Development of the Crushable Stopper as Bogie Parts for Countermeasures against Derailment in Case of Earthquake

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A crushable lateral displacement stopper has been developed whose gap from the center pin expands only when it receives a strong impact in case of a major earthquake. As a countermeasure to improve the running safety of railway vehicles during earthquakes the stopper is used together with a specialized lateral damper. This paper describes the crushable stopper and results of static load tests and shaking tests on the large shaking test facility of RTRI with a full-scale vehicle model consisting of one bogie and half a carbody.

Keywords: earthquake, derailment, bogie, lateral displacement stopper, crushable stopper, shaking test

1. Introduction

It is known that the center pin of a car body strikes strongly against the lateral displacement stopper of the bogie when the vehicle vibrates strongly in the case of earthquake motion with a predominant frequency of over 1.4 Hz. During such movement, and due to considerably large wheel/rail lateral force and bogie rolling, etc., there is a risk of the wheel jumping to a height above the wheel flange, which in turn may result in derailment. It is thought that larger gap between the lateral displacement stopper and the center pin will improve running safety by buffering the strong impact against the lateral displacement stopper and because of a better vibration-damping effect of the lateral damper [1]. Running safety effectively improves [1] when a specially designed anti-seismic lateral damper [2] is used and which can provide large damping forces during a major earthquake.

Accordingly, in this research, for the purpose of improving running safety in case of an earthquake, a crushable lateral displacement stopper was developed with the same nominal gap from the center pin as existing devices, in the normal position, but which can expand in case of a strong impact due to a large earthquake, which in turn can ensure vehicle running stability and quality are maintained. The crushable stopper must be used together with a specially designed anti-seismic lateral damper.

2. Outline of the crushable stopper

RTRI developed a mechanical crushable stopper using a mechanical fuse for the movement mechanism in order to produce a crushable stopper with and expandable gap which operates on strong impact in abnormal conditions, in such an earthquake. The seat of the lateral displacement stopper rubber gets displaced in the same direction as the expanding gap, if a fixed load (a setting load of a movement) acts on the stopper. Two pairs of mechanical crushable stoppers with fixed movement loads of 40kN and 80 kN were built to test the reliability of the stopper movement.

Although a hydraulic crushable stopper designed with a hydraulic circuit for the movement mechanism was also developed, this paper only describes the development of the mechanical crushable stopper.

Figure 1 is a conceptual diagram showing the movement of the mechanical crushable stopper. A nominal gap is maintained in normal conditions, with an internal and outer cylinder with mechanical fuse. When a force in excess of the set moving load is exerted onto the stopper, the mechanical fuses fracture, displacing the internal cylinder and allowing the gap to expand by 50 mm. Repeated use is possible by replacing the mechanical fuses.

Figure 2 shows the outside view of the mechanical crushable stopper. Figure 3 shows the mechanical fuse. The same configuration was used for both set moving loads of 40 kN, and 80 kN. The overall length was 414 mm (including the stopper rubber). The maximum diameter of the cylinder was 110 mm, the height 144 mm and the width 220 mm. The weight was about 28 kg (including the stopper rubber). Brass was used for the mechanical fuses and four mechanical fuses were installed. The diameter of the mechanical fuse depended on the set moving load. The diameter of the mechanical fuse was 7 mm for a set load of 40 kN and 10 mm for 80 kN.
3. Static load test

In order to confirm the basic performance of the crushable stopper, static load tests were carried out.

3.1 Test method

Figure 4 shows the static load test apparatus including a gate type press. Loading was slowly carried out on the crushable stopper with a manual hydraulic jack until the mechanical fuse fractured, and the loading force and the displacement of the moving part (internal cylinder) were measured.

