Stress Evaluation of the PLG Ground Coil Inserted GFRP Fastening Devices

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Hitoshi Matsue, Masayuki Aiba and Masao Suzuki
Railway Technical Research Institute, Maglev Systems Technology Division, 2-8-38 Hikari-cho Kokubunji-shi Tokyo 185-8540 Japan;

matsue@rtri.or.jp, *aiba@rtri.or.jp*, *msbell@rtri.or.jp*

ABSTRACT: Ground coils provided along the entire length of the guideway are essential for outdoor use over a long period of time in the superconducting magnetically levitated transportation system. Therefore, high reliability is inevitable for the ground coils. They are fastening in guideway with bolts, because this fastening method is conceivable to the best for easy setting. Stainless steel fastening devices are formerly inserted in PLG coils (combined Propulsion, Levitation and Guidance coils), however these devices has the problem to loose the interface of them and molded resin under the alternative electromagnetic load condition. We are under developing new fastening devices made of GFRP (Glass Fiber Reinforced Plastics) instead of stainless steel. The GFRP fastening devices are presumably effective to prevent from not only abrasion of resin but also relaxing axial tension of fastening bolts. Ground coils are applied a certain type of stress, for example electromagnetic stress, thermal stress, fastening stress, residual stress and foreign substances impact stress. We describe about the strength evaluation test results for the PLG ground coil with GFRP fastening devices on the point of the stress which caused by the electromagnetic force, thermal expansion and fastening deformation.

1 INTRODUCTION

Ground coils provided along the entire length of the guideway are essential for outdoor use over a long period of time in the superconducting magnetically levitated transportation system. Therefore, high reliability is inevitable for the ground coils.

It is important to evaluate the stress around the fastening devices on the point of the mechanical strength of the ground coil for superconducting maglev, as the stress in generally concentrates there. We describe about the characteristics of this new fastening device which is made of GFRP and the measurement results of the stress on the PLG ground coil (combined Propulsion, Levitation and Guidance ground coil), in which GFRP fastening devices are experimentally inserted.

2 FASTENING DEVICE FOR GROUND COIL

2.1 Style of the fixing coil to the guideway

Some methods for fixing the coil to the guideway have been examined. For example, a direct bolt fixing, an indirect fixing by the FRP auxiliary parts and a burying into the concrete on the guideway. As the result of the comparison, we consider the direct bolt fixing is more preferable than others because it is simple and easy to install the coil to the guideway.

2.2 Development of the direct bolt fixing method

It is necessary for the bolt fixing method to prevent from loosing axial tension of fixing bolts, because the loosing axial tension causes to increase the time for maintenance. Furthermore it can affect the safety of the system.

The fastening devices made of stainless steel, which are expected to have the least creep, have previously been used in PLG ground coil, because a main cause of the decrease in axial tension is considered to be the creep of the mold resin. Figure 1 shows the stainless steel fastening device. Although this could prevent from loosing axial tension, another problem was occurred. The interface between the fastening device and molded resin make the loose and abrasion of the interface under the alternative electromagnetic load condition, because the interface does not adhere to relax the concentration of the stress around the fastening device and to allow the relative displacement on the interface.

Accordingly we are now under developing the fastening device made of GFRP, whose property is nearer to molded resin than stainless steel. Figure 2 shows the GFRP fastening device. This is the thick pipe made by winding of the impregnated GFRP sheets and heating and cutting to suitable length. The inner area of the GFRP fastening device is anisotropic and strongly reinforced in a direction parallel to the axis. And in the outer area of it the glass fiber is orthogonally oriented to make its elastic modulus similar to that of the molded resin. The GFRP fastening device is expected to have some following advantages.

- The anisotropic property of the inner area prevent from loosing the axial tension of the fastening bolt.
- It is possible to adhere the interface between fastening device and molded resin, because the material property of the outer area of GFRP fastening device is close to that of molded resin and it prevents from the abrasion.
- Eddy current loss does not occur on it.
- A variety cylindrical shape can be easily made by a machinery cutting.
- It has the potential to lower the cost of the ground coil.
- It is lighter than stainless steel fastening device.

