Full-scale loading test of a Hybrid SFRC segment lining

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1. Introduction

The use of Steel Fibre Reinforced Concrete (SFRC) in a segment lining has continuously been growing due to its higher bearing capacity and cost-effectiveness than a conventional rebar-reinforced concrete segment (Angelo et al., 2011). However, its definite design rule or specification has not been proposed yet, and it prohibits SFRC segment from becoming more popular in shield tunnels. Moreover, it is true that a full SFRC segment without any rebar is more applicable to a compression-dominant loading condition since it is more brittle than a conventional rebar-reinforced concrete segment. From the reason, a hybrid SFRC segment combining steel fibres with rebars is considered as an alternative to improve the performance and the economic efficiency of a concrete segment (Bernardino et al., 2009).
This study aims to develop a hybrid segment lining where high-strength rebars with the yielding strength of 600 MPa are combined with a minimal and optimal dosage of steel fibres. A series of full-scale bending tests of the hybrid SFRC segment, a full SFRC segment and a conventional RC segment are carried out to validate higher bearing capacity of the hybrid SFRC segment.

2. SFRC mixing design

The basic mixing condition for concrete with the design strength of 45 MPa was obtained from trial batch tests as summarized in Table 1. Hereby, three kinds of steel fibres with different aspect ratios defined as the ratio of fibre length to fibre diameter were used to find out which fibre is more suitable for SFRC segment (Table 2).

Table 1 *Mixing condition for a concrete with its design strength of 45 MPa*

W/B (%)	S/a (%)	Unit weight (kg/m^3)				AD (%)	AE (%)
		W	B	S	G		
35.7	50	150	420	900	903	1.1	0.005

Table 2 *Steel fibres used in SFRC performance tests*

Fibre type	A	B	C
Length, L (mm)	35	60	60
Diameter, D (mm)	0.55	0.90	0.75
Aspect ratio, L/D	64	67	80

In this study, a series of tests to evaluate flexural toughness and fibre distribution of a SFRC were carried out with the notched specimens suggested by BS EN 14651(2005). Their performance and the suitability as a SFRC were evaluated based on Model Code 2010 (FIB, 2010). In Model Code 2010, a SFRC should satisfy Eqs. (1) and (2) defined as characteristic strength ratios obtained from a bending test with a notched specimen (Fig. 1) in order to substitute it for a traditional reinforcement.

$$\frac{f_{R,1}}{f_L} > 0.4 \quad (1)$$

$$\frac{f_{R,3}}{f_{R,1}} > 0.5 \quad (2)$$

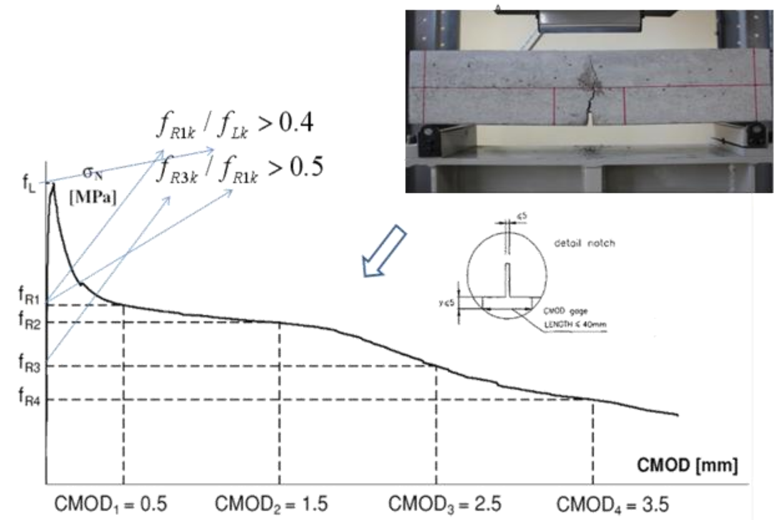


Fig. 1 *Characteristic strengths from a bending test with a notched specimen (FIB, 2010)*

In addition, the uniform distribution of steel fibres is very important to obtain favourable performance of a SFRC since the distribution of steel fibres within a SFRC governs its bending performance (Zandi et al., 2011). In order to investigate fibre distribution for each concrete and fibre mixing condition, the number of fibres visually observed in a ruptured section after a bending test were counted as shown in Fig. 2. Then, the orientation factor representing the degree of fibre distribution was calculated by Eq. (3). When the orientation factor (α) is bigger than 1, the corresponding SFRC is favourable for its application to a segment lining.

