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SPALLING OF RAILWAY TUNNEL CONCRETE AND ITS CAUSES

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ABSTRACT

A number of accidents of concrete block spalling from tunnel linings occurred recently in Japan. Although there were no personal injuries, trust of people in the safety and durability of tunnel was lost, because some accidents took place in Shinkansen (high speed railroad) tunnels. Investigations, model tests and numerical analyses were performed on the largest three accidents in particular to study the mechanisms and causes of spalling of concrete. This paper outlines the accident at the Fukuoka Tunnel out of these accidents and reports the causes of spalling through investigations, model tests and numerical analyses.

KEYWORDS

Tunnel, Concrete, Spalling, Model test, Measurement, Fatigue, Failure

1. INTRODUCTION

It is said that tunnels have longer lives than structures constructed on the ground because they are constructed underground in the stable environment. There are over 4,700 railway tunnels in service In Japan with a total length of about 3,000km. (Figure 1) Half of these tunnels were constructed before World War II. While the tunnel linings are normally made of plain concrete in which cracks easily occur, they remain stable even with a number of cracks because they are arch-shaped and surrounded by the ground.

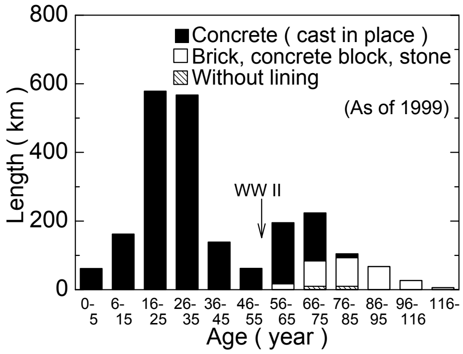


Figure 1: Length of railway tunnels by age and material

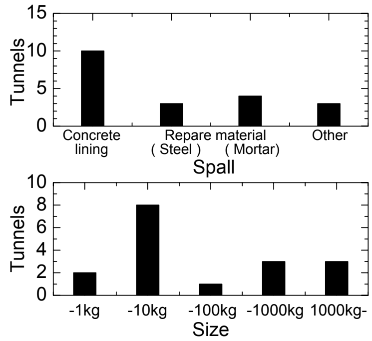


Figure 2: Accidents of tunnel concrete spalling

This is a fact that has already been proved by experience, model tests and numerical analyses. However, a number of accidents of concrete block spalling from tunnel linings occurred recently in Japan. Figure 2 summarizes the accidents of tunnel occurred from January 1998 to January 2000. Among these accidents, there was a case where about two tons of concrete block fell from a concrete lining. Although there were no personal injuries, trust of people in the safety and durability of tunnel was lost, because some accidents took place in Shinkansen (high speed railroad) tunnels. For this reason, the Ministry of Transport held a study meeting to discuss the causes of spalling and how to maintain tunnels from now on. Investigations, model tests and numerical analyses were performed on the largest three accidents in particular to study the mechanisms and causes of spalling of concrete. [1,2,3] They were the accidents occurred at the Fukuoka Tunnel and the Kita - Kyushu Tunnel on a Shinkansen line and the Rebunhama Tunnel on the Muroran Main Line. This paper outlines the accident at the Fukuoka Tunnel out of these three accidents and reports the causes of spalling through investigations, model tests and numerical analyses.

2. ACCIDENT AT THE FUKUOKA TUNNEL

2.1 *Outline*

On June 27, 1999, a block of concrete fell from the arch of the tunnel lining at the Fukuoka tunnel, and hit the roof of a Shinkansen train which was passing by. (Photo 1, Figure 3) This tunnel was constructed in 1975 to a length of 8,488 m, with the lining made of cast-in-place plain concrete. The geology of the ground around the tunnel at the accident point is greenschist and the earth covering is about 100m.

