A study on reinforcement arrangement of the corner segment for a composite arched shielded tunnel

K. Sato & K. Higashiuwatoko
Civil Engineering Technology Division of Obayashi Corporation, Tokyo, Japan

T. Maeda
URUP Kawajiri Construction Project Office of Obayashi Corporation, Tokyo, Japan

A. Takeda
Structural Engineering Department Technical Research Institute Technology Division of Obayashi Corporation, Tokyo, Japan

SUMMARY:
A study on reinforcement arrangement at the segment corner, where is greatly affected by abdominal pressure, was undertaken during the development of a composite arched shielded tunnel using SFRC (Steel Fiber Reinforced Concrete) segment. One arrangement based on the common method applied for rigid frame structures (Basic Model) and another simplified form with less reinforcement (Simple Model) were designed, and performance of each model was evaluated by material non-liner analysis using FEM and cyclic loading test conducted on actual sized specimens. The result shows that Basic Model provides sufficient strength to the segment while Simple Model failed to avoid cracking by abdominal pressure.

Keywords: Shielded Tunnel, SFRC Segment, Material Non-Liner Analysis, Cyclic Loading Test

1. INTRODUCTION

The composite arched shielded tunnel using segments consist of arcs with different curvatures has been developed by authors. Because its section is nearly rectangular, the composite arched shielded tunnel is effective reducing excavation volume to secure necessary space compared with the circular shaped shielded tunnel. Moreover, this type of tunnel enables construction at small overburden area without open-cut excavation which usually accompanies traffic restriction on the ground. On the other hand, because corners of the composite arched shielded tunnel are smaller in curvature compared to slabs and walls, it is expected that their mechanical behaviour is different from that of other areas of the tunnel especially at the time of earthquake. Therefore, arrangement of reinforcement of the corner segment was designed with reference to design methods for corners of box culverts, and performance was examined by FEM analysis and cyclic loading test on actual sized specimens Segments used in this study were fabricated with SFRC (Steel Fiber Reinforced Concrete), and its characteristics are considered in reinforcement designs.

2. REINFORCEMENT ARRANGEMENT MODELS FOR SEGMENT CORNER

2.1. Tunnel Model

Figure 1 is the cross section of a road tunnel used in this study. The section is consists of several arcs with different curvatures; R13400 at outside of top slab (R12900 at inside), R16500 at outside of bottom slab (R16000 at inside), R6100 at outside of walls (R5700 at inside). Thicknesses of segments are 500mm at top and bottom slabs and 400mm at walls. Curvatures at corners are R1300 at upper corners and R400 at lower corners. Thickness changes from 400mm to 500mm sequentially. Angles formed by slabs and walls are 134 degrees at upper corners and 130 degrees at lower corners.

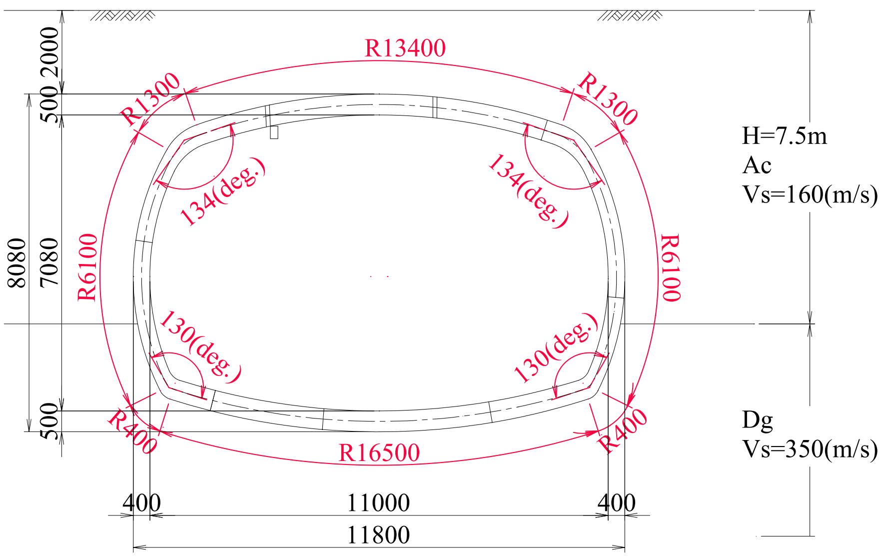
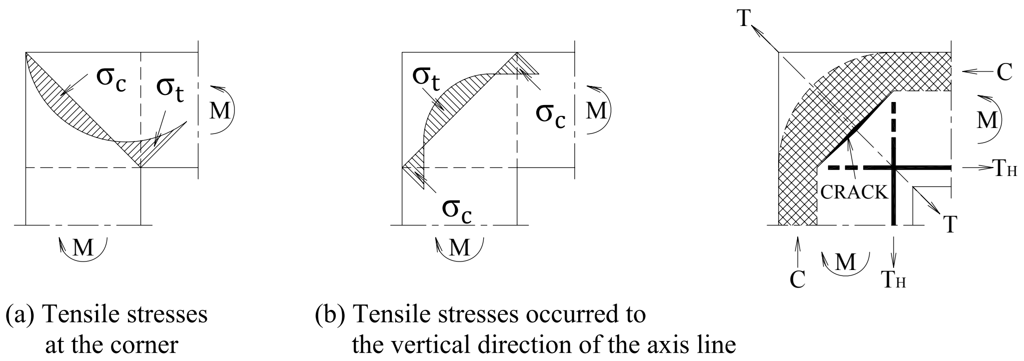


