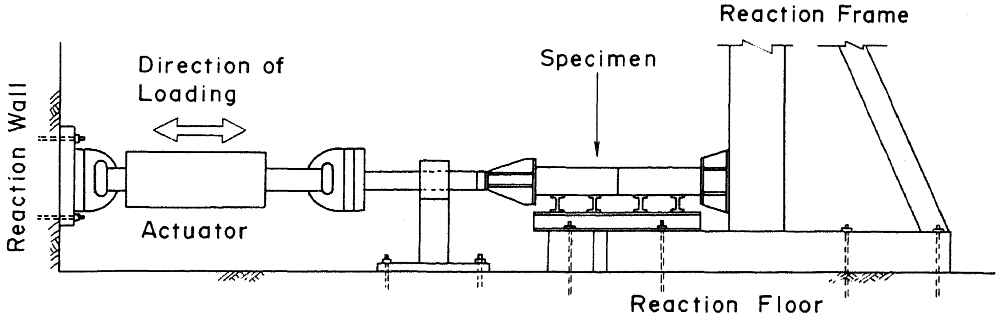


Fig. 4 Experimental Set-up

TEST RESULTS

Failure Mode Fig. 5 shows failure modes for each specimen. Failure of each specimen progressed in the following order:

Type A: 1 Development of diagonal cracks in segment concrete near the ring-joint, 2 flexural deformation of flange plate of ring-joint, 3 failure of ring-joint (rupture of anchor bar).

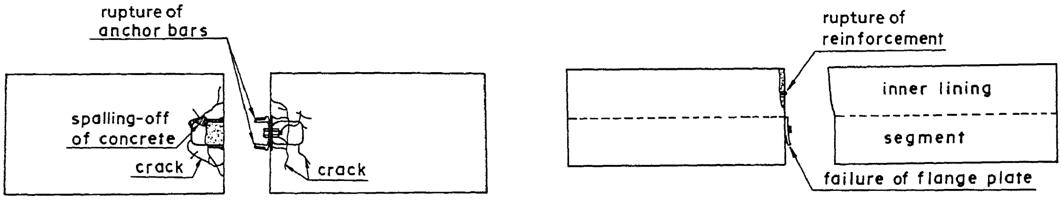
Type B: 1 Obvious tensile crack in inner lining at the joint section, 2 yielding of reinforcement of inner lining, 3 opening of joint section, 4 rupture of reinforcement of inner lining, 5 failure of ring-joint.

Type C: 1 Obvious tensile cracks in inner lining and yielding of reinforcement in succession at each joint section, 2 opening of each joint section, 3 rupture of reinforcement of inner lining at J-1 joint section, 4 failure of ring-joint at J-1 joint section.

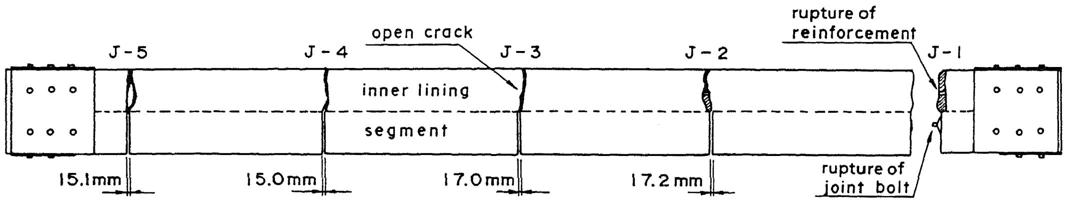
It was common to all the specimens that deformation and damage of tunnel lining concentrated on joint sections. It should be also noted that in specimen type C, concentration of deformation on a specific joint section did not occur unless rupture of reinforcement of inner lining developed. Deformations occurred almost equally on 5 joint sections.

Loading Hysteresis Fig. 6 shows the loading hystereses of load vs. deformation of joint section for each specimen. Deformations developed at segments were negligibly small as compared with deformation at joint section in tension. It is noticed from Fig. 6 that in common to each specimen type, envelope of hysteresis loops by the reversed cyclic loading approximately corresponds to the hysteresis curve by the monotonic tensile loading, while ultimate displacement is considerably larger in the latter case.

Strength and Deformation Capability Strength and deformation capability of each specimen is summarized in Table 2. The following characteristics of the strength and deformation capability of each specimen may be noted:



(a) Type A (A-2) : plan   (b) Type B (B-2): elevation



(c) Type C (C-1): elevation

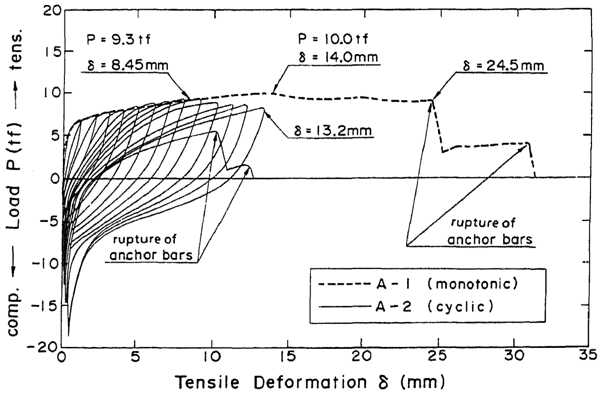
Fig. 5 Typical Failure Mode

(1) Yield strength, yield displacement and ultimate strength in case of reversed cyclic loading test (type A and type B) were approximately equal to those in case of monotonic tensile loading test, while ultimate displacement in the former case was only 54% for type A and 56-68% for type B of the latter case.

