Development of Damage Reducing Rail Surface Height Adjustment Pad

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Rail surface height adjustment pads (RSHAP) are one component in the rail fastening system “Direct Type 8” used for slab track. These pads are made from thermosetting resin, which is reinforced with glass fiber sheet. However, RSHAPs sometimes suffer damage from longitudinal creep in continuous welded rails due to rail expansion and contraction induced by changes in temperature. Two types of RSHAP were therefore developed to counter this problem. One is made from conventional vinyl ester resin reinforced with polyarylate fiber sheet. The other is cycloolefin resin with no fiber sheet. This paper describes the required physical properties and the characterization of developed products.

Keywords: slab track, rail surface height adjustment pad, cycloolefin resin, polyarylate resin fiber

1. Introduction

Rail fastening systems, called “Direct type 8 (Fig. 1)”, have been used as standard fasteners for newly constructed slab track lines since the 1970s. In this system, the rail height can be maintained with an accuracy of 1 mm or less by means of a rail surface height adjustment pad (RSHAP) [1] [2] [3]. RSHAPs are installed by injecting reaction curable liquid resins such as vinyl ester resins, into laminated film bags containing glass fiber sheets for reinforcement. These pads have a serviceable life of around 50 years on commercial lines and their durability has proven through experience. However, some cases of damage are reported mainly due to the effects of expansion and contraction because of changes in rail temperature.

The authors developed two damage reducing RSHAPs as a countermeasure. One is made from the conventional vinyl ester resin reinforced with polyarylate fiber sheet. The other uses cycloolefin resin with no reinforcing fiber sheet. This paper describes the required physical properties and characteristics of these products, and presents the results of evaluations to verify their practicality.

Fig. 1 Rail fastening system “Direct type 8”

2. Overview of current products status of RSHAP

(1) Material composition of RSHAP

Typically, RSHAPs are made by injecting liquid curable resin such as epoxy acrylate or urethane acrylate into a laminated film bag, containing a glass fiber sheet with plain weave structure, which is for reinforcing the resin and also prevents splashing in case of rupture. After curing, RSHAPs become plates of fiber reinforced resin. They can be between 4 and 14 mm thick with high impact resistance and high dimensional stability.

(2) Installation categories

Distortion in continuous welded rails (CWR), caused by rail expansion and contraction due to temperature change, is suppressed in the middle of the rail. However, when longitudinal rail load exceeds the restraining capacity of a rail fastener, it generates rail creep. This rail creep occurs mainly in the vicinity of expansion joints (EJ), where the area of several hundred meters from the end of WCR is defined as a movable section. On the other hand, the middle part of CWR is defined as an immovable section. As such, RSHAPs are classified into two categories: movable section and immovable section.

(3) RSHAP Specifications

An example of the physical property specifications of resins currently used in RSHAPs employed by railway operators, is shown in Table 1. These specifications were based on the material properties of pioneering products

and was standardized in the 1980s when large-scale construction work was planned in cold regions.

For movable sections, load conditions are stricter than for immovable sections due to structural reasons. In addition, there was concern about damage due to embrittlement in low-temperature environment: specifications favoring flexibility and impact resistance were therefore adopted.

Table 1 Example of specifications for physical properties of rail surface height adjustment pads

Properties	Installation categories	
	Immovable	Movable
Compressive strength (MPa)	140 ≤	140 ≤
Compressive yield strength (MPa)	40 ≤	20 ≤
Tensile strength (MPa)	35 ≤	20 ≤
Tensile strain at break (%)	5 ≤	30 ≤
Flexural strength (MPa)	50 ≤	20 ≤
Charpy impact strength (kJ/m ²)	5 ≤	15 ≤

(4) Damage cases and issues

Generally, RSHAPs have been used more than 30 years, just like the life of the rail replacement. As a result of modifications to correct initial faults found in RSHAPs, it was found that these devices were still functioning without severe damage or deterioration after more than 30 years of service on commercial lines.