Figure 1. The cross section of a composite arched shielded tunnel in this study

2.2. Reinforcement Arrangement at Corners

2.2.1. Stresses State at Corners

When positive bending moment (inward tension) is applied to the corner of a Rahmen structure, abdominal pressure occurs to the vertical direction of the axis line by conversion of the internal stress direction. This causes tension to the diagonal direction of the corner, and if not enough reinforcements were placed, cracks initiate to the direction orthogonal to the diagonal line of the corner (Figure 2). Since curvatures at corners of the tunnel section considered in this study are considerably smaller than those of slabs and walls, the structure has potential to fracture by tension caused by abdominal pressure at corners. Therefore, section forces in the condition of Level2 earthquake were calculated, and possibility of positive bending moment occurrence at corners was examined. Figure 3 shows calculated section forces. These section forces are of the maximum angular displacement between soil layers given by two-dimensional dynamic response analysis on an interactive model, in which segment was inputted as non-linear beam element, segment joints as non-linear spring element, ground as linear plane strain element (deteriorated strength for earthquake was used as shear strength). The acceleration wave 2-1-2, a Level2 Type2 seismic motion in The Specifications for Highway Bridges and Commentary [Part5 Seismic Design] was used as seismic motion in this analysis.



M: Bending moment C: Resultant force (compression) T, T_H: Resultant force (tension)
σ_c: Compressive stress σ_t: Tensile stress

Figure 2. Stresses state at corners of rahmen structure

The bending moment distribution diagram shows positive bending moment (inward tension) at upper right and lower left corners. In case of reverse transformation of the tunnel, structure receives the same moment at upper left and bottom right corners. Thus, all corners are potential to have cracks by abdominal pressure and are subject to study on reinforcement arrangement.

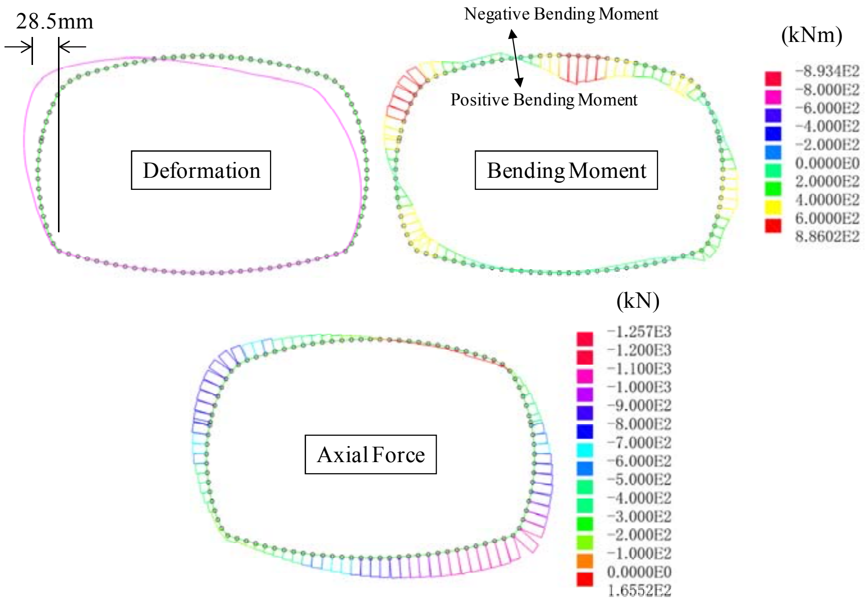


Figure 3. The deformation and section forces of shielded tunnel under a Level2 seismic motion