3.2 Result of the test

Figure 5 and Figure 6 show examples of the measurement results for each set moving load. Moreover, full test results are shown in Table 1. Here, the presumed breaking

![Fig. 1 Conceptual diagram of the movement of the mechanical crushable stopper](image1)

![Fig. 2 Outside view of the mechanical crushable stopper](image2)

![Fig. 3 Mechanical fuse (for set moving load of 80 kN, Diameter 10 mm, Length 29 mm)](image3)

![Fig. 4 Static load test apparatus](image4)

![Fig. 5 Example of measurement results (set moving load of 40 kN)](image5)

![Fig. 6 Example of measurement results (set moving load of 80 kN)](image6)
load was calculated from the material and the diameter of the mechanical fuse, using an experimental equation found beforehand. The equation was established on the basis of verification tests, on the movement of the mechanical fuse by a fundamental experimental model, which were carried out 10 times for each fuse diameter, confirming stability of movement. Although the 80kN set moveable load is larger than the presumed breaking load by about ten percent, the dispersion in measured values between the 40kN set load and 80kN set load was small. These results confirm the stability of the crushable stopper movement.

4. Dynamic load testing by means of shaking tests on a full-scale bogie

Shaking tests on a test body installed on the RTRI large shaking test facility (shaking table) were conducted in order to examine movement security when impact forces, generated by car body and bogie behavior under earthquake conditions, were acting on the crushable stopper, and to verify whether gap expansion did actually prevent derailment.

Figure 7 is an outside view of the test model of a Shinkansen half car-body. The mock up comprised rails fixed to the shaking table, a Shinkansen bogie on the rails, a load frame to imitate the car body, and securing link to prevent toppling of the load frame and to restrain motion in the longitudinal, pitching and yawing directions. Weights can be attached to the load frame to simulate arbitrary car body mass, such as the tare mass or gross weight of the car. In this test, the mass of the load frame was set on the assumption that the model car was carrying a maximum number of passengers (16200 kg). The wheel load was measured by a strain gauge fastened to the rail, directly under each of the 4 wheels.

4.1 Stopper gap expansion test

4.1.1 Test conditions

Although stoppers with larger gaps from the center pin are considered to be better for securing running safety in case of an earthquake with a high frequency component [1], this has not been examined experimentally. As a result, prior to examination of the crushable stopper, this assumed beneficial effect on improving running safety was confirmed by examining and comparing the remaining wheel load in case of sinusoidal excitation with a gap fixed at 23 mm (normal) and at 53 mm (expanded by 30 mm). In addition, since the excitation acceleration in this examination was set at the maximum value under the condition that the impact of the stopper does not exceed the fatigue load limit of the attachment section with its gap fixed at 23 mm, the amplitude and the acceleration differ from one excitation frequency to another.

4.1.2 Results of the test

The ratio of the remaining wheel load to the static wheel load (wheel load remaining ratio) for each excitation frequency is shown in Table 2. This table shows the following: there is no significant difference in the wheel load remaining ratio resulting from the gap difference in the case of the excitation frequency with 0.6 Hz or less, whereas a clear difference can be observed for excitation frequencies of 0.7 Hz or more. This confirms that safety from derailment is improved when the gap is large.

4.2 Crushable stopper functional verification test

Figure 8 shows the bogie equipped with the crushable stopper. It is impossible to attach the crushable stopper on the existing stopper seat on the bogie. Therefore, a crushable stopper support base was welded on the connection beam of the bogie frame. This moved the position of the lateral displacement stoppers upwards by about 170 mm compared with the normal stopper.

The force applied to the lateral displacement stopper was measured by strain gauges attached to the crushable stopper support bases as shown in Fig. 9. Although the strain from the vertical force might be also generated in the crushable stopper support base, the loading in the vertical direction was difficult and only the calibration of the force applied to the lateral displacement stopper was carried out as shown in Fig. 10. Moreover, a reflecting plate was attached to the base plate of the stopper rubber, and the lateral displacement stopper stroke was measured using a laser displacement gauge, as shown in Fig. 11.
4.2.1 Test conditions