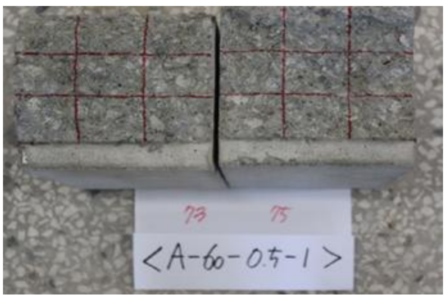


Fig. 2 *Investigation of the number of steel fibres in the ruptured section of a notched bending specimen*

$$N_1 = \alpha \cdot \frac{V_f}{A_f} \quad (3)$$

where α is the orientation factor N_1 is the number of fibre per unit area, V_f is volume fraction of

steel fibre in concrete, A_f is the cross-sectional area of a steel fibre and d_f is the diameter of a fibre.
When the dosage of fibres ranged from 20 kg/m^3 to 40 kg/m^3, every fibre type satisfied the criteria for characteristic strength ratios recommended by Model Code 2010. However, regardless of fibre dosage, the orientation factor of Type B fibre was smaller than 1, showing it cannot be used for SFRC. Type C fibre did not satisfy the criterion for fibre uniform distribution when its dosage was only 20 kg/m^3. In contrast, Type A fibre satisfied both the criteria for flexural toughness and fibre distribution independent of its dosage (Table 3).

Table 3 *Flexural toughness and fibre distribution dependent on fibre types and dosage*

Fibre type	Fibre dosage (kg/m^3)	Flexural toughness criteria		Fibre distribution
		Eq. (1)	Eq. (2)	
A (L/D = 64)	20	O.K	O.K	Favourable
	30	O.K	O.K	Favourable
	40	O.K	O.K	Favourable
B (L/D = 67)	20	O.K	O.K	Unfavourable
	30	O.K	O.K	Unfavourable
	40	O.K	O.K	Unfavourable
C (L/D = 80)	20	O.K	O.K	Unfavourable
	30	O.K	O.K	Favourable
	40	O.K	O.K	Favourable

3. Segment specimen for full-scale loading test

3.1 Segment design

In this study, full SFRC, Hybrid SFRC and rebar-reinforced concrete segments were designed for a subsea discharge tunnel with the length of 1.5 km excavated by an EPB (Earth-Pressure Balanced) shield TBM with the outer diameter of 4.5 m. Ground conditions in the tunnel mainly consisted of weak and hard rocks. Structural analyses based on the two-ring beam model were carried out to calculate structural member forces acting on a segment lining. The cross-sectional view and the two-ring beam model are shown in Fig. 3. The dimensions of a segment in the tunnel are summarized in Table 4 and Fig. 4. In the tunnel, a conventional rebar-reinforced concrete segment was originally designed with concrete design strength of 45 MPa as well as rebars with the yielding strength of 400 MPa.