In the calculation of Level2 seismic motion, positive bending moment was about 550kNm at both upper and lower corners, axial force was about 100kN. Diagonal tensile force caused by abdominal pressure can be estimated geometrically by Equation 1.

$$T=2\cos(\alpha/2)T_H \qquad (1)$$

T: diagonal tensile force
T_H: tensile force working on reinforcement
α: corner angle

According to Equation 1, when section forces are equal, diagonal tensile force at the lower corner, where the angle formed by slab and wall is smaller than the upper corner, is greater. Thus, following examinations were conducted on the lower corner model.

2.2.2. Reinforcement Designs for Corners

The shielded tunnel in discussion uses segments cast with SFRC. Because of shear proof stress provided by steel fibers mixed in the concrete, in many cases, shear reinforcement can be omitted from SFRC segments. The segment used in this study has no shear reinforcement bar in principle. However, composite arched shielded tunnel, unlike common circular shielded tunnel, possibly receives diagonal tensile force at corners. As explained in 2.2.1, corners of the tunnel in discussion are expected to be under positive bending moment which incurs diagonal tensile force. Reinforcement of the structure in a way such placing some shier reinforcement bars to the direction orthogonal to the axial line is necessary. Two types of reinforcement arrangements were proposed as shown in Figure 4. Proposal1 is based on common method applied for Rahmen structures (Basic Model), and some reinforcements are omitted from it in Proposal2 (Simple Model).

As described before, when there is positive bending moment acting on a corner, concrete gets cracks to the axial direction by abdominal pressure, and inward main reinforcement bars tend to be pushed out from the concrete. In Proposal1, inward main bars of the tunnel are crossed (called “crossed reinforcement”) and bended at the position of outward main bars for fixation. Furthermore, inward main bars are banded by three tie-hoops. In Proposal2, crossed reinforcement is omitted to improve productivity and cost competitiveness. The structure resists abdominal pressure only by three tie-hoops. Performance of these two proposals was evaluated by FEM analysis and cyclic loading test conducted on actual sized specimens.

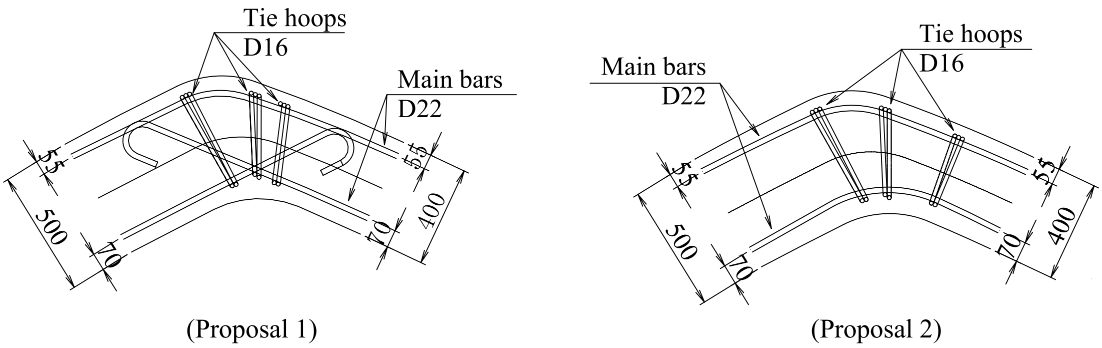


Figure 4. Reinforcement arrangement of the corner

3. ESTIMATION BY FEM ANALYSIS

3.1. Cases and Models

Table 1 shows analysis cases. Two proposals and one case without reinforcement against abdominal pressure were analyzed by “FINAL” a non-linear FEM program for concrete structure.

