In efforts to increase Shinkansen speeds toward a 360 km/h operating speed, we are working to control the increase in risk from earthquakes that comes with speed increase as one of the targets for braking. Specifically, we aimed at keeping emergency braking distance at higher speed to the level of current Shinkansen rolling stock in operation. We thus developed brake gear (center-mounted brake discs, segmented brake lining and pneumatic brake calipers) that meets the requirements of high-speed running and rapid deceleration. Furthermore, we developed equipment for increasing air resistance to supplement adhesion between wheels and rails, as there are limits to adhesion. Performance was checked using FASTECH360 Shinkansen high-speed test trains, and good results from the development were seen.

**Keywords:** Shinkansen speed increase, Braking, Deceleration, Equipment for increasing air resistance, Adhesion

1 Introduction

Speed increase must involve technology that can ensure safe braking of trains. We set controlling the increase in risk from earthquakes as a target for braking technology. As the emergency braking distance of Shinkansen rolling stock in operation is just under 4,000 m (at 275 km/h with series E2 cars), the distance at 360 km/h with the same braking performance would be as long as approx. 7,000 m. In order to control the risk from earthquakes even at higher train velocity, that emergency braking distance of 7,000 m has to be shortened to the current level of 4,000 m. In this development, we set the target emergency braking distance at 4,000 m. Based on this target, we studied and set optimal deceleration taking account of adhesion between the wheel and the rail, developing brake gear that achieves the set deceleration and equipment for increasing air resistance that supplements the shortage of braking force. In bench tests and high-speed test train running tests, those were improved and completed to a level sufficient for use in operation. This article covers the process and results of the development.

2 Setting Deceleration

(1) Deceleration and Adhesion Coefficient

Acceleration and deceleration of rolling stock depends on the friction force between wheels and rails. This friction force is called adhesion force with railways, and the friction coefficient is adhesion coefficient. The adhesion coefficient has been repeatedly measured using actual trains, resulting in an adhesion planning formula. Fig. 1 shows the deceleration curves based on that adhesion planning formula. The figure also shows a curve where the emergency braking deceleration was increased by improving the adhesion coefficient with ceramic particle injection between wheels and rails to achieve the target emergency braking distance. The figure demonstrates that much higher adhesion force than the adhesion shown in the adhesion planning formula is necessary for the required deceleration. We set the deceleration of FASTECH360 on the condition that ceramic particle injection is used. But, as shown in the Fig. 1, such adhesion improvement with ceramic particles does not always secure the required deceleration. In light of those results, we studied installing equipment for increasing air resistance to supplement braking.

![Fig. 1 Adhesion and Required Deceleration](image)

(2) Setting Deceleration

Taking into account the required deceleration and the measurement results of adhesion coefficients explained in the preceding paragraph, we set test emergency deceleration as the test braking as shown in Fig. 2. The deceleration was about double that of normal emergency braking deceleration shown in the figure at 360 km/h.

![Fig. 2 Deceleration Setting](image)
3 Development of Equipment for Increasing Air Resistance

Equipment for increasing air resistance is a device that opens plates on the car roof and consequently increases air resistance. Fig. 3 shows the appearance of that device.

![Equipment for increasing air resistance](image)

The braking force of the plates on the roof can be calculated out in the following formula.

\[ F = \frac{1}{2} C_d \rho V^2 \cdot A \]  

(F: Drag[N], \( C_d \): Air resistance coefficient (Cd value), \( \rho \): Air density [kg/m³], \( V \): Train speed [m/s], \( A \): Area of plate that receives wind pressure [m²])

Resistance is in proportion to the area of the plates and the square of the speed. The formula clarifies that a larger plate area allows larger resistance, but plate area is restricted by dimension limits for moving rolling stock. And, since plates behind those more forward in the direction of travel have less effect due to the turbulent airflow caused by plates in front of them, we studied an effective number of plates. Based on simulation of effective placement of equipment for increasing air resistance, we installed seven units to the FASTECH360S (type E954) high-speed test train. In calculations, we expected that those could shorten braking distance by approx. 500 m at emergency braking at 360 km/h.