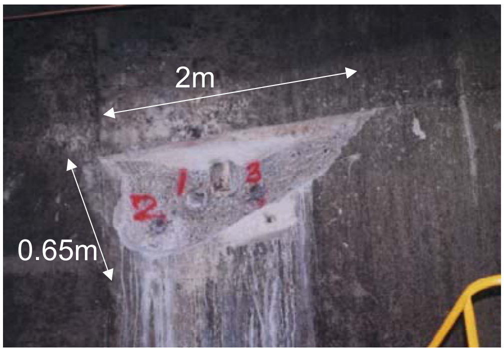


Photo 1: Lining from which a block of concrete fell

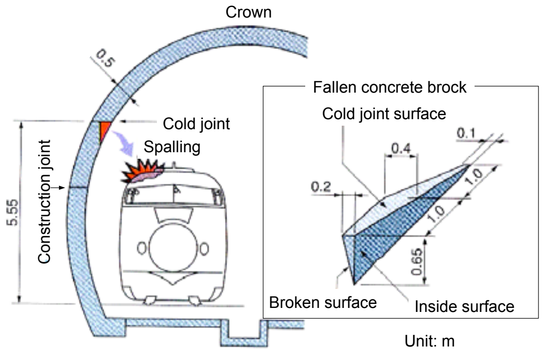


Figure 3: Outline of spalling (illustration)

2.2 *Supposed causes of spalling*

There was a cold joint (discontinuity resulting from a delay in concrete placement to preclude union of the material in two successive lifts) right above the separation area. Because the upper side of the block was the cold joint surface and separated, the lining below the cold joint had been easy to fall. Therefore, the cold joint was obviously one of the main causes of spalling. The maximum depth of carbonation at the broken surface was 5mm. It was found that this crack had occurred behind the surface years before. It was also found that the ground around the tunnel was not such a geology that would cause earth pressure or water pressure. There was no construction work near the tunnel. It was found that concrete of the lining had sufficient strength. (compression strength: about 27.5 MPa) There was a very small quantity of typical gel of the alkali-aggregate reaction on the surface of coarse aggregates, but from the results of accelerated tests of the alkali-aggregate reaction, we found that the ratio of volume swell of specimen from the lining of the Fukuoka tunnel was about 0.005% and it was not so much as it was able to cause a problem usually. Therefore we concluded that the alkali-aggregate reaction was not the cause of spalling. Furthermore, the lining of this tunnel was made of plain concrete, and cast-in chlorides had nothing to do with spalling. After the above mentioned consideration, the following factors in addition to the cold joint were picked out as suspected causes of spalling.

1) Vibration by trains
2) Change of air pressure by trains
3) Decrease of concrete strength due to fatigue
4) Decrease of concrete strength due to change of temperature, water leakage and repetition of wet and dry conditions, etc.
5) Improper construction of tunnel lining which might cause initial discontinuity inside the lining

We were not able to choose only one factor among these factors as the cause of spalling because they influenced each other. In regard to the factor in 4), long-term research is necessary to study a chemical change of concrete. In regard to the factor in 5), there is a problem that the Fukuoka Tunnel was constructed about 30 years ago and lacks the information on its construction work. Because of these reasons, we focus on the factors in 1), 2) and 3) among these suspected factors and discuss the causes of spalling.

3. VIBRATIONS AND CHANGE OF AIR PRESSURE OF THE TUNNEL

As there were few detailed reports on vibration and strain of the lining and change of air pressure in the tunnel caused by trains, at first, we measured them at the accident point. Figure 4 shows the results of the measurement. The results can be summarized as follows.

1. Vibration velocity: Max. 0.3 cm/s (z: vertical direction)
   Max. 0.1 cm/s (x: radius direction)
2. Change of air pressure: Max. - 5 kPa (at the passage of train tail)
3. Tensile strain: Max. $10*10^{-6}$ (z: vertical direction)

It is generally said that the vibration velocity and tensile strain that cause cracks in linings is 20 - 30 cm/s and $200*10^{-6}$, respectively. [4] Then, from these results, we were able to confirm that the vibration and change of air pressure by trains were not the primary causes of spalling of the lining without cracks. On the other hand, we were not able to clarify the relation between the growth of cracks and repeated load caused by vibration or change of air pressure caused by trains. Therefore, we performed bend fatigue tests of plain concrete beams.