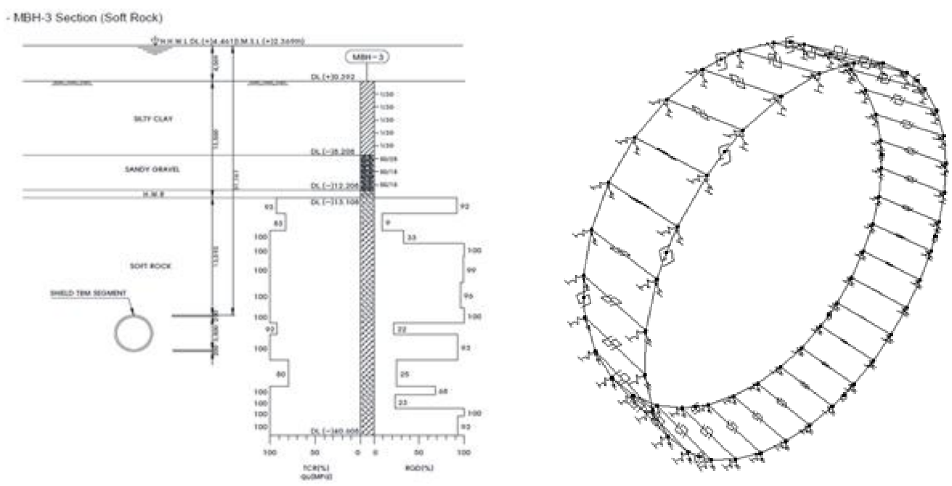


Fig. 3 *Cross-sectional view of a subsea tunnel and its corresponding segment lining model for structural analyses*

Table 4 *Dimensions of a segment used in a subsea discharge tunnel*

Segment length (m)	Segment width (m)	Segment thickness (m)
2.4	0.9	0.2

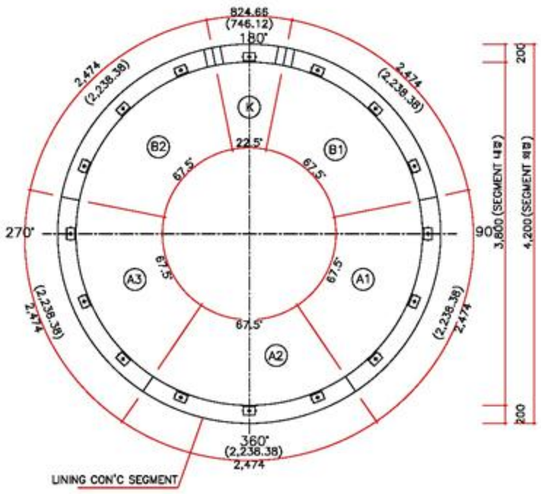
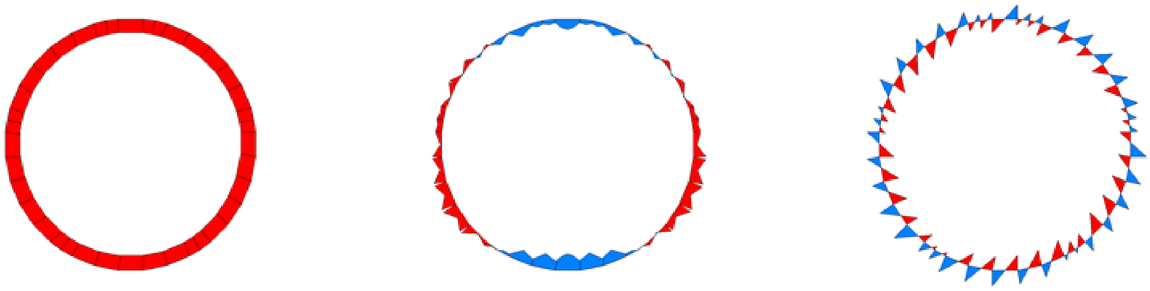


Fig. 4 *Cross-sectional standard drawing of a segment ring in a subsea discharge tunnel*

From the analyses under a variety of loading conditions, the maximum structural member forces such as axial force, bending moment and shear force used for the design of the minimum reinforcement of a segment lining were obtained as shown in Fig. 5.