Fig. 4 shows the measurement results of deceleration using the equipment for increasing air resistance on FASTECH360. Note that pitching occurs with the car body when operating the equipment, but the maximum wheel load variation was just within ± 3% at passing in a tunnel. Also, yawing occurs when operating only plates on one side of the units on one car, but the lateral force on that car was also small. The effect of the equipment for increasing air resistance was approx. twice the running resistance at 360 km/h, while some difference from the running resistance of FASTECH360 was seen.

![Deceleration Effect on Test Train with Equipment for Increasing Air Resistance](image)

4 Development of Brake Gear

Regenerative brakes operated by motors are mainly used in normal braking, but only friction brakes are used to decelerate in an earthquake due to a loss of power. In this development, we studied brake discs (discs), brake lining (lining) and brake calipers (calipers) that compose the friction brake. And we reached the conclusion that present brake gear shown in Fig.5 would not handle such high-load braking within 4,000 m at 360 km/h. For instance, present discs already had problems such as breakage of disc mounting bolts as well as heat deformation and heat cracking of discs. Lining also had problems such as unusual wear when used in test emergency braking at high speed just once and having low friction coefficient. Calipers too, which were hydraulic types with hydraulic pistons behind the lining, had a problem whereby the pistons would stick due to the heat of the lining. As it was extremely difficult to increase speed without dealing with those problems, we changed the structure and system of the brake equipment and also changed material of friction components.

![Brake Gear of Present Shinkansen Rolling Stock](image)

4.1 Center Mounted Brake Discs

Present discs are ring-shaped and mounted to the wheel with bolts on the inner periphery of the disc. Fig. 6 shows their structure.

![Structure of Present Discs (Inner Periphery-Mounted)](image)
deformation. After repeated braking tests, the outward deformation on the outer periphery (Fig. 7) was 2 mm. While friction resistance against the wheels keeps the discs at their original position, they are displaced if the expansion force of the heat expansion due to heat when braking is larger than the friction force. Repeating this causes shear force on the mounting bolts in the bolt holes because the bolt holes of the wheel and those of the disc are displaced in relation to each other. The larger the braking load, the greater the possibility such action will occur. We therefore concluded that the present structure could not handle such high-load braking.

Based on this conclusion, we set requirements for a disc structure that could handle high-speed braking. Those requirements were “no shear force on mounting bolts” and “accepting heat expansion (heat deformation) of the disc”. Additionally, we emphasized reducing wheel weight since weight reduction was important from the perspective of reducing rolling noise too.

With a disc structure having sliding keys that guide in a radial direction, the disc can be kept centered and accept heat expansion. To supplement heat expansion of the disc, the wheel surface which the disc contacts is coated with lubricant. Mounting bolts are placed at the center of the friction surface, eliminating the area for mounting on the inner periphery. The holes on the wheel in which mounted bolts are fit were made larger to prevent mounting bolts from contacting the wheel even when the disc expands. Cooling fins are added to the rear surface of the disc to improve cooling performance.

This structure with high cooling performance caused strong air flow from the inner periphery to the outer periphery by a ventilating function similar to that of a sirocco fan (dual-intake fan), and that air flow created considerable wind noise. Thus, we added ribs on the inner periphery side of the cooling fin on the rear side of the disc to control ventilation. We also developed another type (Type B) of center-mounted disc of similar structure. This type has a structure where a rib at the center of the cooling fins controls ventilation.

The mass of the center-mounted disc was reduced to 50 kg compared to the 75 kg mass of the present disc mounted at the inner periphery by eliminating the area used for mounting.

For both types of discs developed this time, we chose a material that was not quench-hardened much so slight heat spots would not cause heat cracks.

Fig. 7 shows a comparison of outward deformation of the discs in braking tests. Condition for testing was repeated emergency braking at 400 km/h. While the deformation of the present disc reached 2 mm, that of the center-mounted disc was around 0.5 mm, proving that it has little deformation.

4.2 Segmented Lining

The friction coefficient of the present lining is as low as 0.25. This is because the technology at the time the Shinkansen was first developed could not make it larger. That low friction coefficient has remained the same up to the present. But large pressing force would be needed at that small value to achieve large braking force required now, so calipers would have to be more solid. Increasing the force would be inadvisable, however. Existing linings also have a disadvantage of the friction coefficient dropping in the high-speed range due to melting wear. To handle high-speed braking, the lining should have stably high friction coefficient from the high-speed range to stopping.