However, a handful of problems did occur that were common to the RSHAPs: the major problems were cracks and fractures in the convex edges (ribs) of the pads. Figure 2 shows a cross-sectional image of rib-crack damage, from the top (rail pad side) of the RSHAP and to the bottom with the reinforced glass fiber sheet. This damage was found to be caused by the rail pad climbing the rib due to rail creeps because of movement caused by strong friction with the rail. The same damage was found to occur when the RSHAP moved causing the rib to climb the baseplate.

Fig. 2 Cross section image of crack in RSHAP

3. Development of damage reducing products

In order to reduce damage to RSHAPs, especially the occurrence of rib cracks, the following studies were conducted:

- ① Clarification of required properties
- ② Improvement of reinforcement fiber and structure
- ③ Improvement of matrix polymer resin

3.1 Clarification of required properties

The temperatures of each member of the rail fastening system “Direct Type 8” were measured to estimate usage temperature conditions for RSHAPs from the relationship

between the rail and RSHAP temperature. The fastening system was installed on a slab track laid on an earth structure at the Railway Technical Research Institute (Kokubunji, Tokyo, from May 2017 to March 2018). Figure 3 shows the mean hourly temperature at the rail and the surface of RSHAP. Here, the correlation between the both temperatures can be observed. The maximum mean hourly temperature was 53.0°C for the rail and 46.8°C for the RSHAP, and the minimum was -9.3°C for the rail and -5.0°C for the RSHAP. Rail temperature is affected by solar radiation conditions and air temperature: however, the frequency of temperatures exceeding 50°C was relatively low, and only for a few hours a day [4]. For these reasons, the usage temperature range of RSHAP is generally assumed to be around -10°C to 50°C. However, in harsher climates, where the rail temperature falls below -20°C or exceeds 60°C, the usage temperature should be assumed accordingly.

Fig. 3 Temperature of rail and RSHAP

(2) Load conditions

RSHAP is subjected mainly to two external loads, vertical compression load by the wheel load and shear load between the rail pad and the baseplate due to longitudinal rail creep. To estimate these loads, analysis and experiments were conducted giving the following results.

① Vertical load

The analysis was conducted on a ‘Direct type 8’ fastening system, using the rail tilting motion FEM analysis model shown in Fig. 4 (a). The rail bottom displacement inside (GC side) and outside (FC side) the fastening part

(a) Rail displacement calculation using rail tilting motion FEM analysis model [5]

(b) Analysis result of stress at surface of rail pad

Fig. 4 Stress at surface of rail pad loaded with design wheel load of Shinkansen vehicle

were calculated under loaded condition, i.e. the vertical component of resultant loads of wheel load P and Q defined in the design standard [5] [6]. Next, the rail pad shape was modeled with solid elements. Then, with the rail bottom displacement obtained in above, the stress on the bottom surface of the rail pad was calculated by nonlinear static analysis. As a result, the stress of the rail pad was concentrated at the edge of its vertical groove as shown in Fig. 4 (b), partially exceeding 35 MPa and decreasing to 10 MPa or less in other parts. For these reasons, the target values of the required properties related to the vertical load of RSHAP were set to a compressive strength of 40 MPa and compressive yield strength of 10 MPa.

② Shear load

To estimate the local load applied to the rib by the longitudinal rail creep, the rail creep test was performed as follows:

i) Test method

Figure 5 shows the rail creep test equipment. Rail displacements were applied repeatedly to the equipment, where a rail was fastened only by a central fastening system. The test conditions are shown in Table 2. Here, the exciting load was measured as a restraint via a fastening system. At the same time, grease was applied between the rail and the leaf springs in the rail fastening system to reduce the effect of friction. In addition, 4 types of rail pad with different stiffness and shapes (Fig. 6) were compared. All of these pads had sliding surfaces made from polysulfide hard rubber resin (PSR), which were integrated during manufacturing into the contact surface with the rail. PSR has been used as a substitute for stainless steel sheet, for about 10 years.

