EXPERIMENTAL RESEARCH ON THE EFFECT OF INNER REINFORCEMENT ON DAMAGED TUNNEL LININGS

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INTRODUCTION

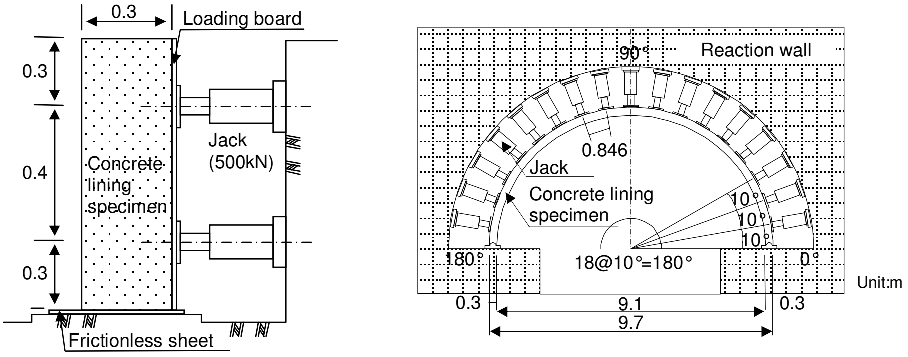
In Japan, there are some existing road tunnels in service that have suffered serious damage such as compression or shear failure on their concrete lining by the action of excessive earth pressure. In these damaged tunnels, the load bearing capacity of the concrete lining has deteriorated and it becomes a crucial problem to rehabilitate these damaged tunnels to secure safety of tunnel users. Therefore development of the method to restore the load bearing capacity of damaged tunnel concrete lining has been growing in demand and inner reinforcement such as installation of thin steel plate, steel arch support onto the damaged concrete lining is expected as one of the effective method. However, the mechanism of the effect of these inner reinforcements onto the damaged lining has not been clarified yet and establishment of the design method of inner reinforcement is necessary to apply this method widely to the damaged tunnel.

In this paper, model experiment using full-scale tunnel concrete lining specimen was carried out to clarify the mechanism of the collapse of tunnel concrete lining by the action of excessive load on crown. Furthermore, model experiments using full-scale damaged tunnel concrete lining specimens with inner reinforcement such as thin steel plate and steel arch support were carried out to clarify the effect of these reinforcements on the load bearing capacity of the damaged concrete lining. Finally, the mechanism of the effect of the inner reinforcement on the recovery of the load bearing capacity of the damaged concrete lining is discussed.

FULL- SCALE MODEL EXPERIMENTS

Test facility

Figure 1 presents a schematic of the test facility for a full-scale tunnel concrete lining. The facility consists of reaction wall and several oil pressure jacks that can act on the specimen in the radius direction (Mashimo et al. 2004). Two jacks per one section were placed in 17 sections every 10 degrees and they were placed at each 0.3m and 0.7m height from the bottom of the specimen. Loading boards were inserted between the two jacks and the specimen to make the load act on the specimen uniformly. The concrete lining specimen which had a half-round shape with an outside diameter of 9.7m, a thickness of 0.3m and a depth of 1m was prepared. During tests, strains generated at both outer and inner surfaces of the concrete lining, strains at surface of inner reinforcement and radial deformations of the concrete lining were measured in almost every load step.



(a)Sectional view (b)Plane view

Figure 1 - Schematic diagram of test facility

Experimental conditions

To clarify the mechanism of the collapse of tunnel concrete lining and the effect of inner reinforcement on the load bearing capacity of damaged concrete lining, the experiments were performed in two stages. In the first stage, for the purpose of producing a damaged concrete lining specimen, a loading for an undamaged concrete lining specimen, which was called the first loading, was conducted until the collapse of the specimen occurred and the load showed the maximum value. In the next stage, the loads on the specimen were removed once and inner reinforcement was installed onto the inside of the damaged specimen. And then, a reloading for the damaged concrete lining with inner reinforcement, which was called the second loading, was conducted again. For comparison purposes, the second loading for the damaged concrete lining specimen without inner reinforcement was also conducted. The first loading and second loading condition adopted in the experiments were the same as shown in Figure 2. The loading was done in all of 17 sections up to 20kN/jack, and then the loading was continued in 3 sections at 80-100° in the coordinates that regulated anticlockwise starting from the right bottom of the specimen. The hydraulic valves of the rest of oil pressure jacks were closed to induce reaction force against the deformation of the specimen, which simulates subgrade reaction around a tunnel. In this loading condition, the influence of axial force is dominant comparing with that of bending moment and this loading condition is assumed as the typical case in which load due to loosened rock acts on tunnel crown and the lining is supported by ground.