The friction surface of the present lining (Fig. 8) would expand and deform outwards by braking friction as it is made of a single plate. Thus, the friction contact point became smaller and friction was localized. At those local friction points, abnormal heat eventually melted the material. Friction force thus decreased, and wear increased remarkably. In order to avoid this phenomenon, we segmented the lining and increased friction points, lowering the load on individual friction points.

The segmented lining (Type A), the appearance of which is shown in Fig. 9, consists of a pair of groups of nine blocks each. The segmented lining has a basic structure where three friction blocks in one group are joined with three supporting arms. This structure features small friction coefficient drop in the high-speed range because distributed friction points prevent localized heating. Fig. 10 shows a comparison of friction coefficients of the present lining and of the segmented lining. We also developed another type of lining (Type B).
Present bogies have a pneumatic-hydraulic conversion unit that converts air pressure into hydraulic pressure for the hydraulic caliper. Using pneumatic calipers enables weight reduction by eliminating the unit, and also creates space that allows easy installation of a new active suspension and an anti-rolling device.

**5.1 Emergency Braking Distance**

We carried out braking tests using a test train on the Tohoku Shinkansen section. Fig. 13 shows the braking distance measurement results of the rapid deceleration braking tests. In the braking tests, the train stopped at the expected distance even in rain. Using equipment for increasing air resistance in conjunction with brakes, we could achieve the target of braking within 4,000 m from 360 km/h.

The effect of equipment for increasing air resistance on shortening braking distance was approx. 300 m. That was smaller than expected. We found that the air resistance was large with the plates of the equipment at the front car and smaller at the plates toward the rear cars, probably because of air turbulence.

The discs and linings after the test were of a condition sufficient to be continuously used, so we judged that there were no problems with them. Fig. 14 shows the linings after the test.

**4.3 Pneumatic Caliper**

As the present hydraulic caliper (Fig. 11) has hydraulic cylinders behind the lining, it was not suitable for high-load braking that heats up the lining. Thus, we chose two types of leveraged pneumatic calipers. The appearance of each type is shown in Fig. 12.

![Fig. 9 Appearance of the Segmented Lining](image)

![Fig. 10 Comparison of Friction Coefficients (EB Test Result)](image)

![Fig. 11 Present Hydraulic Caliper](image)

![Fig. 12 Leveraged Pneumatic Calipers](image)
5.2 Improvement of Skid Control

Wheel locking occurred in emergency braking tests with water sprayed in winter, and that induced wheel flat on the tread. The cause of sliding was that the car with locked wheels lost its own speed in relation to the speed of the train as a whole. Fig. 15 shows the wheel speed at that time. Skid control was done with all four wheelsets.

To control sliding, braking of the sliding wheel is eased to facilitate readhesion. The benchmark for readhesion is the highest wheelset speed of the four wheelsets of a car. If all of four wheelsets slide, the benchmark is the speed found from the estimated deceleration of the brake equipment. In these tests, all of four wheelsets started sliding at high speed and the benchmark speed gradually fell below the actual train speed, and finally all of them locked again.

We changed the conditions to recognize recovery of wheels from sliding as a countermeasure against wheel locking. As a result, no wheel locking reoccurred in the condition where water was sprayed in winter. In this rapid deceleration emergency braking test, we also confirmed that the expected braking distance was achieved except in unusual cases.

6 Conclusion

The results of the development of a brake control method and brake gear to increase Shinkansen speed to 360 km/h are as follows.

(1) We were able to achieve the target braking distance of 4,000 m when braking from 360 km/h.
(2) We decided that the brake gear is to consist of center-mounted discs, segmented lining and pneumatic calipers. Such a drastic change from the present equipment enabled improvement of high speed braking performance and weight reduction.
(3) Improvement of skid control solved the wheel locking, a problem that hinders train running.

We believe that the brake equipment for increased speeds is almost ready for practical application. Still, it is common for unexpected failures to come up, requiring many improvements when new items are equipped to Shinkansen rolling stock in operation and used for a long time. We will thus deal with those issues as they come up and further develop brake equipment of higher performance.