Figure 1. Stainless steel fastening device

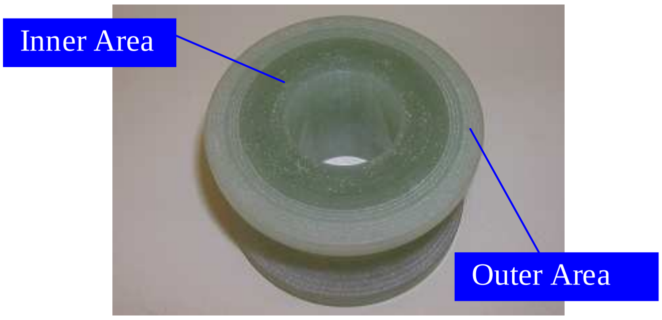

Figure 2. GFRP fastening device

(The difference of the direction of glass fiber in GFRP fastening device changes the color. Outer area is whiter than inner area.)

3 SPECIMEN

The PLG ground coil has three functions of propulsion, levitation and guidance. Accordingly the number of the coils installed on the guideway can be reduced and expected to be reduce the construction cost of the system. We experimentally made the PLG ground coil in which GFRP fastening devices inserted. In addition, we measured the stress on it by the bench test equivalent to the practical use. Figure 3 shows the coil used as a specimen.

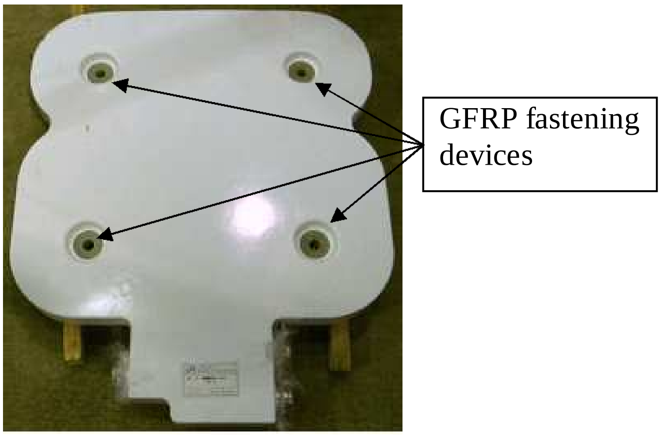

Figure 3. PLG ground coil in which GFRP fastening devices are inserted

4 THE WAY OF STRESS MEASUREMENT

The PLG ground coil is exposed from various stresses as described in Table 1. Moreover, it is essential to evaluate the mean value, the amplitude of the stress and the number of cycle in view of fatigue of molded resin. We measured the three types of the stresses which are listed in the Table 1, the stress from electromagnetic force, the stress from the temperature rise of the conductor and the stress from the slight deformation by fixing the coil on the guideway.

4.1 The stress from the electromagnetic force

The electromagnetic vibration test apparatus for a ground coil was used to measure the stress from the electromagnetic force. Figure 4 shows electromagnetic vibration test apparatus. The PLG ground coil was set in front of the superconducting magnet as showed in Figure 4. We assumed the practical running condition such as Table 2, which applies the highest electromagnetic stress on the PLG ground coil. A direct current of a one-tenth of a necessary current to occur equivalent electromagnetic force of the condition of the Table 2 was applied to the PLG ground coil and we measured the stress. In addition, we considered a value of 10 times of the measured value to be stress which occurs in electromagnetic force of the condition as listed of Table 2, because the current which generate equivalent electromagnetic force is too large to distinguish between the stress from the electromagnetic force and the thermal stress.

Table 1 Factor of the stress on the PLG ground coil

Elecromagnetic force	levitation force
	guidance force
	propulsion force
Thermal stress	thermal rise of conductor
	change of the environmental temperature
Fixing stress	unevenness of the surface of the guideway to which coil is fixed
	unevenness of the surface of the coil
	axial force of the fixing bolt
Wind pressure	
Residual stress	
Foreign substances impact stress	

Figure 4. Electromagnetic vibration test apparatus for a ground coil

4.2 The stress from the thermal rise of conductor

The PLG ground coil was set on the stainless plate which is the model of the guideway to which the coil is fixed (The plate will hereinafter be abbreviated “guideway model”). After that the direct current was applied to the PLG ground coil so that the thermal rise of the upside coil conductor will be saturated at 30 degrees. The thermal rise was estimated by the resistivity of the conductor. Figure 5 shows this measurement.