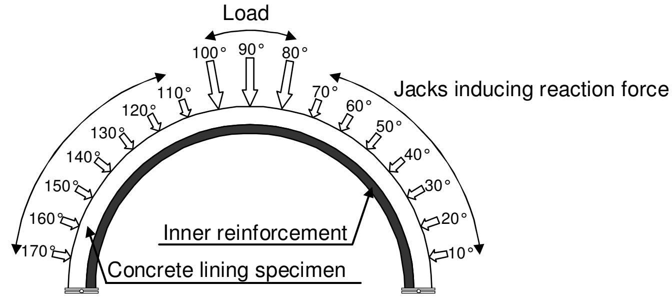
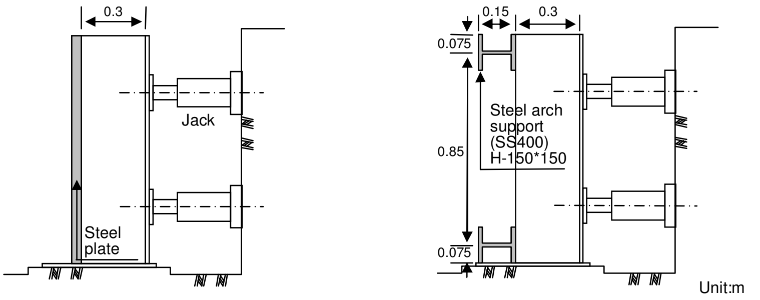


Figure 2 - Loading condition

The experiments were carried out on the following three types of inner reinforcement as shown in Figure 3: no reinforcement (Case-1), thin steel plate with a thickness of 4.5mm (Case-2), and steel arch support. Plain concrete was adopted as the material of concrete lining in each case. The compressive strength and elastic modulus of the plain concrete are 18-22N/mm^2 and 17-20kN/mm^2, respectively, according to compression test using cylinder specimen. H-beams with a height of

150mm and a width of 150mm were adopted in Case-3. The tensile strength and elastic modulus of the steel plate and the steel arch support are 410N/mm^2 and 210kN/mm^2, respectively.



(a) Steel plate (Case-2) (b)Steel arch support (Case-3)

Figure 3- Types of inner reinforcement

EXPERIMENTAL RESULTS AND DISCUSSION

Mechanism of the collapse of concrete lining

Figure 4 shows the load-displacement curve at the tunnel crown in Case-1 (no reinforcement). The load in the vertical axis of the figure represents the average value of the loads of the jacks in 3 sections at the part of the tunnel crown. The load value of 10kN/jack is the equivalent of the overburden load with a height of about 1m assuming the load acts on the part of 75-105 ° around the crown uniformly. Regarding the first loading for the undamaged concrete lining, the load bearing capacity of the concrete lining, which is defined as the maximum load of the load-displacement curve, shows 341kN/jack. In this case, the spalling of the concrete fragments due to the compressive failure around the outside of the crown was observed before the load reached the maximum load and the spalling of the concrete fragments around the inside of the shoulders was observed at the same instant when the load reached the maximum load. Regarding the second loading for the damaged concrete lining, the load bearing capacity reaches 261 kN/jack, which accounts for about 75% of that of the undamaged concrete lining. Also the gradient of the load-displacement is about 0.9 times that of the undamaged concrete lining. The spalling of the concrete fragments around the inside of the left shoulder was observed again when the load reached the maximum load.