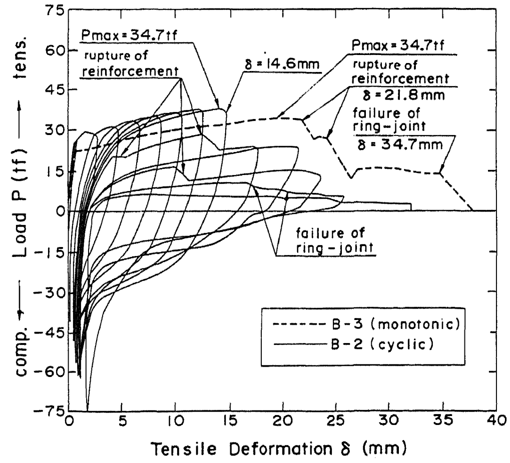
(2) Yield strength and ultimate strength of type B was respectively 3.0 times and 3.7 times those of type A.

(3) Both ultimate strength and ultimate displacement of ring-joint of type B, after rupture of reinforcement of inner lining, were greater than those of type A. This can be explained by the fact that in type A extra stress in ring-joint due to its displacement toward the space as a bolt box was caused, while in type B inner lining concrete filled the bolt box and restrained the displacement.

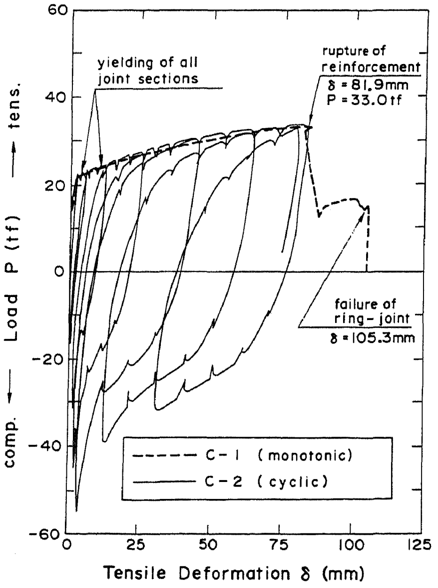
(4) Yield strength and ultimate strength of type C was approximately equal to those of type B and ultimate displacement of type C was about 4 times as much as that of type B, i.e., nearly equal to 5 times which is suggested for type C. Therefore, strength and deformation capability of type C may be considered simply to be equal to those of the structural system with five type-B specimens being connected in series.



(a) Loading Hysteresis of Type A



(b) Loading Hysteresis of Type B



(c) Loading Hysteresis of Type C

Fig. 6 Loading Hysteresis of Each Specimen Type

Table 2 Strength and Deformation Capability of Specimens

Type of specimen		Type A		Type B			Type C	
Name of specimen		A-1	A-2	B-1	B-2	B-3	C-1	C-2
Loading pattern		Monotonic	Cyclic	Monotonic	Cyclic	Monotonic	Monotonic	Cyclic
Load at cracking in inner lining (tf)		---	---	14.8	15.7	7.9	17.9(22.2)	13.2(19.1)
Yield strength (tf)		7.1	6.9	22.7	22.3	22.0	21.5(24.2)	21.2(23.0)
Yield displacement (mm)		1.4	1.1	0.8	0.7	0.8	1.2(10.1)	2.5 (3.8)
Ultimate strength (tf)	Reinforcement	---	---	37.2	34.7	34.7	33.0	Over 33.9
	Ring-joint	10.0	9.3	17.3	12.1	16.1	16.8	---
Ultimate displacement (mm)	Reinforcement	---	---	22.5	14.6	21.8	83.5	Over 79.5
	Ring-joint	24.5	13.2	41.9	23.5	34.7	105.3	---
Tensile stiffness (tf/mm)	Before yielding	3-30	6-30	30	30	20	25	13
	After yielding	0.27	0.30	0.9	1.1	1.0	0.1-0.2	0.1-0.2
Failure part of ring-joint		Anchor	Anchor	Anchor	Plate	Bolt	Bolt	---

Value in parentheses indicates the one when the event occurred at all joint sections.

CONCLUSION

Based on the test results, the following conclusions concerning the stability in the longitudinal direction of shield tunnels during earthquake may be deduced:

1) Deformation and damage of shield tunnel linings concentrate on ring-joint sections, i.e., the sections which connect segment-rings in the longitudinal direction of tunnel. When the tunnels are subjected to severe earthquake, possible damage may be cracks at joint sections, water leakage due to open cracks and failure of ring-joints.

2) Longitudinal stiffness of shield tunnel linings is more pronouncedly controlled by stiffness of joint sections than by that of segment rings. Mechanical characteristics of joint sections are the important points of attention for earthquake resistant design of shield tunnel.

3) In case of lining such as specimen type B used for this study, failure of joint sections progresses in the order of tensile crack at inner lining, yield and rupture of reinforcement of inner lining, and final failure of ring-joint.

4) Adequate longitudinal reinforcement in inner lining is required to prevent excessive deformation developed at a specific joint section by distributing it to several joint sections.

REFERENCE

Kawashima, K., Obinata, N., Shiba, Y., and Kano, T., "Development of Seismic Resistant Design Procedure for Shield Tunnels --- Part 3 Loading Tests of Reinforced Concrete Segment of Shield Tunnel ---", No. 2381 of the Technical Memorandum, Public Works Research Institute, Ministry of Construction, (1986) (in Japanese).