Table 1. Cases of Material non-liner analysis

Cases	Reinforcement arrangement patterns	Loading method
Case1	Combination case of crossed reinforcement and tie-hoops (Proposal 1)	Monotonic loading
Case2	Tie-hoops only (Proposal 2)	Monotonic loading
Case3	Non reinforcement	Monotonic loading

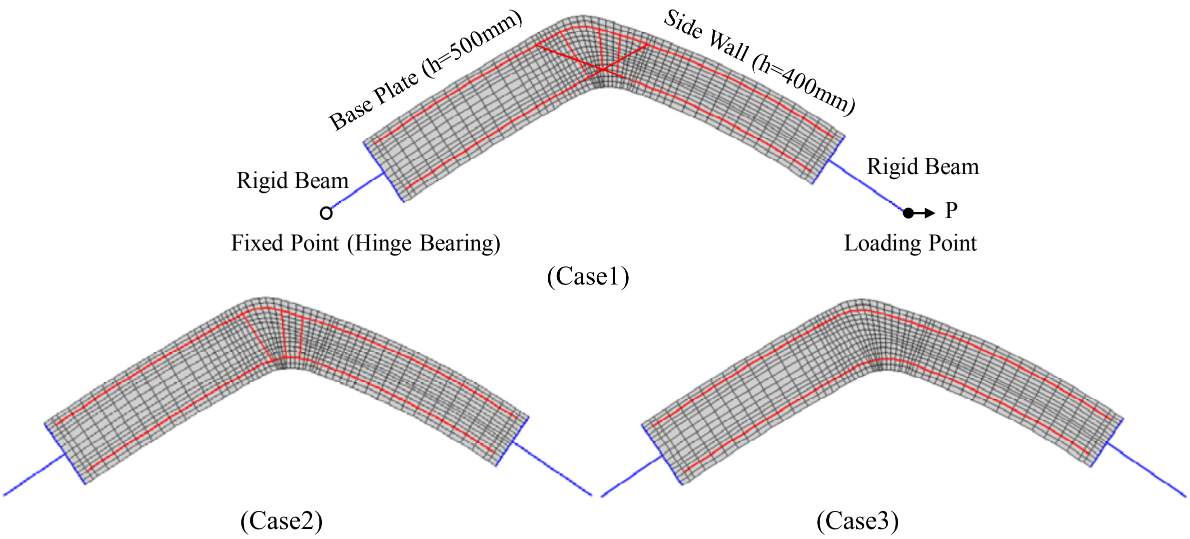


Figure 5. Models of material non-liner analysis

Figure 5 is the model used. General property of the model is identical to actual sized specimen used for loading test. Rigid beams on both ends represent jigs of loading machine. One end is a fixed point (hinge bearing), the other is a loading point to generate positive bending moment to the corner by monotonic loading. Specifications of materials are as shown in Table 2 and Table 3. Figure 6 is "tensile stress - crack amplitude" and "compressive stress - strain" diagram which were estimated based on a previous study with allowance for the efficacy of SFRC. Strength of concrete and yield stress of reinforcement bar used hereto are rated values. Stress - strain relation of the bar in the model is bilinear, rigidity decrement rate after yielding is 1/100.

Table 2. Material Parameter (Concrete)

Element type	Non-liner plane stress element
Unit weight	24.5 kN/m^3
Unconfined compressive strength	42.0 N/mm^2
Unconfined tensile strength	2.78 N/mm^2
Young's modulus	35.8 kN/mm^2
Poisson's ratio	0.17

Table 3. Material Parameter (reinforcement bar)

Element type	Non-liner beam element
Outward main bars	D22 (7/0.85m)
Inward main bars	D22 (7/0.85m)
Tie-hoops	D16 (4/0.85m)
Yield stress	345 N/mm^2
Young's modulus	200 kN/mm^2
Poisson's ratio	0.30
Stress-Strain curve	Bilinear
Rigidity lowering rate	1/100