(a) Axial force (Max. 1,164.58 kN) (b) Moment (Max. 25.65 kN·m) (c) Shear force (Max. 145.93 kN)

Fig. 5 *Structural member forces in a segment ring*

The applicability of SFRC as a structural member under the loading condition shown in Fig. 5 was evaluated by ACI 544. 4R-88(1999), Technical Report No. 63(Concrete Society, 2007) and RILEM TC 162-TDF(2003). Its corresponding P-M diagram of a full SFRC segment lining shows it can retain its structural stability even in the most unfavourable condition of the subsea tunnel (Fig. 6).

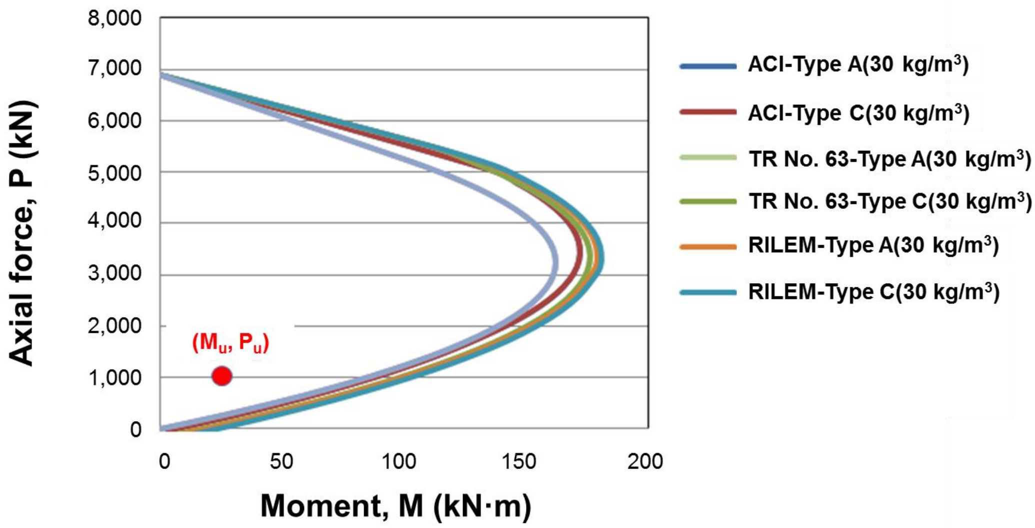


Fig. 6 *P-M diagram of full SFRC segments reinforced with two kinds of steel fibres (dosage: 30 kg/m^3)*

3.2 Segment specimens for full-scale loading tests

Based on the experimental results for SFRC performance summarized in Table 3, five-different kinds of segment specimens including a conventional reinforced concrete segment were built (Table 5). Hereby, a high-strength rebar reinforced concrete segment was also designed and made for the comparisons with Hybrid SFRC and full SFRC segments. The dosage of steel fibres was fixed as 30 kg/m^3 for full SFRC segments since the dosage of 20 kg/m^3 was revealed to be insufficient to retain its structural stability from preliminary beam bending tests and the structural analyses, even though it showed satisfactory flexural toughness and uniform fibre distribution as shown in Table 3. The conditions for fibre dosage of 40 kg/m^3 were not included in this study by considering its economic efficiency. Every segment specimen was made to be a real-scale A-type segment as shown in Fig. 4 with the dimensions in Table 4.

Table 5 *Segment specimen with different reinforcements for full-scale loading tests*

Specimen	Rebar		Steel fibre		
	Type	Amount	Type	Aspect ratio	Dosage
Case 1 (Conventional RC)	SD 400	H13@85 (10EA)	-	-	-
Case 2 (High-strength RC)	SD 500	H10@155 (6EA) (66%↓)	-	-	-
Case 3 (Hybrid SFRC)	SD 500	H10@155 (6EA) (66%↓)	A	64	20 kg/m^3
Case 4 (Full SFRC)	-	-	A	64	30 kg/m^3
Case 5 (Full SFRC)	-	-	C	80	30 kg/m^3

Strain gauges were installed on rebars for Hybrid SFRC and RC segments before concrete pouring in order to measure internal strain of a segment during a full-scale loading test (Fig. 7).

