Theoretical and Experimental Analysis of Nb_3Sn Strand Buckling in Large Scale CIC Conductor*)

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The assessment of the performance of toroidal field (TF) coil of ITER has been progressing. Unpredictable strand buckling was observed by the destructive investigation of the conductor. The buckling direction was perpendicular to the Lorentz force (LF), and the mechanism of it was due to the thermal shrinkage caused by the difference of thermal contraction between strand material and conduit. Our previous work utilized a 2-dimensional string model and demonstrated that the observed 2 mm stand bending could have led to strand bending if the total amount of slide at the contact cross over was assumed to be 53 μm. To verify this estimation, we fabricated a device for the measurement of friction force between strands under constriction force comparable to the LF several hundred kN/m. Our results for Cr-coated 0.89 mm diameter strand surrounded by bare Cu strand indicate that thermal contraction stress applied to strand of 45 N would be sufficient to overcome the static friction force when the contraction force reduced to tenth of maximum LF. The mechanism of slide motion could be divided into two processes: separation of the inner wall of the conduit and the separation from other strands due to a gradual reduction of LF.

Keywords: cable-in-conduit conductor, Nb_3Sn strand, buckling, thermal contraction, static friction

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1. Introduction

In the ITER project, Japan is in charge of procurement of magnet system. At the SULTAN test facility, which checks the performance of cable-in-conduit conductors (CICCs), a series of toroidal field (TF) coil tests for the assessment of the current sharing temperature (T_{cs}) conducted. The degradation of T_{cs} was found with increasing of loading cycles [1]. To investigate the origin of T_{cs} degradation, destructive inspection was carried out in which the stainless conduit was stripped away after the initial test. The two opposite side of surfaces showed different appearances. The outermost strands on the highly compressed side on which the local void is smaller didn't change initial positions because of Lorentz Force (LF). On the other hand, another side of strand on the local void is larger became deformed and had a wavy appearance. Some of the deformed strands was so large that macroscopic cracks were observed. This bending has characteristics as follows: (i) the direction of bending is completely perpendicular to LF, i.e. the direction of LF is across the conductor cross section and that of bending is tangential to conductor surface. (ii) the strands which deformed a lot are located where local void became large. These facts indicate that LF isn't critical factor of bending and other forces are considered.

The most likely expected mechanism is due to the thermal contraction which is originated by difference in the thermal expansion between the material of strand and that of conduit when the conductor is cooled. The amount of contraction force is estimated to be 45 N [2]. Once LF is applied, the strand is pushed by LF. In the large void fraction area, strand is gradually apart from inner wall of the steel jacket and free from the friction force, then thermal shrinkage occurs. We previously simulated the situation of strand deformation introducing new modeling based on structural mechanics. This method and calculated result is explained later. In order to verify the calculated result, we investigated experimental analysis using device to measure friction force between strands under constriction force comparable to LF.

2. Theoretical Background

We previously introduced new simulation model based on structural mechanics. This is "discrete string model" and it can simulate the situation of buckling. In this work, the model was established for two dimensional simulation.

The strands are suppressed by the stainless steel wrap and the distance between both ends in which the strands are free to move is about 30 mm [2]. We assume that the

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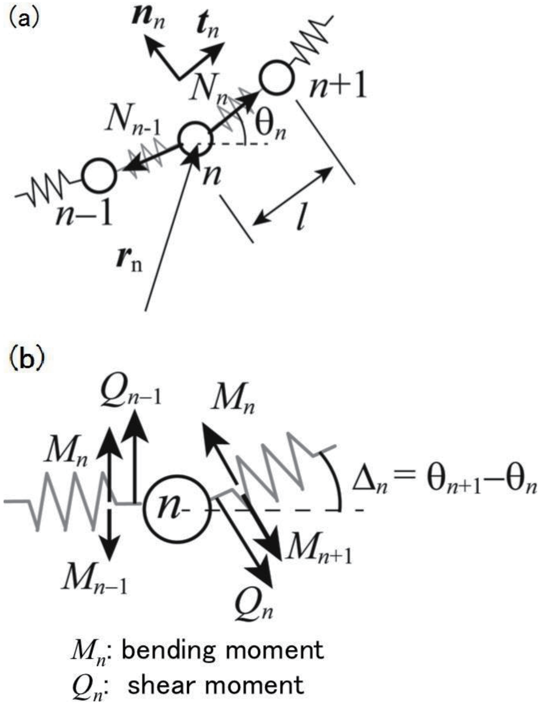

Fig. 1 (a) Schematic of modeling based on the structural mechanics, which is a curved beam of which both ends are parallel to the x axis. (b) Extensible discrete string model for numerical analysis.

strand trace for the calculation model has initial curve but completely parallel to the x-axis around both ends, which means there is an offset between the ends as shown in Fig. 1 (a). Left end is fixed and right end is free to move and parallel to x-axis. In the initial curve, we use clothoid curve in which the local curvature changes continuously. The trace is divided into mass points which are connected by springs as shown in Fig. 1 (b). Without using plastic theory, this model can simulate large deformation which leads to strand buckling.