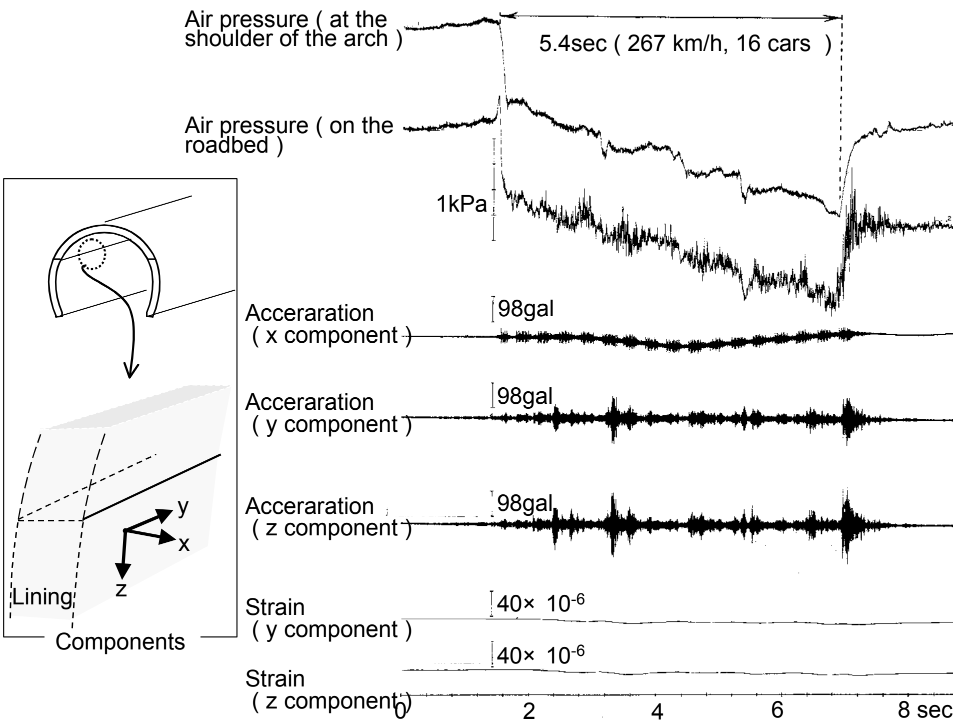


Figure 4: Results of the measurement

4. BEND FATIGUE TEST OF CONCRTE

4.1 *Testing procedure*

Based on the results of measurement shown in Chapter 3, a negative air pressure of 5kPa was repeatedly caused on linings by trains. Therefore, we performed bend fatigue tests of plain concrete to study the effect of repeated load on linings. We performed static bend tests and bend fatigue tests. Photo 2 shows the experimental equipment, and Figure 5 the dimension of specimens. The specimen was a concrete beam made of plain concrete with a width of 200mm, height of 200mm and length of 700mm. The compressive strength of concrete was about 18 N/mm^2. On some specimens, we made a notch with a width of 0.2mm on their bottom side to study the effect of the presence and depth of initial cracks. The depth of the notch was 10 mm or 50 mm. In the tests, we measured the load and displacement at the loading point and strain at the bottom and side surface of the specimen. At first, we performed static bend tests to grasp the behavior of plain concrete at failure, and decide the input condition of loads for bend fatigue tests. TABLE 1 shows the test cases.

Photo 2: Experimental equipment

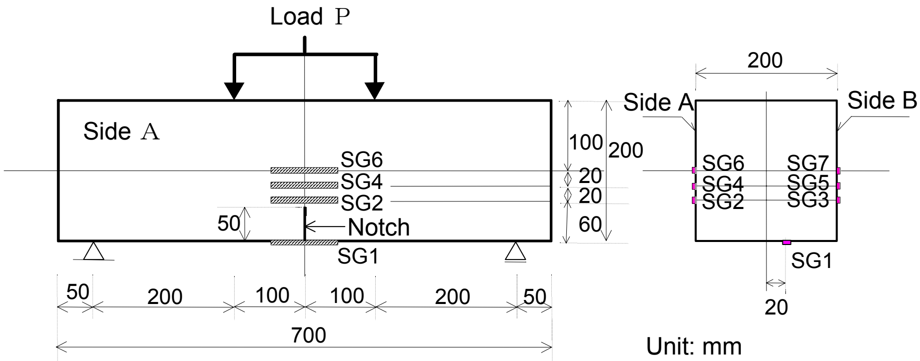


Figure 5: Dimension of specimens

TABLE 1: Test cases

Case No.		Notch	Method of loading
Static bend test	1	None	Monotonic
	2	Depth: 10 mm	
	3	Depth: 50 mm	
Bend fatigue test	4	None	Cyclic
	5	Depth: 10 mm	
	6	Depth: 50 mm	

4.2 ***Results of static bend tests***

Figure 6 shows the results of static bend tests, and Photo 3 a specimen after failure. The results of static bend tests can be summarized as follows.