Next, assuming fixation between rails and rail pads due to high friction or corrosion on the surface of rail bottom, the same tests were conducted with a rail pad restrained to the rail bottom.

ii) Test results

As an example of the test results, Fig. 7 shows a rail displacement and restraint curve using stud-U shape rail pad with spring constant of 30 MN. In this example, when the restraint (absolute value) reaches approximately 2 kN, a slight slippage occurs between the RSHAP and the baseplate. Then, the edge of the RSHAP comes into contact with the baseplate and the contact force increases. When it reaches about 4.5 kN, the rail slips on the rail pad. As shown in Table 3, the restraint per fastening system is between 2.9 and 5.3 kN. Therefore, the friction between the RSHAP and the baseplate is assumed to be approximately 2 kN as described above, while the contact force at the rib is estimated to be between 0.9 and 3.1 kN.

Figure 8 shows the relationship between the height of the RSHAP's ribs and the restraint per fastening system. The restraint depends on the stiffness and shape of the rail pad and also on the height of the rib. In this case, where the rail pad with stiffness for 30 MN/m and grooved surface shape was used, it deformed easily around the part that was in contact with the rib making it relatively easier for the rail pad to climb the RSHAP. In the other case, it was confirmed that with the rail pad with 30 MN/m stud-U shape type rail pad, there was almost no slippage of both RSHAP and a rail pad, due to the uneven surface shape. It was also confirmed that the U shape type suppressed the

rib rising onto the baseplate, so that the slippage between the RSHAP and the baseplate decreased.

In this way, the restraint per fastening system was estimated to be approximately 4 kN, when the rib height was less than 1 mm, although both are affected by the surface shape of the rail pad and its friction. On the other hand, the rail restraint required on the slab track was 5 kN / m (approximately 3.1 kN per one fastener) [6]. Assuming a rib height of 2 mm (half the minimum design thickness of 4 mm, cross-section 280 mm²), with all the restraint on the rib, it is estimated that the local load on the rib would correspond to approximately 11 MPa.

(3) Required properties of RSHAP

Table 4 shows the required properties of the matrix polymer resin for the RSHAP damage reducing counter-measure product. These required values were set based on the results presented above.

Fig. 5 Rail creep test equipment

Table 2 Test condition for rail restraint force

Items	Test Conditions
Rail	JIS 60 kg
Fastening system	Direct type 8 (improved version), Rail Pad : 4 different types (see Fig. 6; Polysulfide rubber resin on the surface), Bolt axial load : @5.0 kN
Excitation Condition	0.5 Hz sine wave, Amplitude : ±5.0 mm

Fig. 6 Rail pads with different stiffnesses and shapes

Fig. 7 Rail displacement and restraint curve for a fastening system with a PSR surface rail pad, 30 MN/m type U

Table 3 Rail restraint forces for fastening systems with PSR surface rail pads

Items	Resistance forces (kN)
Average	3.9
Max	5.3
Min	2.9
Standard deviation	0.6

Fig. 8 Relationship between Heights of RSHAP ribs and restraints

Table 4 Required properties of the matrix polymer resin for damage reducing countermeasure products

Properties	Required Value
Compressive strength (MPa)	40 ≤
Compressive yield strength (MPa)	10 ≤
Compressive modulus (MPa)	0.2 ≤
Flexural strength (MPa)	35 ≤
Flexural strain (%)	5 ≤

3.2 Development of countermeasure products

In the previous section, the authors focused on cracks in the ribs, typical of the type of damage found in RSHAPs, and identifying the required properties for the countermeasure: this made it clear that it was necessary to improve the reinforcing effect by changing the material and arrangement of the reinforcement fibers, or to improve the performance by changing the polymer in the matrix resin. Therefore, the following countermeasure products were developed:

(1) Reinforcement fiber

The synthetic fiber, which has a lower elastic modulus than glass fiber, should relieve the concentrated load on the ribs and impact load [7]. A number of fiber sheets with plain weave structures made of polyvinyl alcohol fiber (VF) and polyarylate fiber (PARF) and shown in Table 5 are compared and examined as alternative reinforcing fibers for glass fiber (GF).

Table 5 Specification of the reinforcing fiber sheets

Specimens	Weave	Materials	Number of yarns/inch	Weight (g/m ²)	Thickness (mm)
GF	Plain	Glass	Fill:16×Warp:15	328	0.33
VF	Plain	Polyvinyl alcohol	Fill:18×Warp:18	210	0.58
PARF	Plain	Polyarylate	Fill:12×Warp:12	160	0.25

Figure 9 shows the flexural test results of specimens made of conventional unsaturated polyester resin reinforced by the fiber sheets (composite specimens). At 60°C, there was no improvement in properties due to the application of the new reinforcing fibers. However at low temperatures below 0°C, the flexural strength of PARF rose by a factor of approximately 1.5 times higher than that of GF, indicating a significant improvement in low-temperature properties.

