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Behavior of composite segment for shield tunnel

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ABSTRACT

Composite segment has been developed for obtaining high capacity in lining of shield tunnel subject to high hydraulic pressure and earth pressure in deep underground, which is made of steel plates connected to an infill of high fluidity concrete with shear connectors. However, a rational design method for composite segments can not be established, because the behavior of composite segments is not clarified. The purpose of this paper is to study the behavior of the most complicated composite segment with six steel plates using finite element method and the four-point bending tests. The effects of the shear studs and the thicknesses of steel plates were verified and estimated quantitatively. Meanwhile, the failure modes of composite segments were investigated. Comparisons show that the finite element model is suitable for composite segments and predicts the behavior of composite segments accurately.

1. Introduction

The subsurface under-roads in major cities are already crowded with underground facilities such as railroads, and tunnels for electricity, gas, communications, sewage and drainage, and conduits. For example, the subsurface of a national highway in Tokyo has about 33 km of conduits per kilometer of road as shown in Table 1 (MILT, 2005).

Previously, the use of underground space was moving from shallow underground to deep underground. However, at depths of down to 10 m below the surface, there is congestion in recent years. Therefore, new underground construction works for road tunnels of large cross-section, regulating ponds (underground rivers) have been constructed at progressively greater depths.

The frequency of using underground space in urban area tends to increase, because the technologies for tunnel excavation are advanced significantly. The use of underground space is not just to excavate deeply, but also to enlarge the cross-section of tunnel and to replace the circular shape with rectangular, multi-circle or other shape of cross-section in recent years. For these reasons, hydraulic pressure and earth pressure on tunnel are high and the occurred resultant forces are very large. Therefore, segments for shield tunnel must satisfy the required performances under severe conditions.

For concrete segment, it must thicken the thickness of concrete segment. The weight increases with increasing thickness of concrete segment, and it spends a large amount of labor on producing and handling in factory, transporting from the factory to site, removing from the construction yard to tunnel, and assembling at face. Meanwhile, it easily causes to damage the corner edges of concrete segment due to the segment weight and lack of tensile strength. On the other hand, the costs of producing, assembling temporarily, dividing, transporting, and re-assembling increase with increasing outside diameter of the shield machine. In addition, the treating cost of surplus soil will increase, because the amount of the excavated soil increases in proportion to the square of the excavated outside diameter. For steel segment, it must use the thick steel plates to ensure the necessary load carrying capacity and rigidity subject to high hydraulic pressure and earth pressure, jack thrust and backfill grouting pressure. However, steel segment has economic and welding disadvantages. The adopted ductile cast iron segment has economic disadvantage as well as steel segment (JSCE, 2007). Therefore, a new composite segment combined a box-shaped thin steel frame and high fluidity concrete is developed as shown in Fig. 1. This type of composite segment has the following advantages: (a) reducing the producing periods of composite segment by using steel form as formwork in cast; (b) obtaining high dimensional accuracy because of minimizing the deflection of steel form in welding process; (c) manufacturing an arbitrary section and an arbitrary shape because of excellent weldability; (d) not be damaged easily like concrete segment in assembling stage because of all sides covered with the steel plates, and compositing a uniform tunnel section; (e) easily assembling the composite segments because of having high stiffness, the few openings of the joints, and high dimensional accuracy; (f) decreasing the construction cost with decreasing the outside diameter of the shield machine and excavated soil, because the reduction of segment thickness can be achieved; (g) resisting large flexural moment because of having large carrying capacity; (h) resisting the particular

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Table 1
Conduits under national roads in the wards of Tokyo (161.2 km of national road under direct administration of National Government).

	Total length (km)	No. of kilometers (km) of underground facilities per one road km
Telephone lines	2684.1	16.7
Electric lines	1660.7	10.3
Gas	325.9	2.0
Hydraulic supply lines	364.6	2.3
Sewage lines	315.7	2.0
Total	5351.0	33.3

Note. (1) As of April 1, 2004. (2) Total length refers to total length of under-road conduits. (3) Does not include conduits to each building.