1) A crack occurred at the maximum load on the constant bending section, and grew immediately to lead a beam failure.
2) The bending strength is the largest at the model without notch and becomes smaller with the depth of the notch.
3) The deflection at the failure is the smallest at the model without notch and becomes larger with the depth of the notch

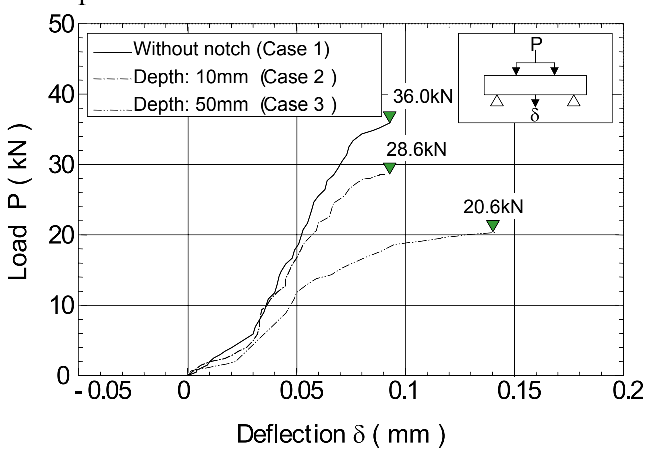


Figure 6: Relation between load and deflection

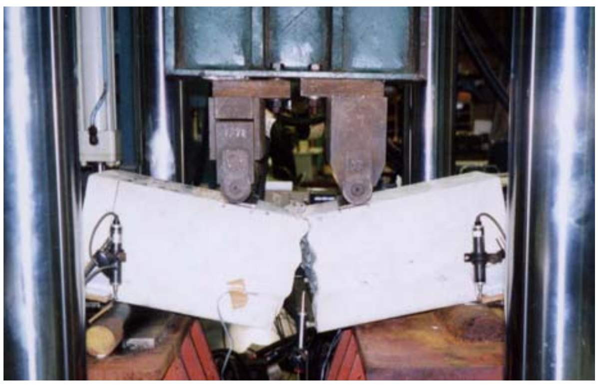


Photo 3: Specimen after failure (static bend test)

4.3 ***Results of bend fatigue tests***

Then, we performed bend fatigue tests by applying a repeated load. Figure 7 shows the input condition of the load. The load was input as a sine wave. The upper limit of the load was varied between 50% and

90% of the maximum load of the static bend test, and the lower limit was fixed at 3.2kN because of the restriction of the test unit. Figure 8(a)-(c) show the relation between the strain at the beam surface and the number of load cycles obtained from the tests. Figure 8(a)-(c) indicate that the strain increases with the number of load cycles at every strain gauge. Figure 9 shows the relation between the normalized strain and the number of load cycles, where the strain is normalized by that when the number of load cycles is 80. We can realize that the strain near the bottom surface of the beam increased first and then that near the upper surface. From this Figure, we can also realize that the crack grows upward with the repeated load. We performed a number of bend fatigue tests by changing the depth of the notch and the upper limit of the load. Figure 10 shows the relation between the upper limit load at the failure and the number of load cycles to cause failure. From this Figure we can conclude that the load is larger and the initial cracks is deeper, in other words, the stress at the edge of the notch is larger, a small number of load cycles is enough to break the beam. Therefore, we can confirm that plain concrete is influenced by fatigue.