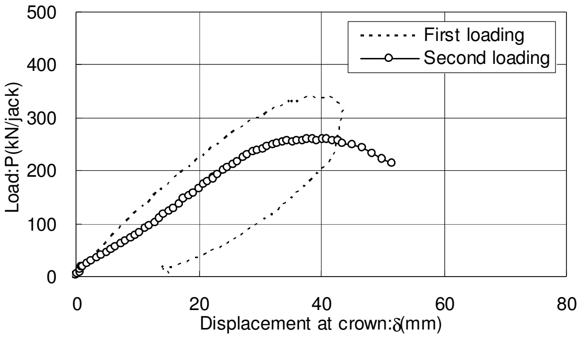
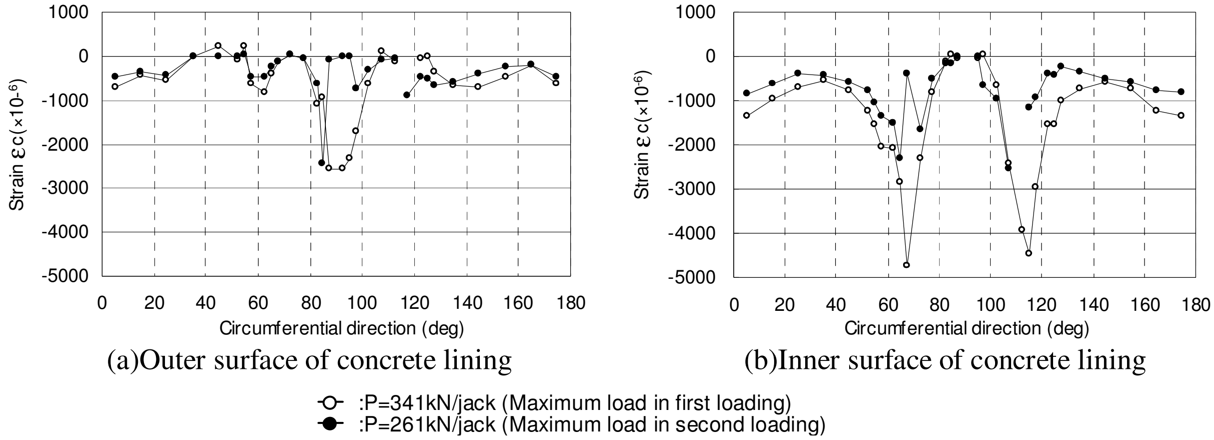


Figure 4- Load-displacement curve (no reinforcement)

Figure 5 shows the circumferential strain distribution of the concrete lining generated in the first and second loading in Case-1 when the load reaches the maximum load. The minus sign of the strain means compressive strain and the circumferential direction in the horizontal axis of the figure represents the angle from the right bottom of the specimen. The strains include only the strains generated in the second loading and the residual strains generated in the first loading are ignored. It can be seen that the strain at the outside of the crown reaches about -2,600 μ and the strains at the inside of both shoulders reach over -4,000 μ, which exceeds the ultimate compressive strain of -3,500μ in the first loading. On the other hand, the strains at the inside of the shoulders and the outside of the crown remain at about -2,500 μ, which is far smaller than that in the case of first loading, even if the load reaches the maximum load. From these results and the state of the failure of the concrete lining as mentioned above, we can conclude that the load bearing capacity of the concrete lining is governed by the sectional failure due to the compressive failure at two more sections, in particular, the development of the compressive failure zone at the shoulders.



(a)Outer surface of concrete lining

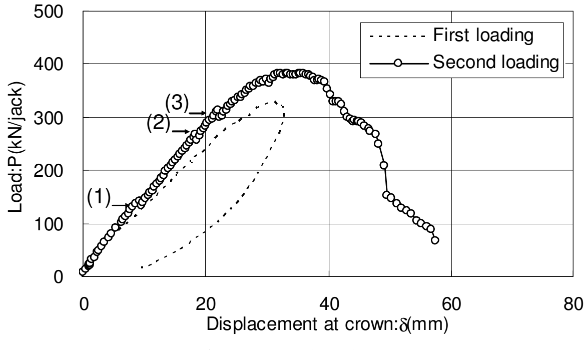
(b)Inner surface of concrete lining

Figure 5- Strain distribution (no reinforcement)