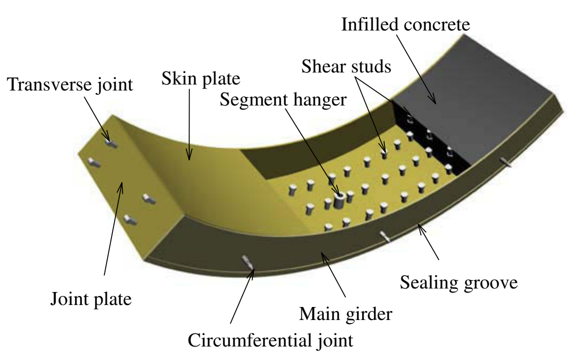

Fig. 1. Schematic of composite segment.

loads for neighboring construction and sharply curved construction by increasing thickness of the skin plates; (i) a rational structure for seismic design because of having superior ductility; (j) the segment width can be enlarged for having stronger main girders of steel.

However, a rational design method for composite segment can not be established, because the behavior of composite segments is still not clarified. To further optimize a rational design method of composite segment, the purpose of this paper is to study the behavior of the most complicated composite segment with six steel at the limit ultimate state. The authors used the tests and numerical analysis to discuss the restraint effect, load carrying capacity, stress distributions of steel plates, and failure modes. Recently, ductile and reinforced concrete (DRC) segment and Steel Segment with pre-filled concrete (SSPC) segment were developed (Shirato et al., 2003). The proposed analytical method can be used in the design codes for these type composite segments, if the behavior of the most complicated composite segment with six steel plates can be clarified.

2. Experimental program

2.1. Specimens

Ten steel–concrete composite model segments were designed, constructed, and air-cured. The details of the composite segment specimens are shown in Fig. 2 and Table 2. The compressive strength of the concrete at 28 d concrete was determined by testing standard 100×50 mm concrete cylinders according to Japanese concrete specification. Tensile and yield strengths of the structural steel were obtained by tensional testing according to

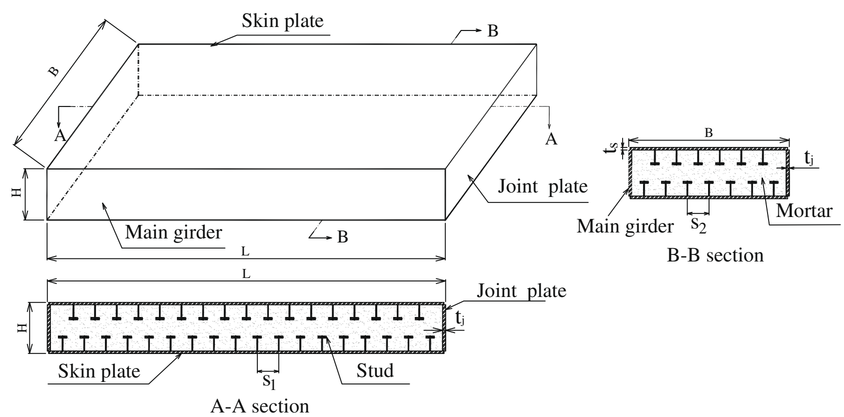

Fig. 2. Detail of composite segment specimen.

Table 2
Details of segment specimens.

Specimen	Dimension			Skin plate	Main girder	Joint plate	Diameter of the shank (mm)	Stud arrangement	
	Width *B* (mm)	Length *L* (mm)	Height *H* (mm)	Thickness				Spacing	
				t_s (mm)	t_m (mm)	t_j (mm)		S_1 (mm)	S_2 (mm)
Case 1	200	900	100	4.5	4.5	4.5	No stud		
Case 2	200	900	100	4.5	4.5	3.2	No stud		
Case 3	200	900	100	4.5	4.5	6.0	No stud		
Case 4	200	900	100	4.5	3.2	4.5	No stud		
Case 5	200	900	100	4.5	6.0	4.5	No stud		
Case 6	200	900	100	3.2	4.5	4.5	No stud		
Case 7	200	900	100	6.0	4.5	4.5	No stud		
Case 8	500	900	100	4.5	4.5	4.5	4.0	60	37.5
Case 9	300	900	100	3.2	6.0	6.0	8.0	60	60
Case 10	750	2100	150	4.5	9.0	9.0	13.0	150	100