Hereinafter, the PARF composite material is referred to developed product "A".

Fig. 9 Comparison in effect of reinforcing fiber sheets for flexural strength

(2) Matrix polymer

A cycloolefin is applied as a matrix resin, which can be injected on work site (hereinafter developed product "B"). Table 6 shows the properties of the curable liquid of cycloolefin. In addition, the developed product has high flexibility of resin, and does not scatter if broken as frequent among conventional materials, so it was decided not to use reinforcing fibers.

Table 6 Liquid resin properties [2]

Items	Properties	
Reagent A	Density (kg/m ³)	980 ± 20
	Viscosity (Pa·s)	0.30 ± 0.10
Reagent B	Density (kg/m ³)	980 ± 20
	Viscosity (Pa·s)	0.30 ± 0.10
Mixed liquid resin	Pot life time (s)	30 ± 5
	Cure time (s)	100 ± 10
	Curing shrinkage (%)	0.9%

4. Characterization of countermeasure products

4.1 Test methods

The outline of methods of the physical property tests for the cured resin materials of RSHAP product is shown in Table 7. For the evaluation of compression and tensile properties, the specimens were prepared only from the matrix polymer without any reinforcing fiber. For the others, the specimens of same resin or resin composite materials with products were used. These tests were also conducted at various temperatures between -20°C and 60°C.

Table 7 Tests methods of cured resin

Test items	Test methods and conditions
Compression test	JIS K7181, Test rate : 2 mm/min, Unreinforced resin specimen 12.7×12.7×12.7 mm
Tensile test	JIS K7162, Test rate : 5 mm/min, Unreinforced resin specimen : Dumbbell 1B type
Flexural test	JIS K7171, Test rate: 2 mm/min, Support point distance : 64 mm, Indenter r = 5 mm, Composite specimen : 100×80×4 mm
Charpy impact test	JIS K7111-1, Weighing : 5 J, Composite specimen : 80×10×4 mm, Flatwise Type 1
Tensile impact test	JIS K7160, Weighing : 15 J, Composite specimen Dumbbell type 3, Thickness : 4 mm

4.2 Characterization results

Table 8 shows the results of the physical properties tests for the damage reducing countermeasure products, which were compared with representative samples of current products for immovable sections, called “current A”, and movable sections “current B”. The outlines of compressive yield strength and flexural properties are described as follows [2].

(1) Compressive yield strength

Figure 10 shows the compressive yield strength of the RSHAP resin specimen at various temperatures. The current product for the movable section (current B) has the advantage of being flexible in cold conditions meanwhile compressive yield strength is lower than 10 MPa at 60°C due to softening which means that it does not satisfy the criteria. However, both the current products A and B satisfy the criteria under the low and high temperature conditions.

(2) Flexural strength and strain

Figure 11 shows the relationship between the flexural

strength at 60°C and the flexural strain at -20°C. The former is an index for mechanical strength at high temperatures and the latter is for flexibility at low temperatures. Both developed products have a better balance of properties compared to the two current products, and satisfy the criteria of flexural strength for 35 MPa at 60°C and flexural strain for 5 % at -20°C.

Fig. 10 Compressive yield strength of RSHAP resin specimen at various temperatures

Fig. 11 Comparison of flexural properties between current and developed products

Table 8 Test results and required properties for cured resin of RSHAP damage reducing product [2]