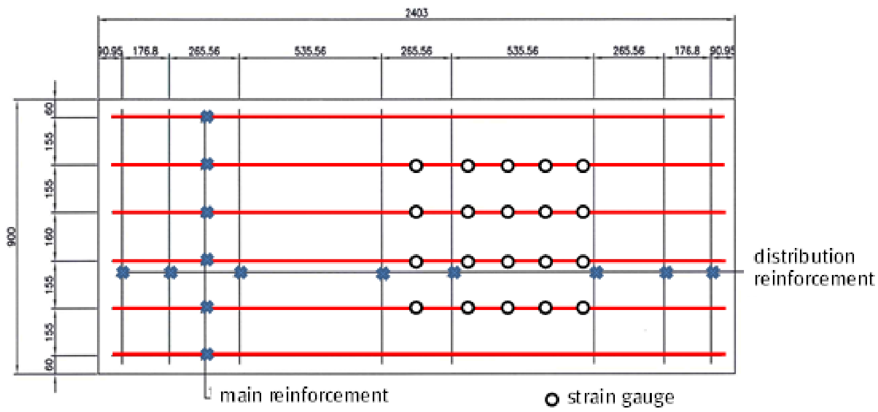


Fig. 7 *Strain gauge installation positions in Hybrid SFRC and RC segment specimens*

3.3 Full-scale loading test system

The full-scale loading test system used in this study is installed in Korea Institute of Civil Engineering and Building Technology with its maximum loading capacity of 500 tons. Every hydraulic actuator installed to the system is fully servo-controlled by a 17-channel servo controller.
In this study, a series of full-scale bending tests were carried out to simulate the condition where a very high stress concentration could act on a segment due to tail void formed behind its outer surface. Moreover, the full-scale bending test is a representative test to evaluate the structural performance of a segment (Gettu et al., 2004).
Four-point full-scale bending test system used in this study is shown in Fig. 8. The span of two rollers in the upper loading plate is 0.8 m. On the other hand, the loading span in the lower part of a segment specimen is set to be 2.4 m by using a roller base system designed for the dimensions of a segment used in this study.
Every full-scale test was carried out under constant displacement-control conditions with its

displacement rate of 2 mm/min. In addition, a photogrammetric system was used to quantitatively measure crack initiation and propagation in a segment during a loading test.