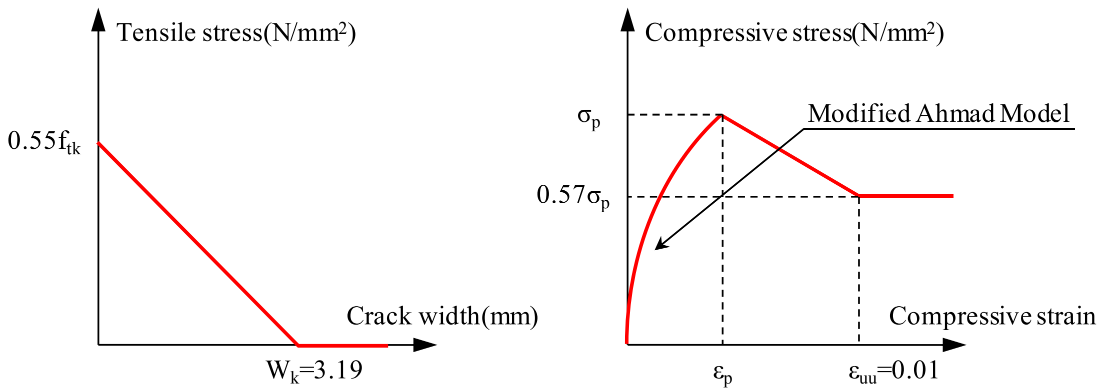


Figure 6. Non-liner model of concrete

3.2. Result

Figure 7 shows P-δ relation. P represents the load at loading point, δ represents relative displacement between loading point and fixed point. The figure also shows initial yield points of reinforcements on tensile side at each case. The maximum yield load of 308kN was recorded in Case1, the combination case of crossed reinforcements and tie-hoops. The load was 261kN at Case2, tie-hoops only case, which is approximately 15% smaller than Case1, and 212kN at Case3, 31% less Case1. In Case3, the inclination of the graph changed before tensile reinforcement reached its yield point.

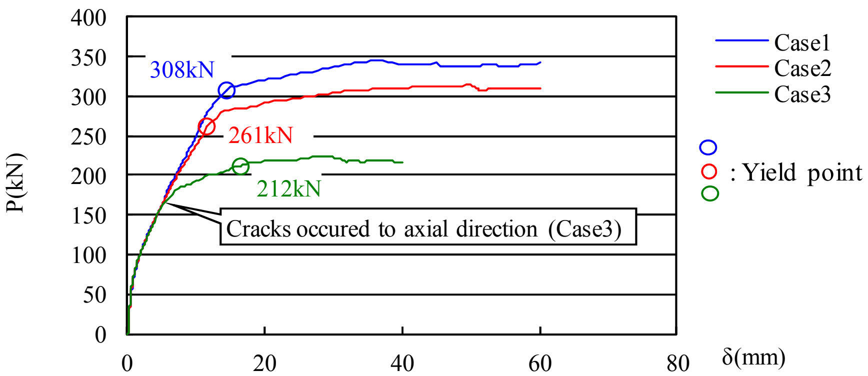


Figure 7. Results of Analysis (P-δ relation)

Figure 8 shows distribution of major cracks. In terms of Case1 and Case2, it displays cracks at double yield displacement (2δy), while for Case3 it is at the yield displacement (1δy). Numerous cracks were initiated to the axial direction in Case3 surmised to be a result of abdominal pressure, although no remarkable cracks were observed at 1δy in Case1 and Case2.