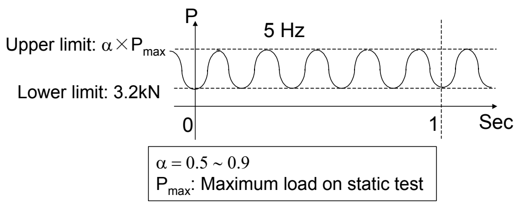


Figure 7: Input condition of load

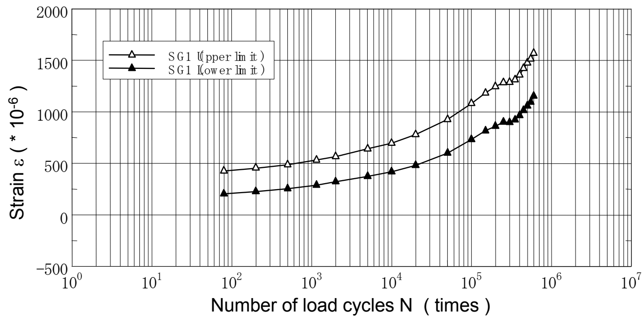


Figure 8(a): Relation between the strain at the beam surface and the number of load cycles

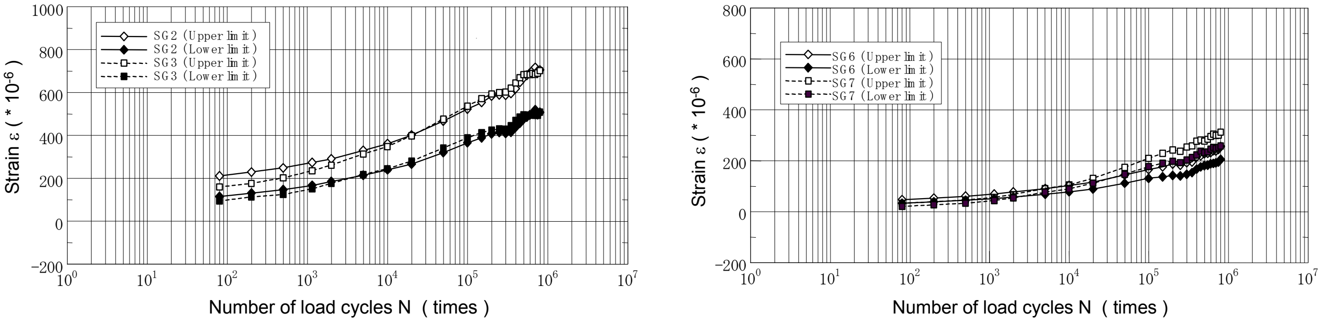


Figure 8(b), (c): Relation between the strain at the beam surface and the number of load cycles

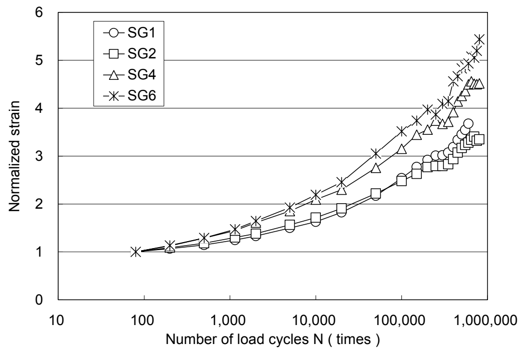


Figure 9: Relation between normalized strain and the number of load cycles

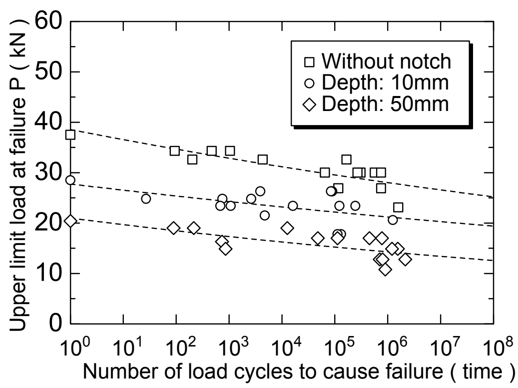


Figure 10: Relation between upper limit load at failure and the number of load cycles to cause failure