The bogie was excited in the lateral (sleeper) direction by sine wave and seismic wave. Excitation conditions are shown in Tables 3 and 4 for each set moving load. The estimated seismic waveforms which caused derailment in the Mid Niigata Prefecture Earthquake in 2004 (Chuetsu wave) [3] were used for the seismic wave excitation, changing its magnification. In addition, since the crushable stopper must be used together with a specially designed anti-seismic lateral damper, as mentioned above, all tests to confirm movement reliability and effectiveness were carried out accordingly, with a specialized lateral damper.

| Frequency, Hz | Acceleration, gal | Gap expansion (53mm) | Gap normal (23mm) |
|--------------|-------------------|----------------------|-------------------|
| 0.5          | 130               | 0.0                  | 2.6               |
| 0.6          | 120               | 0.0                  | 0.0               |
| 0.7          | 110               | 59.4                 | 0.0               |
| 0.8          | 140               | 67.6                 | 61.9              |
| 0.9          | 240               | 60.6                 | 49.9              |
| 1.0          | 320               | 55.5                 | 46.3              |
| 1.1          | 420               | 52.8                 | 28.1              |
| 1.2          | 500               | 59.4                 | 40.1              |
| 1.3          | 800               | 34.5                 | 8.8               |
| 1.4          | 500               | 58.2                 | 27.8              |
| 1.6          | 400               | 69.3                 | 27.0              |
| 1.8          | 400               | 83.9                 | 29.4              |
| 2.0          | 500               | 77.4                 | 51.0              |
| 2.1          | 550               | 71.4                 | 63.7              |
| 2.2          | 650               | 65.1                 | 46.7              |
| 2.3          | 750               | 62.8                 | 42.0              |
| 2.4          | 800               | 61.1                 | 51.6              |
| 2.7          | 1000              | 60.3                 | 45.4              |
| 3.0          | 1100              | 68.0                 | 61.9              |
Table 3  Test condition of shaking test (set moving load 40kN)

| Test No. | Frequency, Acceleration / Waveform, Magnification |
|---------|--------------------------------------------------|
| 1-1     | 1.2 Hz, 500 gal                                   |
|         | 1.2 Hz, 600 gal                                   |
| 1-2     | 1.0 Hz, 320 gal                                   |
|         | 1.1 Hz, 420 gal                                   |
|         | 1.2 Hz, 660 gal                                   |
| 1-3     | 0.6 Hz, 50 gal                                    |
|         | 0.6 Hz, 70 gal                                    |
|         | 0.6 Hz, 80 gal                                    |
|         | 0.6 Hz, 90 gal                                    |
| 1-4     | Chuetsu wave, 40 %                               |
|         | Chuetsu wave, 45 %                               |

Table 4  Test condition of shaking test (set moving load 80kN)

| Test No. | Frequency, acceleration |
|---------|-------------------------|
| 2-1     | 1.4 Hz, 1100 gal        |

4.2.2 Results of the test

The excitation conditions leading to gap expansion and the maximum force applied to the lateral displacement stopper before gap expansion occurred in each case are shown in Table 5.

The time history of the force applied to the stopper and the stopper stroke for the 6 second period just before and after the gap expansion movement under the excitation conditions in No.1-2 (sine wave 1.2 Hz, 660 gal) in Table 5 is shown in Fig. 12. It was proved that the gap was maintained as long as the force applied to the mechanical crushable stopper was below the set moving load, and that when the set moving load was exceeded, the gap expanded according to the force applied to the stopper.

Moreover, the comparison of the time history of the wheel load between the case where the gap of the mechanical crushable stopper expanded and that where it is fixed at 23 mm, on the same excitation conditions as Fig. 12 is shown in Fig. 13. Although the wheel load was zero when the gap was fixed at 23 mm, it was confirmed that the reduction in wheel load variation and an increase of 10.1 kN of the remaining wheel load was due to the gap expansion movement of the mechanical crushable stopper. This is equivalent to an increase of 20.3 % in the wheel load remaining ratio.