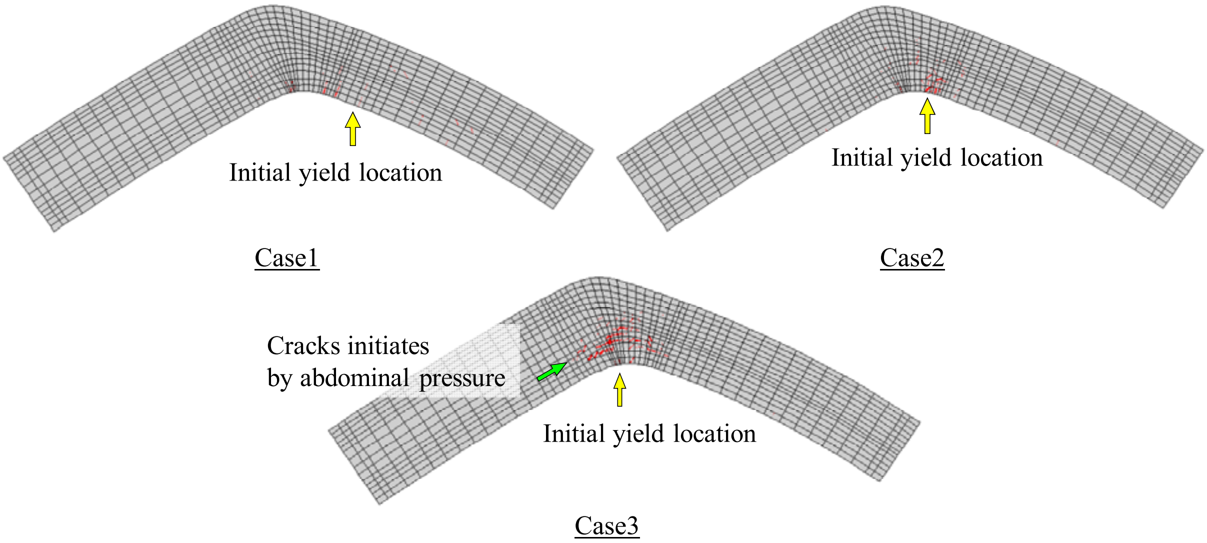


Figure 8. Distribution of major cracks

Going into details of Case3, the P-δ inclination change at around P=160kN was almost simultaneous with initiation of cracks to the axial direction. In the reference analysis undertaken with the same reinforcement as Case3 but without allowance for the effect of SFRC in "tensile stress - crack amplitude" relation (no bear of tensile stress by concrete), load P dropped the moment a crack initiated to the axial direction. It is inferred from these results that steel fibers in SFRC segment bear tensile stress when a crack to the axial direction initiates by abdominal pressure, and thus load P continues rising without fall.

Initial yield locations of main bars in Case1 and Case2 were rather on the wall side than the center of the corner, and were related to the distribution of reinforcements. It was outside but beside tie-hoops in Case2, or beside the fixing point of crossed reinforcement outer tie-hoops in Case1. The fact that the yield load in Case2 was smaller than Case1 in Figure 7 means that crossed reinforcements at corners have certain effect to increase load resistance. When the displacement was 2δy, cracks in Case1 improved to the sectional direction around initial yield location of the tensile reinforcement while cracks surmised to be a result of abdominal pressure were observed in Case2 in addition to cracks to the sectional direction. It indicates that three tie-hoops are not sufficient as reinforcement at the corner, and crossed reinforcements are effective to be used together with tie-hoops. It was also confirmed that the yield load in Case2 was smaller than in Case1 because minor cracks, although not as greatly as in Case3, initiated to the axial direction at 1δy.

4. CYCLIC LOADING TEST ON ACTUAL SEGMENT

4.1. Cases and Models

Table 4 and Table 5 show test cases and specifications of specimens. The test was conducted for Proposal1 and Proposal2 mentioned above. Specimens are SFRC segments with steel fiber mix rate 6% and concrete design strength 42N/mm2. Their depth is 850mm, seizes and numbers of reinforcement bars used is the same as the analysis model in Table 3. Outlines of the specimen (Case1) are shown in Figure 9. Tie-hoops are placed at three locations, each tie-hoop consists of two sets of bars which are fixing main reinforcement bars. Steel jigs are attached at both ends of the specimen, one is fixed point (hinge bearing), the other is loading point. Arrangement of major gages at the corner is also shown in Figure 9. Gages for main reinforcement bars are placed mostly around crossed reinforcements and curvature transition points. Loading method is positive and negative cyclic loading7). Among the displacements of tensile side main bars, measurement of the displacement gage set nearby the border between corner and wall (pointed by an arrow in Figure 9) was used to judge the yield state (1δy) referring to the yield displacement (2,140μ) given by the material test, and then load was given up to 2δy, 3δy, and 4δy. Loading at each step was repeated for three times7).

Table 4. Cases of Cyclic loading test

Cases	Reinforcement arrangement patterns	Loading method
Case1	Combination case of crossed reinforcement and tie-hoops	Cyclic loading
Case2	Tie-hoops only	Cyclic loading

Table 5. Specifications of Specimens

Design strength of concrete	42 N/mm^2
Steel fiber mix rate	0.6 %
Yield stress of reinforcement bar	345 N/mm^2
Outward main bars	D22 (7/0.85m)
Inward main bars	D22 (7/0.85m)
Tie-hoops	D16 (4/0.85m)