Properties	Criteria			Test results of damage reducing products					
	Standard temperature	High and/or Low temperature		23°C		-20°C		60°C	
		60°C	-20°C	A	B	A	B	A	B
Compressive strength (MPa)	140	40	-	308	399	333	482	300	352
Compressive yield strength (MPa)	40	10	-	127	79.9	172	101.3	76.6	60.0
Compressive modulus (GPa)	0.2	0.2	-	3.4	2.0	3.8	2.1	2.3	1.6
Tensile strength (MPa)	35	-	-	90.6	48.7	71.9	66.7	44.6	31.8
Tensile strain at break (%)	5	-	-	6.0	24.9	2.2	20.1	6.1	84.9
Flexural strength without reinforcement (MPa)	50	35	-	121	-	96.0	-	69.2	-
Flexural strain without reinforcement (%)	5	-	5	5.3	-	2.7	-	4.6	-
Flexural modulus without reinforcement (GPa)	1	1	-	3.3	-	3.7	-	2.4	-
Flexural strength of composite (MPa)	50	35	-	130	74.7	212	88.9	67.1	49.4
Flexural strain of composite (%)	5	-	5	5.5	6.4	5.9	6.4	5.8	5.5
Flexural modulus of composite (GPa)	1	1	-	3.6	2.1	5.1	2.3	1.7	1.6
Charpy impact strength (kJ/m ²)	50	-	25	57.4	79.3	68.0	91.7	62.6	72.8
Tensile impact strength (kJ/m ²)	100	-	-	141	227	169	254	109	269
Deflection Temperature (°C)	-	-	-	81.2	142	-	-	-	-

5. Evaluation of practical use of damage reducing products

5.1 Performance verification

The following tests were conducted to verify the performance of the developed product in service on an actual track using a modified version of the “Direct type 8” rail fastening system.

(1) Durability against train load

Static loading and cyclical loading tests were conducted to verify the durability against train loads and safety in case of fatigue failure, in accordance with railway structure design standards [6].

As a result, in the static loading tests, lateral displacement at the head of the 60 kg rail was 4.5 mm, which was less than the design limit value of 5.2 mm and satisfied the safety criteria against fatigue failure.

(2) Longitudinal rail restraint

Regarding the contribution of RSHAPs in longitudinal rail restraint, a rail creep test was conducted at a minimum thickness of 4 mm, which is the most disadvantageous thickness in terms of strength. As a result, no deformation was observed in the entire RSHAP, including the ribs, and its condition remained stable.

These results confirmed that the developed product can be applied to actual tracks.

5.2 Field injection test

The practical scale test was conducted on the slab track at the Hino civil engineering test site, to confirm the workability and curing properties of cycloolefin, which is the curable liquid resin used for the newly developed product B.

The test statuses are shown in Fig. 12. As a result, the workability and curing properties for RSHAP thicknesses of 4 mm and 12 mm were confirmed to be almost same as with conventional materials.

However, when the rail temperature was less than 15°C, it was necessary to heat the materials as seen Fig. 12(c).

Fig. 12 Cycloolefin curable liquid resin field injection test

6. Conclusions

Rail surface height adjustment pads (RSHAP) were developed as a countermeasure to reduce damage caused by external loads, represented by longitudinal rail loads. The authors proposed a set of required specifications for the

physical properties of RSHAPs. The outline of this study is as follows:

- (1) Based on temperature measurements between the rail and RSHAPs, the assumed temperature range of use was clarified to be between -20 and 60°C in harsh climates.
- (2) FEM analyses of stress on the bottom surface of the rail pad under a tilting rail, revealed that a local stress exceeding 35 MPa was generated at the edge of the track pad vertical groove and 10 MPa or less in other locations.
- (3) Rail creep tests showed that rail restraint was affected by the height of RSHAP ribs, and the shape and stiffness of the rail pads. Thus, it is necessary to assume a local load of approximately 3 kN is applied to the rib.
- (4) Based on the results of examinations (1) to (3) a set of standard properties were proposed for the cured resin used in the developed RSHAP.
- (5) As damage reducing countermeasure products that satisfy the above criteria, a composite made of conventional vinyl ester resin reinforced by the polyarylate (PAR) fiber sheet (product A) and the cycloolefin resin (product B) were developed.
- (6) As a result of performance verification tests, it was confirmed that developed product (B) satisfies the criteria for the durability against train loads and rail creep, and can be applied to actual tracks.
- (7) As a result of the injection test, the developed product can be injected in the same way as the current product. However, if the rail temperature is less than 15°C, the material needs to be heated.

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