The time history of the force applied to the lateral displacement stopper and the lateral displacement stopper stroke for the 6 second period just before and after the gap expansion movement while being excited to 45 % of the Chuetsu wave is shown in Fig. 14. In the case of seismic wave excitation as well as in the case of sinusoidal excitation, it was proved that the gap was maintained as long as the force applied to the lateral displacement stopper was below the set moving load, and that when the gap did expand because the set moving load had been exceeded, it was according to the force exerted on the lateral displacement stopper.

The time histories of the wheel load compared with when the gap of the mechanical crushable stopper expanded, and when it was fixed at 23 mm under the same conditions as in Fig. 14, are shown in Fig. 15. Although the wheel load is zero when the gap is fixed at 23 mm, confirmation was obtained of a fall in wheel load variation and an increase in the remaining wheel load of 10.9 kN due to the gap expansion movement of the mechanical crushable stopper. This is equivalent to an increase of 18.2 % in the wheel load remaining ratio.

Under the excitation conditions listed Table 5, and after gap expansion movement on one side, there was no evidence of a strong force being applied to the other side of the lateral displacement stopper, and the gap expansion movement only occurred on one side. Therefore, the motion of the center pin seen from the bogie frame at the time of

Table 5  Results of the shaking test

| No. | Set moving load, kN | Shaking condition | Lateral displacement stopper applied force maximum, kN |
|-----|---------------------|-------------------|----------------------------------------------------------|
| 1-1 | 40                  | 1.2 Hz, 600 gal   | 42.9                                                     |
| 1-2 | 40                  | 1.2 Hz, 660 gal   | 45.4                                                     |
| 1-3 | 40                  | 0.6 Hz, 90 gal    | 50.0                                                     |
| 1-4 | 40                  | Chuetsu wave, 45 %| 44.5                                                     |
| 2-1 | 80                  | 1.4 Hz, 1100 gal  | 113.9                                                    |
the gap expansion movement, and before and after it was examined. The result is shown in Fig. 16 for a sinusoidal of 0.6 Hz, 90 gal; where the vertical axis is the absolute vertical displacement of the center pin and the horizontal axis is the bogie frame - the relative lateral displacement of the center pin is based on position No.2. This proved that after gap expansion movement on one side, the center pin is displaced toward the lateral displacement stopper on the side where the gap has expanded. There was no problem of the vibrating car body leaning to one side because it was stabilized thanks to the air spring acting as a stabilizer. However, it should be noted that the increase in the movable range of the car body in the lateral direction following gap expansion, generates a risk of fouling the loading gauge, depending on the extent of the gap expansion.
5. Conclusions

For the purpose of improving running safety during earthquakes, a crushable lateral displacement stopper was developed, which must be used together with specially designed anti-seismic lateral dampers. The gap between the developed crushable stopper and the center pin is the same as in other stoppers, in nominal position, but can expand on impacts, such as those caused during earthquakes. Two prototype sets of mechanical crushable stoppers were built including mechanical fuses attached to the movement mechanism, one with a set moving load of 40 kN and the other of 80 kN. These prototypes were used to confirm stability of movement under static load tests and the movement itself under shaking tests on a full-scale vehicle model consisting of one bogie and a half car body on a large shaking test facility. The results can be summarized as follows.

(1) Although the 80kN set moveable load is larger than the presumed breaking load by about ten percent, the dispersion in measured values between the 40kN set load and 80kN set load was small. These results confirm the stability of the crushable stopper movement. Here, although 40 kN and 80 kN were used as the set moving loads for the purpose of the experiment, the set moving load should in practice have to be adapted to the actual vehicle or relevant earthquake conditions.

(2) The results of sinusoidal excitation tests for the gap fixed at 23 mm (normal) and 53 mm (expanded by 30 mm), showed no significant difference in the wheel load remaining ratio due to the gap difference when the excitation frequency was 0.6 Hz or less, whereas the wheel load remaining ratio was higher in case of the larger gap for excitation frequencies of 0.7 Hz or more. This confirms that the safety from derailment is improved when the gap expands.

In the future, while fatigue tests are performed on the mechanical crushable stopper, similar trials will be conducted in parallel to make progress on the development of a hydraulic crushable stopper.

References

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