Mechanical behavior of concrete lining with inner reinforcement

(1) Steel plate

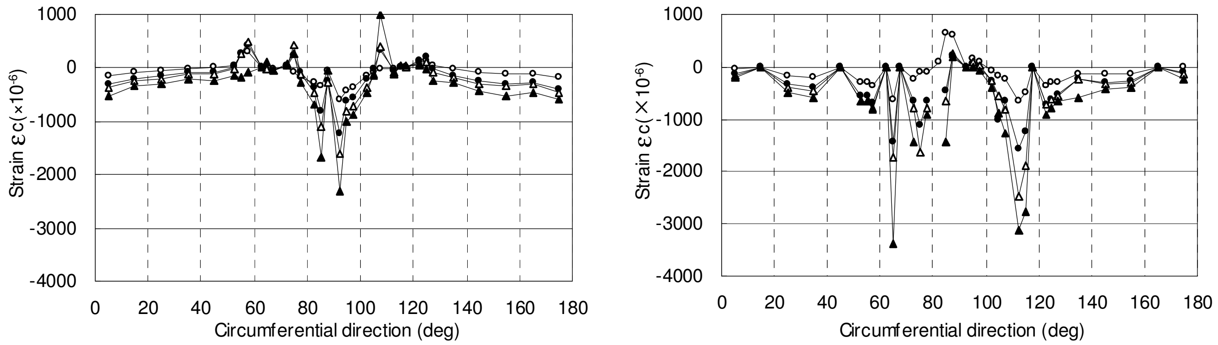
Figure 6 shows the load-displacement curve at the tunnel crown in Case-2 (thin steel plate reinforcement). The load bearing capacity of the damaged concrete lining with reinforcement reaches 382kN/jack, which accounts for about 120% of the load bearing capacity of the undamaged concrete lining of 328kN/jack. The gradient of the load-displacement curve of the damaged concrete lining with reinforcement is about 1.1 times that of the undamaged concrete lining. Therefore, thin steel plate reinforcement will have the effect of restoring the load bearing capacity and stiffness of the damaged concrete lining up to the values greater than those of the undamaged concrete lining. In this case, flaking of the steel plate from the concrete lining was observed around the whole crown at a load of 137 kN/jack, and local flaking around the left shoulder at 115 ° and the right shoulder at 65 ° were observed at a load of 267 kN/jack and 309 kN/jack, respectively. The local flaking of the steel plate around the both shoulders spread with increasing load, and in the moment when the flaking of the steel plate on the both shoulders spread across the whole areas of shoulders, the load reached the maximum load.



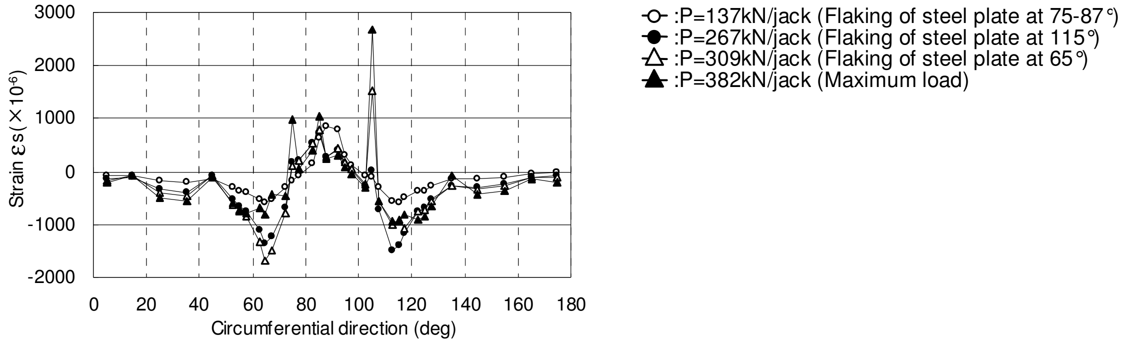
(1):Flaking of steel plate at 75-87°
(2):Flaking of steel plate at 115°
(3):Flaking of steel plate at 65°

Figure 6- Load-displacement curve (steel plate)

Figure 7 shows the circumferential strain distribution of the damaged concrete lining and the steel plate generated in the second loading in Case-2. It can be seen that the strains of the concrete lining at the inside of the shoulders reach up to -3,400μ , which are far greater than those of the case without reinforcement, when the load reaches the maximum load. On the other hand, no apparent increase of the strain of the concrete lining around the outside of the crown can be observed in comparison with the case without reinforcement. Regarding the strains generated in the steel plate, both the tensile strain around the crown and the compressive strain around the shoulders decreased drastically when the flaking of the steel plate was observed around these parts, and then maintained constant values until the load reached the maximum load. From these results, we can conclude that thin steel plate bonded to the damaged concrete lining at the shoulders, where the concrete lining was damaged by excessive compressive stress, will have the effect of improving the resistance of the damaged concrete lining to the axial force by restraining the inward deformation of the shoulders. This effect works for a while even after the local flaking of the steel plate from the damaged concrete lining has occurred at the shoulder and wears off as the flaking of the steel plate spreads across the whole areas of shoulders. In other words, the cohesion between the damaged concrete lining and the steel plate is crucial to have the effect of restoring the load bearing capacity of the damaged concrete lining.