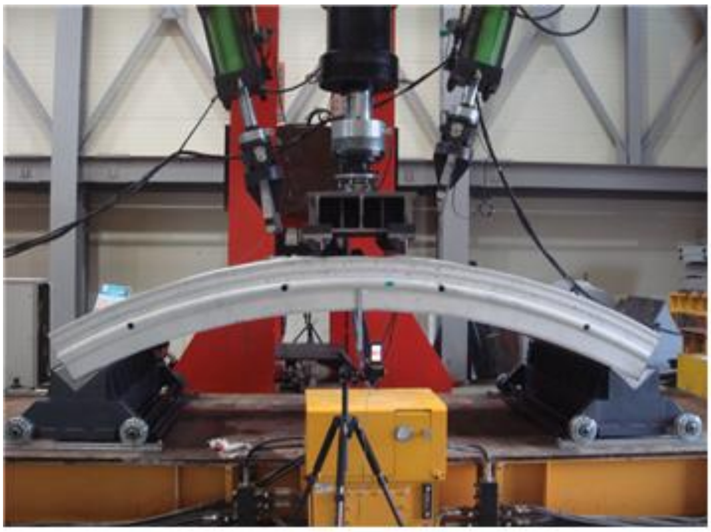


***Fig. 8** Full-scale loading system for a segment*

4. Testing results

The design cracking load and the design maximum load calculated for the subsea discharge tunnel was 37.6 kN and 65.6 kN respectively. From the tests, every segment specimen showed much higher a cracking load and a maximum load than the design loads (Table 6 and Fig. 9). Especially, the Hybrid SFRC segment showed the best crack resistance with the increase of the cracking load by 247.3%. On the other hand, its maximum load was 192.1% higher than the design maximum load, which was smaller than that of the conventional RC segment (Case 1). The reason arise from the fact that two main rebars in the corners were cut to install bolt boxes in the segment. Therefore, the secondary test was carried out for a hybrid SFRC segment with a modified bolt box capable of preventing rebars from being cut. From the additional test, the modified hybrid SFRC segment showed the maximum load of 247.5 kN, which was higher than the design maximum load by 377%. Two kinds of full SFRC segments were also satisfactory as a substitute for a conventional RC segment showing higher cracking and maximum loads than the design values. The reason is why the loading condition in the subsea tunnel is dominant in compression.

***Table 6** Summary of full-scale loading tests for different reinforced concrete segments*

Specimen	Cracking load			Maximum load		
	Design	Experiment	Note	Design	Experiment	Note
Case 1	37.6 kN	51 kN	135.6% ↑	65.6 kN	185 kN	282.0% ↑
Case 2		63 kN	167.6% ↑		101 kN	154.0% ↑
Case 3		93 kN	247.3% ↑		126 kN	192.1% ↑
Case 4		47 kN	125.0% ↑		78 kN	118.9% ↑
Case 5		51 kN	135.6% ↑		73 kN	111.3% ↑

From the photogrammetric observation of segment cracks during full-scale loading tests, it is revealed that steel fibres have a very good effects on cracking prevention and the increase of cracking load. Fig. 10 shows crack patterns observed in the lower surface of segments at their failure. It is clear that relatively few major cracks were found on the hybrid SFRC and full SFRC segments in comparison with the conventional and the high-strength RC segments. Especially, only one major crack was observed at each full SFRC segment by its failure.

After validating the applicability of the hybrid SFRC segment to the subsea discharge tunnel condition, it was applied to the tunnel as shown in Fig. 11. Due to the crack resistance effect of steel fibres observed in the full-scale loading tests, it was hard to find an observable crack by naked eyes in the installed Hybrid SFRC segments. Contrastively, a few major cracks induced by the propulsion of shield jacks were observed at the corners of conventional RC segments resulting in their repairs by mortar.

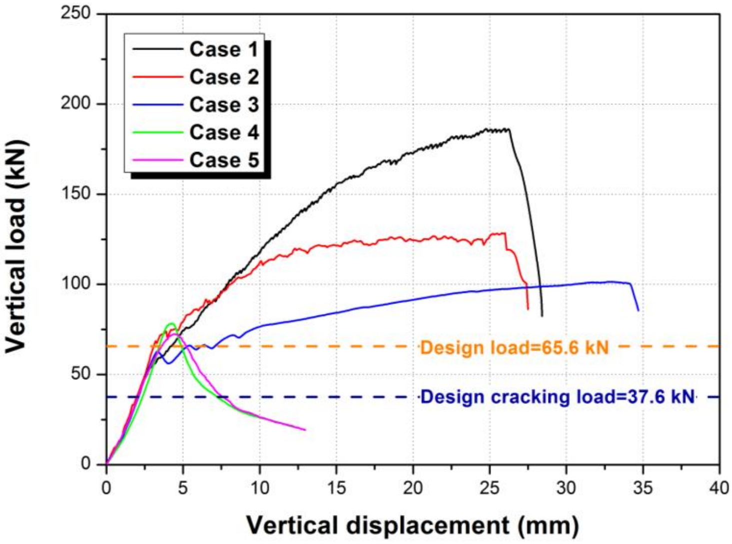
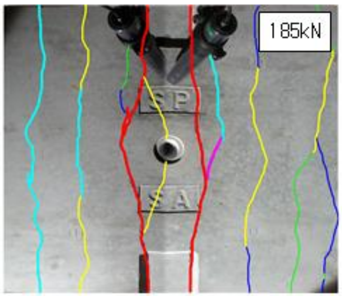
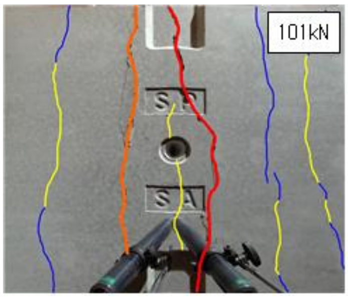