Table 2. The practical running condition, which assumed to apply the highest electromagnetic stress to the PLG ground coil

Vertical displacement	10mm under the balancing displacement
Horizontal displacement	20mm (The magnetic force is equalized to that of the PLG ground coil which is set on the far side from the superconducting magnet.)
Current for propulsion	The current is maxium and the phase delay 40 degree from the syncronized that.
Speed of the train	500km/h
Load which a boggie sustains	230kN/boggie

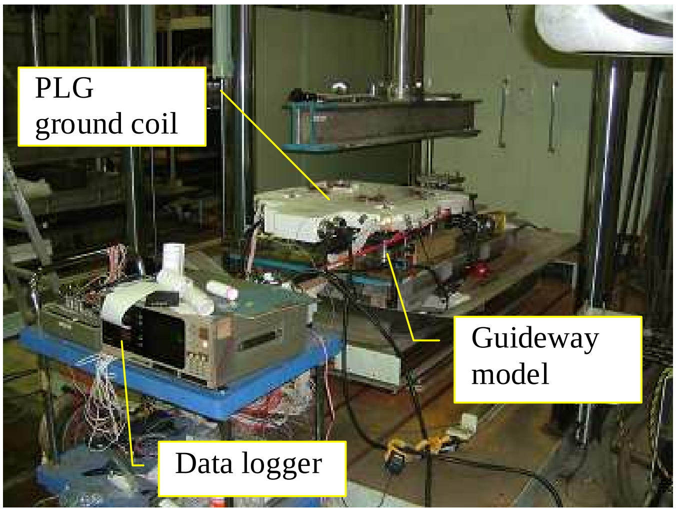

Figure 5. Measurement of the stress from thermal rise of conductor

4.3 The stress from the deformation by fixing the coil on the guideway

The PLG ground coil was set on the guideway model with the condition in which the space between the GFRP fastening device and guideway model was adjusted to ±1.5mm by using the stainless steel shim plates.

5 THE RESULTS OF STRESS MEASUREMENT

Figure 7 shows the measurement results of the stress on the PLG ground coil and Figure 6 shows the points of the stress measurement. We consider the each result by comparing with the FEM calculation result as follows.

5.1 *The stress from the electromagnetic force*

Figure 8 shows the calculated results of the coil deformation by electromagnetic force and the distribution of the force. Downward force on the central line applies the tensile stress on the lower points around the each fastening device and the compressive stress on the upper point around it according to the calculated results. And the horizontal force applies the tensile stress on the lower parts of the vehicle side around the each fastening device.

The measurement results of Figure 7 also shows high stress on the point of s3-s5 and s11-s13 where is the lower part of the vehicle side around the GFRP fastening devices.

5.2 *The stress from the thermal rise of conductor*

Figure 9 shows the calculated results of the coil deformation by the thermal stress of the conductor. Tensile stress occurs at the forward and back point around GFRP fastening device by the depressing of the center part of the coil like Figure 9. The measurement results of Figure 11 also indicate a high stress on the point of s2-s3 and s5-s6 where is the forward and back point of the vehicle side around the