(a)Outer surface of concrete lining (b)Inner surface of concrete lining

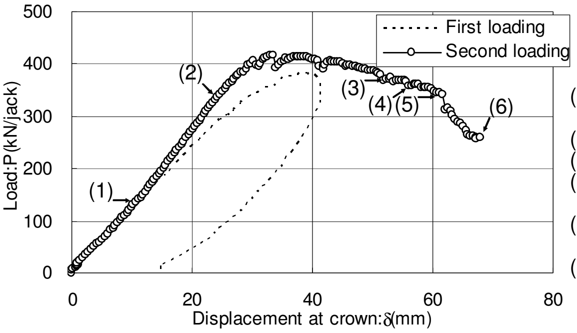


(c)Inner surface of steel plate

Figure 7- Strain distribution in the second loading (steel plate)

(2) Steel arch support

Figure 8 shows the load-displacement curve at the tunnel crown in Case-3 (steel arch support reinforcement). The load bearing capacity of the damaged concrete lining with reinforcement reaches 416kN/jack, which accounts for about 110% of the load bearing capacity of the undamaged concrete lining of 382kN/jack. The gradient of the load-displacement curve of the damaged concrete lining with reinforcement is about 1.2 times that of the undamaged concrete lining. Therefore, steel arch support reinforcement will have the effect of restoring the load bearing capacity and stiffness of the damaged concrete lining up to the values slightly greater than those of the undamaged concrete lining. In addition, the extent of decrease of the load after the maximum load is considerably small and we can therefore conclude that the steel arch support excels in ductility for the collapse after the maximum load. In this case, the spalling of the concrete lining was not observed even if the load reached the maximum load, though the cracks at the outside of the crown and the inside of the shoulders generated in the first loading developed. After the maximum load, the compressive failure of the concrete lining around the outside of the crown at 90-95 ° and the inside of the shoulders at 65 ° and 110-115° gradually developed and the load decreased rapidly with the spalling of concrete lining. Regarding the steel arch support, no apparent failure of the steel arch support was observed until the load reached the maximum load, though the separation between the steel arch support and the concrete lining at 50-115 ° occurred at a load of 142kN/jack. After the maximum load, the local buckling of the upper steel arch support at 115° was observed at a load of 382 kN/jack.

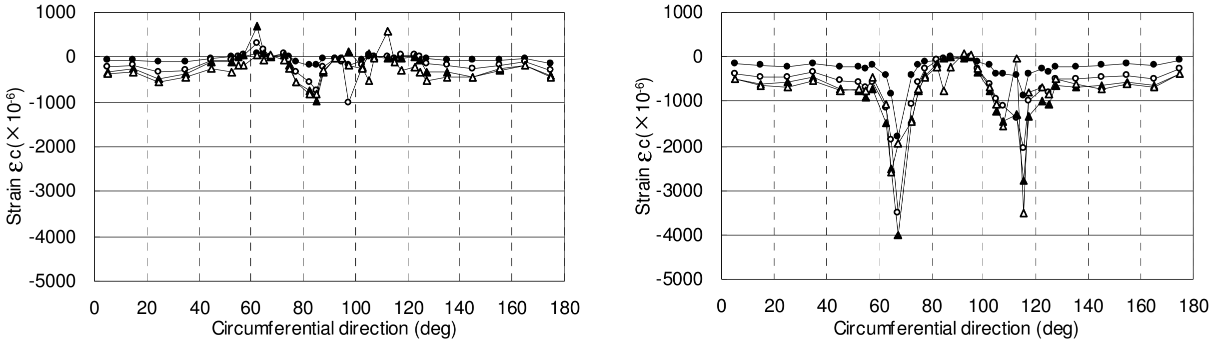


(1):Separation between steel arch support and concrete lining at 50-115°
(2):Strain 1,200μ of steel arch support at outside crown
(3):Buckling of steel arch support at 115°
(4):Spalling of concrete fragment around outside crown at 90-95°
(5):Development of compressive failure of concrete lining around inside shoulder at 65°
(6):Spalling of concrete fragment around inside shoulder at 110-115°

Figure 8- Load-displacement curve (steel arch support)