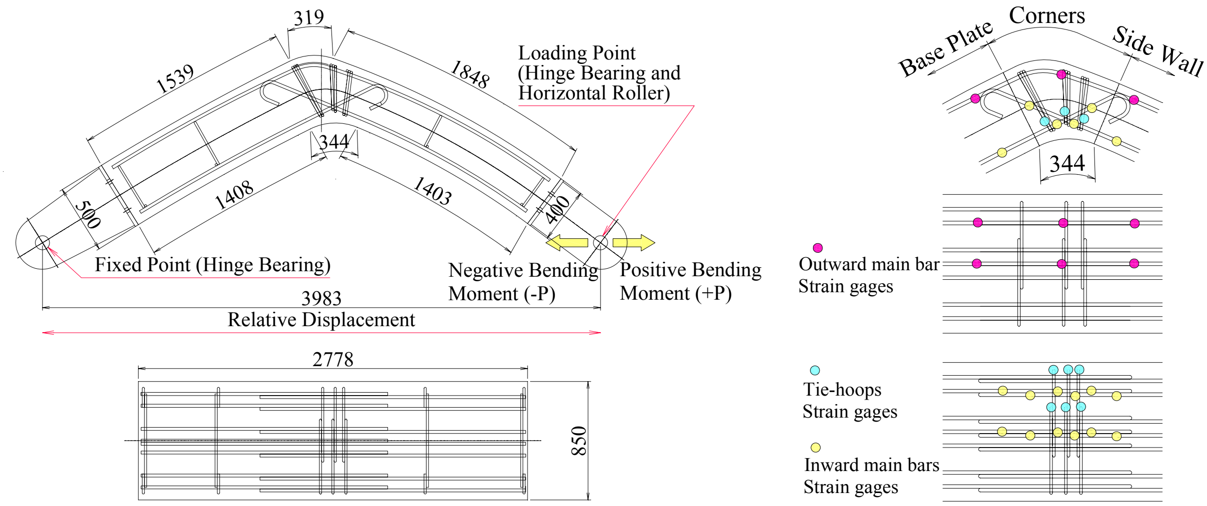


Figure 9. Outlines of the Specimen (Case1)

4.2. Result

P-δ relation gained by the test is shown in Figure 10. Experimental yield displacement and yield load are shown in Table 6. Results of previous estimate by FEM analysis from chapter3 (positive bending load) are also overlaid in Figure 10 to check accuracy of the estimate. The FEM analysis is not exactly a simulation of the test because it takes material strength from design specification, not from the result of material test. Compared to results of FEM analysis, experimental yield load was approximately 10 to 20% smaller but matching with it qualitatively. Because actual material strength is generally higher than design specification, if actual material strength is used in the FEM analysis, the difference will be larger. It is necessary to improve accuracy of the analysis by reviewing non-linear component model of the concrete for example tension softening property of SFRC.

Picture 1 and Picture 2 show crack states of Case1 and Case2 at 2δy. In Case1, cracks to the sectional direction at the wall side of the specimen were observed but none to the axial direction. In Case2, there were cracks to the axial direction at the wall side which were supposed to be initiated by the influence of abdominal pressure. These crack states were also recognized by the previous estimate by FEM analysis and they show that three tie-hoops reinforcement doesn't have enough strength against abdominal pressure. It was also confirmed that Case1 model which is reinforced by crossed reinforcements and tie-hoops can secure healthiness of the corner by the fact that destruction by bending tensile occurred at the wall side where the segment is thinner than slab side.

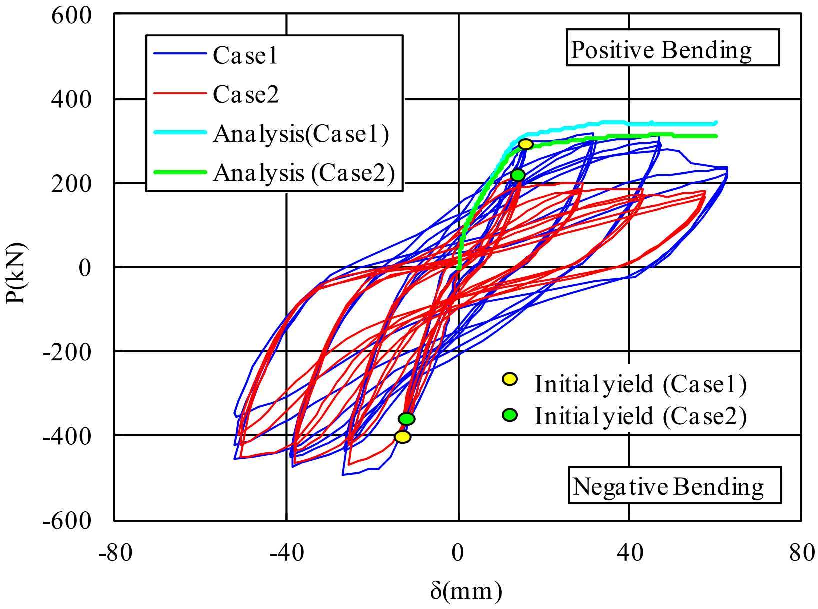
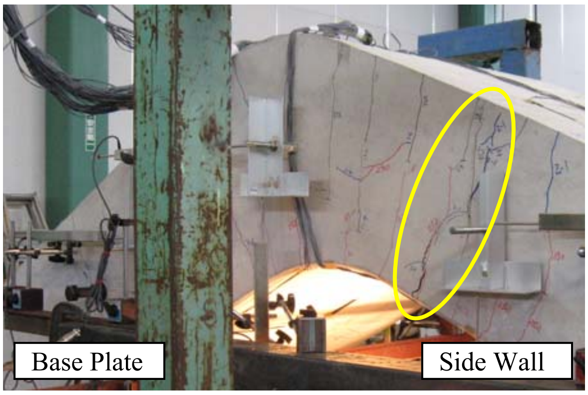