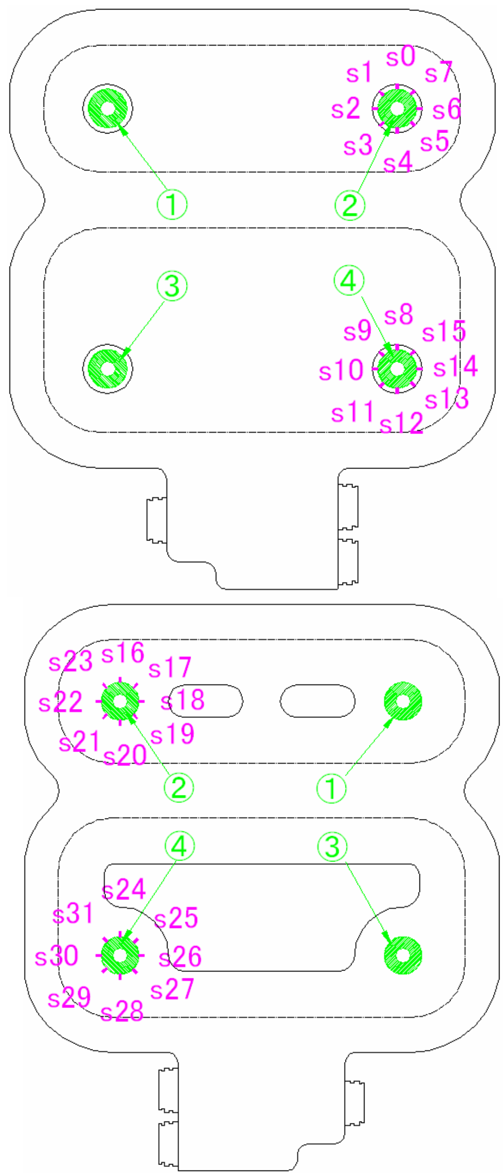

Figure 6 Measurement point of the stress

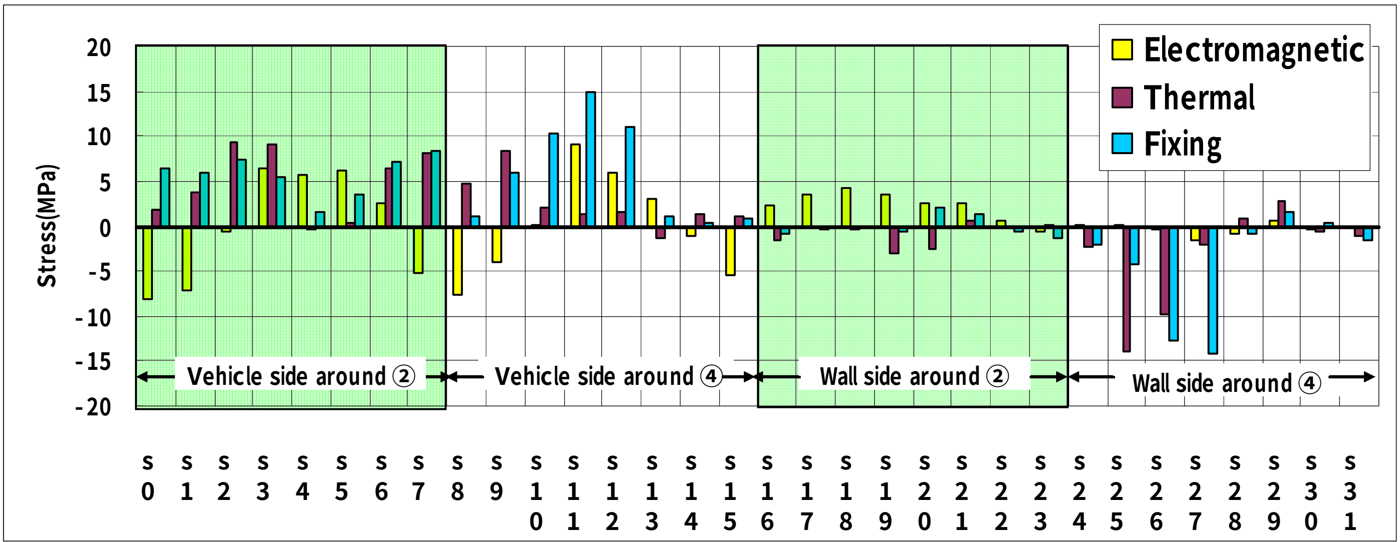

Figure 7 Measurement results of stress on PLG ground coil

GFRP fastening device. Figure 10 shows the measurement results of the displacement in vertical direction. This also shows the center depressing deformation.