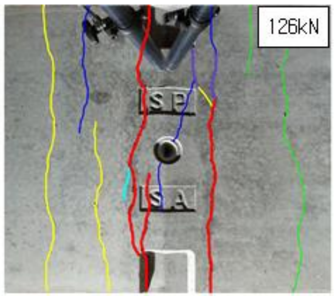
Fig. 9 *Load-displacement curves obtained from each segment specimen*



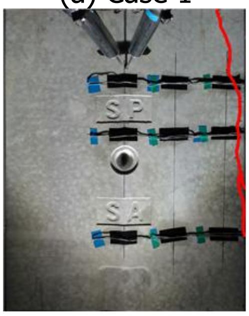
(a) Case 1



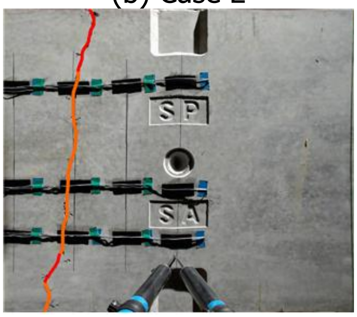
(b) Case 2



(c) Case 3



(d) Case 4



(e) Case 5

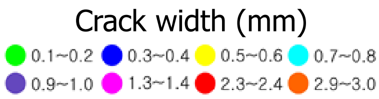


Fig. 10 *Crack patterns for each segment specimen at failure*

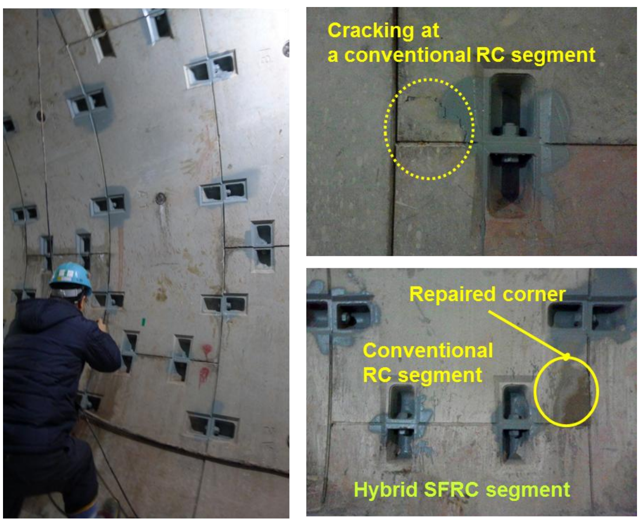


Fig. 11 *Hybrid SFRC segment after its field application*

5. Conclusions

In this study, a hybrid SFRC segment where high-strength rebars with their yielding strength of 600 MPa are combined with a minimal steel fibre dosage of 20 kg/m^3 was compared with a conventional RC, a high-strength RC and a full SFRC segment in a series of full-scale loading test. From the study, the cracking load as well as the ductility of a hybrid SFRC segment increases approximately by over 100% compared with a conventional RC segment. Especially, in comparison with the conventional RC segment, the production cost of the hybrid SFRC segment can be reduced by approximately 27%. It results from the optimal combination of high-strength rebars and steel fibres. After the application of the hybrid SFRC segment to the subsea tunnel, it was hard to find its observable major crack due to its higher crack resistance, even though many major cracks arising from shield jack propulsion were observed at the corners of conventional RC segments necessitating their repair. The full SFRC segments also showed the best applicability under a compression-dominant condition such as the subsea discharge tunnel examined in this study since it satisfied every design load criterion with the highest economic efficiency.

6. Acknowledgements

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