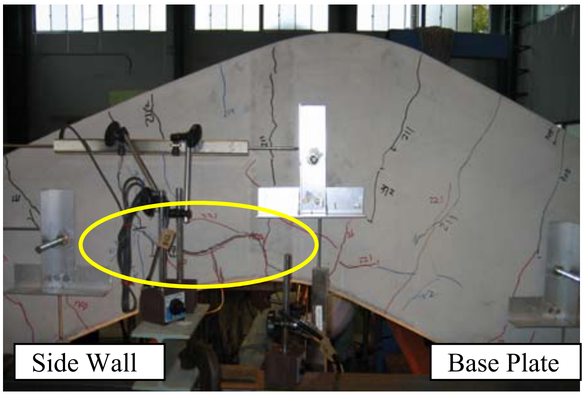
Figure 10. P-δ Relation gained by the test

Table 5. Specifications of Specimens

Cases	Load	Yield Load P (kN)	Yield Displacement δ(mm)
Case1	Positive Bending	290	15.1
	Negative Bending	401	12.9
Case2	Positive Bending	219	14.4
	Negative Bending	380	12.7



Picture 1. Crack states of Case1 (2δy)



Picture 2. Crack states of Case1 (2δy)

5. CONCLUSION

Reinforcement arrangement at the corner of a composite arched shielded tunnel under abdominal pressure was studied for crossed reinforcements and tie-hoops combination case and tie-hoops only case. Results of the numerical simulation for monotonic loading by FEM analysis and cyclic loading test on actual sized segment specimens were as follows;

(1) Combination case of crossed reinforcements and tie-hoops surpassed tie-hoops only case in both load resistance performance and toughness.
(2) In the combination case, no damage on segment corner such as crack by abdominal pressure or yield of main reinforcement bar were observed at the displacement 4δy. Structure reached tensile fractured by bending at the wall side.
(3) In the tie-hoops only case, structure failed to control cracks to the axial direction by abdominal pressure.
(4) Previous estimate of monotonic loading by FEM and result of loading test were qualitatively consistent although experimental yield load was smaller than analytical one.
(5) Causes of yield load difference in FEM analysis and loading test were considered being effect of cyclic loading, inconformity of input invariables in analysis and actual strength, and inconformity of SFRC's tension softening property used in analysis and of the specimen. Further investigation of the causes and understanding of mechanical characteristics by element test are expected in the future.

Development of reinforcement arrangement for highly productive and cost competitive design will continue focusing retaining required performance without crossed reinforcement with increased numbers of tie-hoop, or with crossed reinforcement and less tie-hoop.

REFERENCES

Metropolitan Expressway Company Ltd. (2008). Design Guidelines for Tunnels (Cut and Cover Tunnel). (in Japanese)

The Japan Road Association (2002). The Specifications for Highway Bridges and Commentary, Part3 Concrete Bridges. (in Japanese)

The Japan Road Association (2002). The Specifications for Highway Bridges and Commentary, Part5 Seismic Design. (in Japanese)

Japan Society of Civil Engineering (1999). Concrete Library 97, 8-17. (in Japanese)

Naganuma, K. (1995). Stress-strain relationship for concrete under triaxial compression. *Transactions of AIJ. Journal of structural and construction engineering*, No.474, 163-170. (in Japanese)

Earthquake Engineering Research Team, Earthquake Disaster Prevention Group, Public Works Research Insthitute (2006). Draft Guidelines for Experimental Verification of Seismic Performance of Bridges (Quasi-Static Cyclic Loading Tests and Shake Table Tests for Bridge Columns).