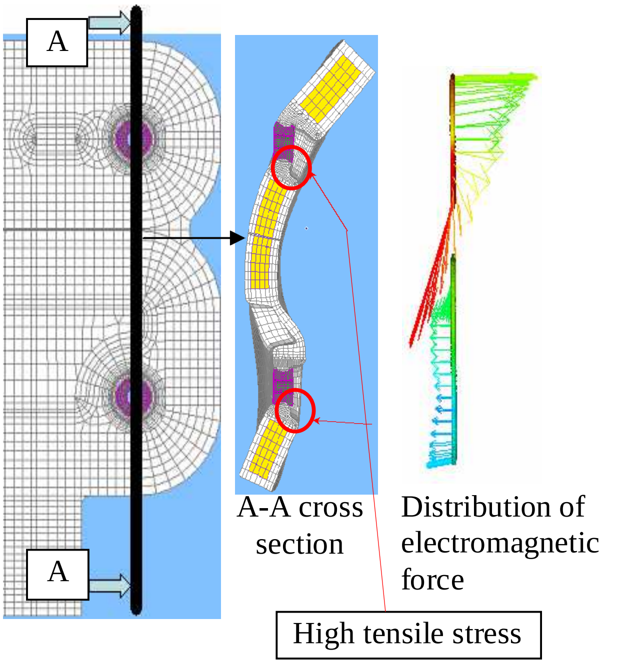

Figure 8. Calculated results of the coil deformation by electromagnetic force and the distribution of the electromagnetic force

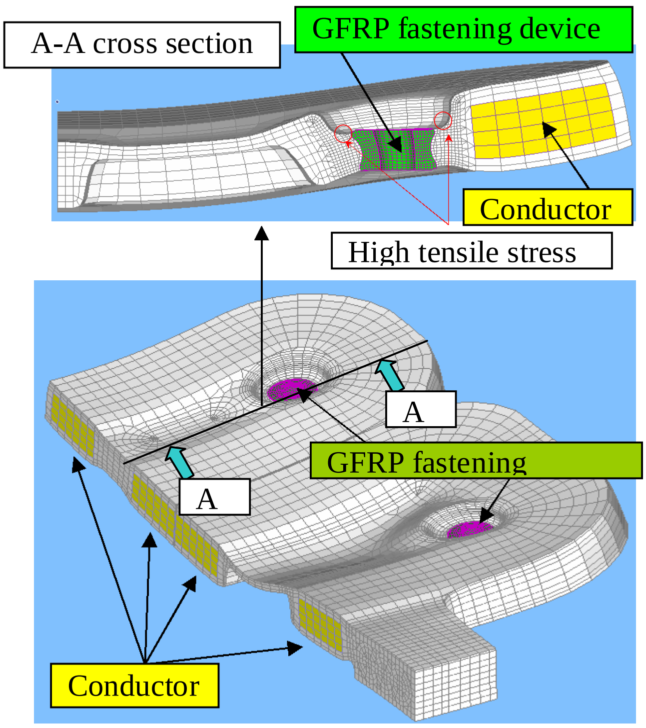

Figure 9. Calculated results of the coil deformation by thermal stress of the conductor

5.3 *The stress from the deformation by fixing the coil on the guideway*

Figure 11 shows the calculated results of the coil deformation in case that No.③ GFRP fastening devices are forced 1.5mm to the sidewall direction to simulate the unevenness of the guideway where the coil is fixed. The measurement results of Figure 17 indicate a high stress on the point of s10-s12. The calculated deformation result gives a reasonable explanation of this phenomenon.

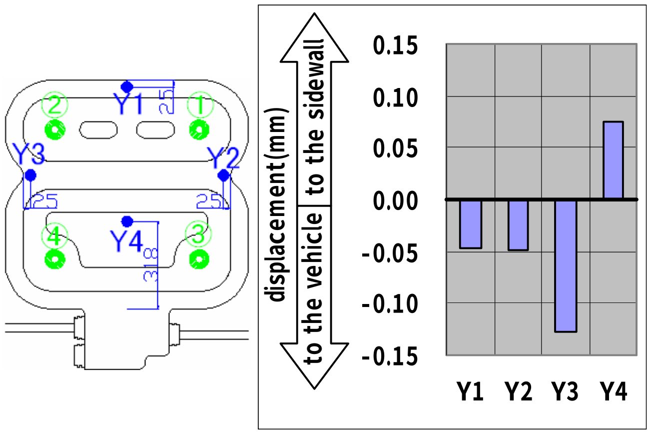

Figure 10. Measurement results of the coil displacement by thermal stress of the conductor