Figure 2 (a) is close-up of discrete string model and Fig. 2 (b) focuses on one mass point. The equation of balance of force is as follows:

$$\rho \frac{d^2 \boldsymbol{r}_i}{dt^2} = (N_i - N_{i-1}\cos\Delta_{i-1} + Q_{i-1}\sin\Delta_{i-1})\frac{\boldsymbol{t}_i}{l} + (N_{i-1}\sin\Delta_{i-1} - (Q_i - Q_{i-1}\cos\Delta_{i-1}))\frac{\boldsymbol{n}_i}{l}. \quad (1)$$

Here ρ is mass density along the string defined as m/l and m is mass of a bead, l is an unstretched length of a spring. The $\boldsymbol{r}_n$ is a position vector, and Δ_{i-1} is defined as

$$\Delta_{i-1} \equiv \theta_i - \theta_{i-1}. \quad (2)$$

Where θ_i is an angle between the x-axis, $\boldsymbol{t}_i$ and $\boldsymbol{n}_i$ are unit vectors related by the Serret-Frenet formula of a discrete format as follows:

$$\begin{pmatrix} \boldsymbol{t}_{i+1} \\ \boldsymbol{n}_{i+1} \end{pmatrix} = \begin{pmatrix} \cos\Delta_i & -\sin\Delta_i \\ \sin\Delta_i & \cos\Delta_i \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{t}_i \\ \boldsymbol{n}_i \end{pmatrix}. \quad (3)$$

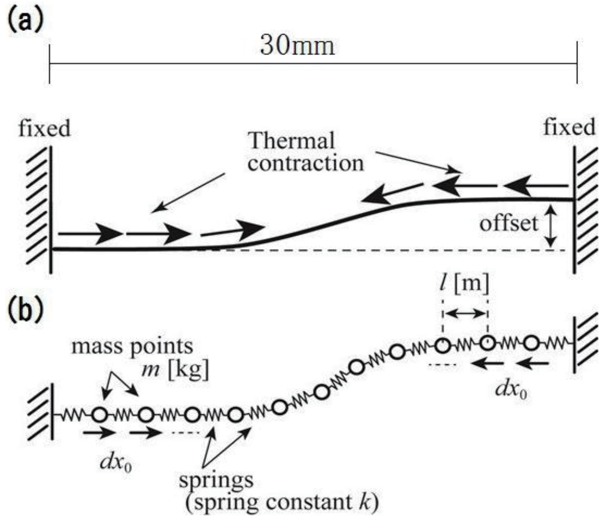

Fig. 2 Close-up of discrete string model. (b) Schematic of focusing on one mass point of discrete string model.

N_n and Q_n represent the axial force and the shear force of a spring, respectively [3]. They are given by

$$N_i = k\frac{(|\boldsymbol{r}_{i+1} - \boldsymbol{r}_i| - l)}{l} \equiv k\frac{(G_i - l)}{l}, \quad (4)$$

$$Q_i = \frac{M_{i+1} - M_i}{G_i}. \quad (5)$$

Where G_i is distance between $\boldsymbol{r}_{i+1}$ and $\boldsymbol{r}_i$, k represents ES/l, M_i is bending moment of the trace and given by

$$M_i = EI\frac{\Delta_{i-1}}{l} \equiv K\frac{\Delta_{i-1}}{l}. \quad (6)$$

Where K is a stiffness constant which is defined as the product of Young's modulus E and moment of inertia of area I. The value of E is 125 GPa [4] and I is $\pi d^4/64$ where d is diameter of strand of 0.89 mm.

As a initial curvature of trace, we assumed maximum curvature of 3% because in 486-strand conductor, 95% of strand has curvature less than 2.5% [5].