4.4 ***Comparison of stress state between a real tunnel and the model***

We calculated the estimated stress at the edge of the initial crack at the separation area of the Fukuoka Tunnel by FEM analysis and compared it with the stress at the bend fatigue test. It was supposed that there had already been considerable deep cracks in the tunnel at the separation area of the Fukuoka Tunnel, but we were not able to know the exact depth of the cracks. So, we assumed that the depth of the crack had been 700mm from the surface of the lining as shown in Figure 11. The shape of the real lining was three-dimensional, but we modeled it by a two-dimensional model for simplification. The cracks were modeled by duplicated nodes and we applied the negative air pressure (- 5 kPa) by trains on the surface of the lining. From the analysis, we found that the stress at the edge of the crack was about 1.2 N/mm^2. Figure 12 shows the relation between the stress at the edge of the notch and the number of the load cycles to cause failure, where we calculated the stress at the edge of the notch by Equation 1. The stress at the edge of the crack of the real tunnel acquired from the FEM analysis was visualized by a spotted line. Shinkansen trains pass the Fukuoka Tunnel about 40,000 times per year and total passage of the trains after opening of the Shinkansen is about a million times. Therefore, we can conclude that the fatigue failure might occur at the assumed crack depth of 700mm and exsistence of the initial crack. (such as the cold joint) We can expect that the possibility of fatigue failure becomes higher with deeper cracks and severer stress concentration.

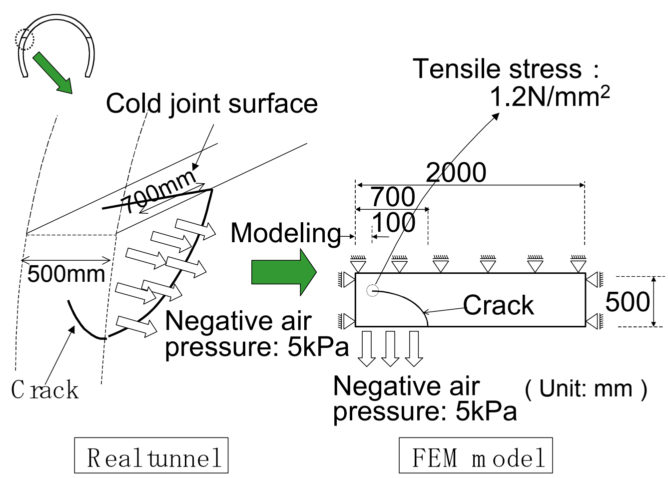
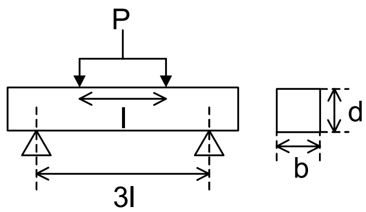


Figure 11: Analysis model of the lining of the separation area of the Fukuoka Tunnel



$$\sigma_e = \frac{M}{Z} = \frac{Pl/2}{bd^2/6} \quad (1)$$

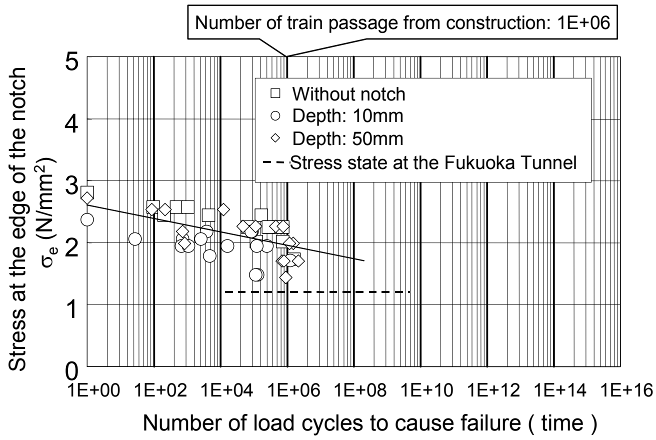


Figure 12: Relation between the stress at the edge of the notch and the number of load cycles to cause failure

5. CONCLUSIONS

We can conclude that plain concrete is influenced by fatigue and its strength decreases with repeated loads from results of bend fatigue tests. We can also conclude that if there are initial deep crack in the lining and the stress is concentrated at the edge of the crack, the fatigue failure or spalling of concrete can occur by the vibration and change of air pressure by trains. We were not able to consider other factors sufficiently such as change of temperature, water leakage, repetition of wet and dry conditions, and cracks due to improper construction works, which affect the durability of the lining. We will study the effect of these factors from now on. At the close of the report, we express special thanks to Mr. Murata and Mr. Kondo (West Japan Railway Co.) and Mr. Sasaki and Mr. Saito, (Railway Technical Research Institute) who gave us quire a lot of advice on this study.

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