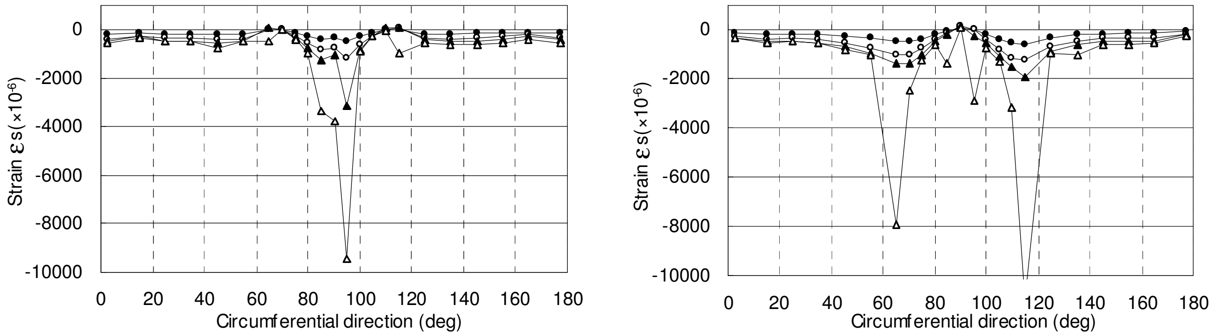
Figure 9 shows the circumferential strain distribution of the damaged concrete lining and the upper steel arch support generated in the second loading in Case-3. The strains of the steel arch support were measured at the surface of the web of H-beams. It can be seen that the strain of the damaged concrete lining at the inside of the right shoulder reaches up to -4,000μ when the load reaches the maximum load, while the strain at the inside of the left shoulders increases slightly for a while after the maximum load. On the other hand, the strains of the steel arch support reaches

-3,100 μ and -1,400 to -1,900 μ around the outside of the crown and the inside of the shoulders, respectively, when the load reached the maximum load and these strains increases until the experiment is over. The yield strain of steel arch support is estimated about 1,200 μ, therefore, it is assumed that the steel arch support reaches yield region at the maximum load. However, according to the previous experience obtained at some tunnel construction sites, it is known that steel arch support can keep its structural stability for a while even after the strain of a portion of steel arch support exceeds yield strain. From these results, we can conclude that damaged concrete lining can resist a great deal of axial force at the maximum load, along with the steel arch support that will have the effect of improving the resistance of the damaged concrete lining to the axial force by restraining the inward deformation of the shoulders. After the maximum load, the main member supporting the load acting on the concrete lining with the steel arch support transfers from the damaged concrete lining to the steel arch support with the development of the compressive failure of the concrete lining, and the local buckling of the steel arch support due to the excessive compressive stress leads to the further decrease of the load. This means that the strength of the damaged concrete lining itself in addition to the strength of the steel arch support is crucial to have the effect of restoring the load bearing capacity of the damaged concrete lining.



(a)Outer surface of concrete lining

(b)Inner surface of concrete lining



(c)Outer surface of steel arch support

(d)Inner surface of steel arch support

-●-:P=142kN/jack (Separation between steel arch support and concrete lining at 50~115°)
-○-:P=337kN/jack (Strain 1,200μ of steel arch support at outside crown)
-▲-:P=416kN/jack (Maximum load)
-△-:P=382kN/jack (Buckling of steel arch support at 115°)

Figure 9- Strain distribution in the second loading (steel arch support)

CONCLUSION

A series of full-scale model experiments were carried out to clarify the mechanism of the collapse of tunnel concrete lining and the effect of inner reinforcement on damaged concrete lining under the load condition that the influence of axial force is dominant comparing with that of bending moment. The main conclusions obtained from the study are as follows.

1) The load bearing capacity of concrete lining is governed by the sectional failure due to the compression at crown and shoulders.

2) Both thin steel plate and steel arch support have the effect of restoring the load bearing capacity of the damaged concrete lining where the compressive failure has occurred.

3) The restraint of the deformation at the shoulder by installing steel arch support or thin steel plate on the damaged concrete lining plays an important role to restore the load bearing capacity of the damaged concrete lining.

4) The cohesion between the concrete lining and the inner reinforcement material is crucial to have the effect of restoring the load bearing capacity of the damaged concrete lining in the case of steel plate reinforcement. On the other hand, the strength of the damaged concrete itself in addition to the strength of the reinforcement material is crucial in the case of steel arch support reinforcement.

REFERENCE

Mashimo,H., Hakoishi,Y. and Ishimura,T.(2004), "Experimental investigation of the effect of reinforcement of internal structure on loadbearing capacity of damaged tunnel linings", *Proceedings of EUROCK 2004&53rd Geomechanics Colloquy*, pp.327-332