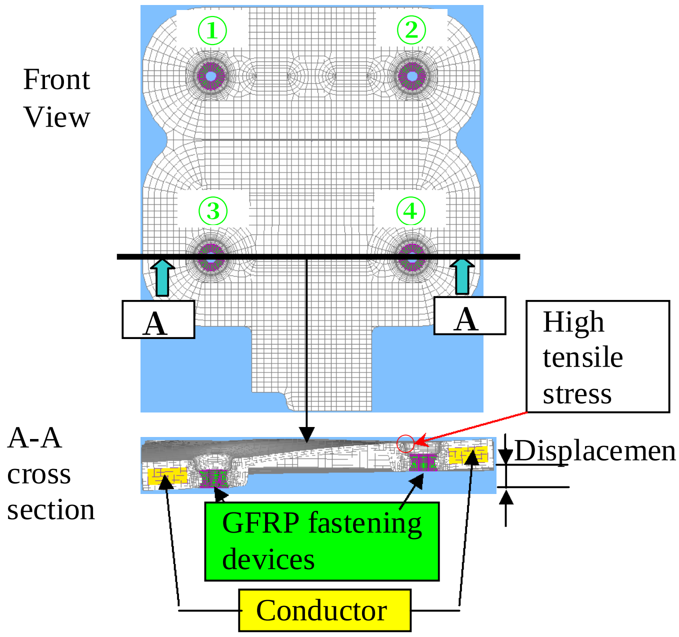

Figure 11. Calculated results of the coil deformation by fixing

6 STRESS EVALUATION

6.1 The mean stress and the stress amplitude

The stress on the PLG ground coil is the resultant stress of the static stress and the dynamic stress. The stress from the electromagnetic force is the zero-to-peak amplitude stress. We considered the stress from the thermal rise of conductor to the static stress, because the cycle of the thermal rise is sufficiently less than that of the electromagnetic force. Moreover we considered that the residual stress is constant at all point. Therefore we calculated the mean stress and the stress amplitude in the manner given by Equation 1 and 2.

$$\sigma_{mean} = \frac{1}{2}\sigma_e + \sigma_t + \sigma_f + \sigma_r \qquad (1)$$

$$\sigma_{amp} = \frac{1}{2}\left|\sigma_e\right| \qquad (2)$$

σ_{mean} :mean stress, σ_{amp} :stress amplitude, σ_e : the stress from electromagnetic force, σ_t : the stress from the thermal rise of the conductor, σ_f : the stress from the deformation by fixing the coil on the guideway, σ_r :the residual stress

6.2 The stress limit diagram of molded resin

Figure 12 is the stress limit diagram of molded resin, which contains three presumptions as follows.

- The fatigue strength of 10^8 cycles was extrapolated from the fatigue test result of 10^7 cycles.
- The environmental factor such as ultraviolet rays and moisture will deteriorate the strength of the molded resin to 81%.
- The shape of the stress limit line is resembled to that of another epoxy resin.

As a result, the stress value of the representative point on the PLG ground coil is plotted under the stress limit line.

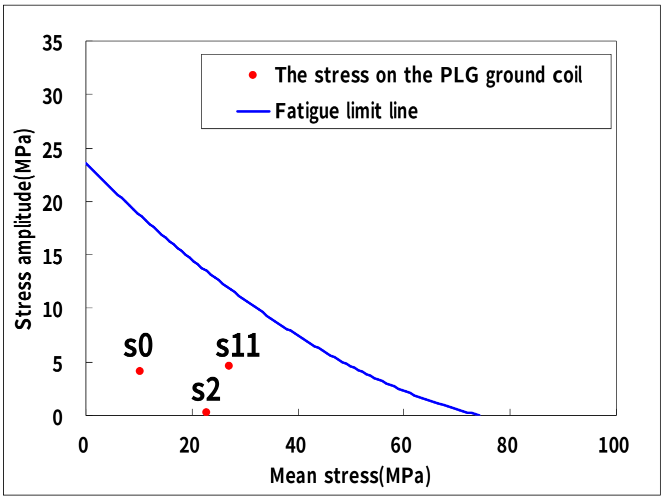

Figure 12 the stress limit diagram of molded resin

7 CONCLUSION

GFRP fastening device is expected to improve the reliability of the PLG ground coil for the superconducting maglev system. The PLG ground coil in which the fastening devices were inserted was experimentally made and we measured the stress on them. The stress of the representative point on the PLG ground coil was under the extrapolated stress limit line.

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8 REFERENCES

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