Figure 3 (a) represents the result of calculations. As times go on, the deformation of strand occurs. At the center of the strand, the maximum amount of deformation whose maximum initial curvature is 1%, 2% 3% is 0.67 mm, 1.25 mm, 1.89 mm, respectively. According to visual inspection, the amount of deformation at the center of strand is about 2 mm, thus the situation of maximum initial curvature of 3% represents the buckling situation. In this trace, the total amount of slide at right end is 53 μm. As a result of these simulations, we can say that total slide of 53 μm could cause strand bending of approximately 2 mm. According to elastic theory, elastic deformation by thermal contraction can cause only elongation of 13 μm, so it isn't main factor of buckling. The slide in crossover of strands is main factor and we need experimental analysis.

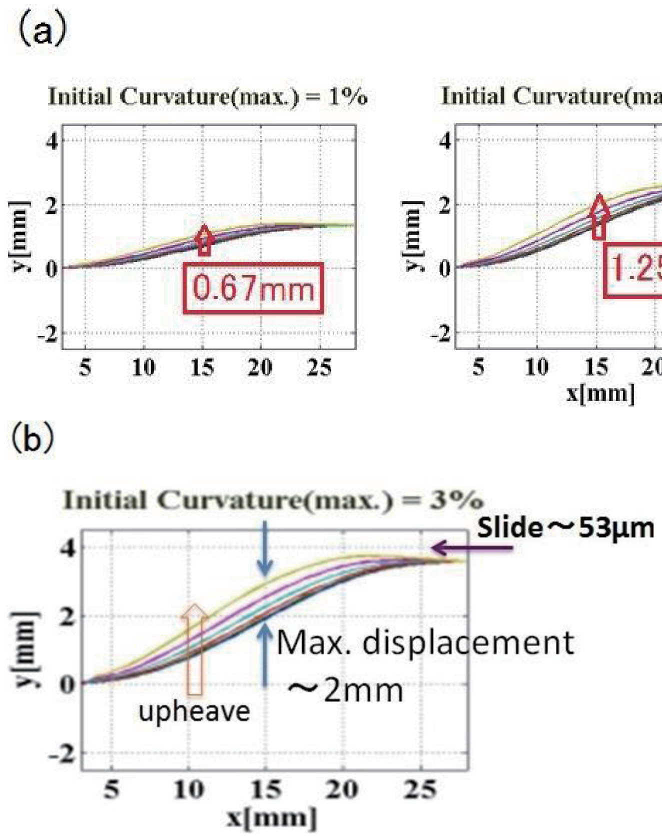

Fig. 3 Time evolution of strand deformation due to the axial compression force. (b) The amount of max displacement and slide when the maximum initial curvature is 3%.

3. Experimental Analysis

To verify that the slide is the main factor of strand buckling, we fabricated device to measure friction force between strands under constriction force of 45 N comparable to LF. Figure 4 is schematic view of experimental setup. The sample is surrounded by four round Cu wall and compressed from one direction. This replicates the situation in which strand is compressed by LF. The maximum compression force is 500 kN/m which is the same order of magnitude of the LF under operating conditions. This force was detected by strain gauges. The maximum of draw force (shear force) is 200 N, which is larger than actual thermal contraction forces of 45 N. This force is detected by a load cell. The slide distance of strand caused by the shear force is measured by laser displacement meter with a resolution of 1 μm. The procedure of experiment is as follows:

1. Press the sample with the force of 100 kN/m.
2. Apply a draw force to the sample up to 45 N.
3. Gradually release the compression force.

The sample strand is 2 μm Cr-coated Nb_3Sn with 0.89 mm diameter.

Figure 5 is the result of experiment. In this graph, a steep slope can be seen. In this area, a slip between Nb_3Sn strand and Cu wall occurred. It starts when the released compression force is about 40 kN/m, which is approximately one tenth of the maximum LF load. Because this slip leads to large displacement, the shrinkage may start at the situation of decreasing LF. At the compression force is about 40 kN/m, the slip distance of approximately 3 μm was observed. After the slip, along the relaxation of compression force, the shear force was moderately released. The amount of slide in this situation is approximately 72 μm, which is included the elastic deformation of the rod. Our estimation of the elastic elongation of the pulling of rod that was 1.5 m in length was roughly 8 μm. This was found using a SUS 304 rod with a width of 6 mm and Young's modulus of 197 GPa. Thus the net amount of slide is approximately 64 μm. This result agrees to calculated result of 53 μm. Although our calculation is based on two-dimensional model, this experimental result indicated that calculation results show good agreement with the observed strand buckling.

Figure 6 represents the appearance of conductor when LF is charged and discharged. The experimental result showed that the strand slipped and draw force is released when the compressive force is reduced to approximately 40 kN/m. From this result, we can say these facts as follows:

(i) Before operation, the outermost strands can't move because they contact with inner wall and LF isn't applied although thermal contraction of 45 N is applied.

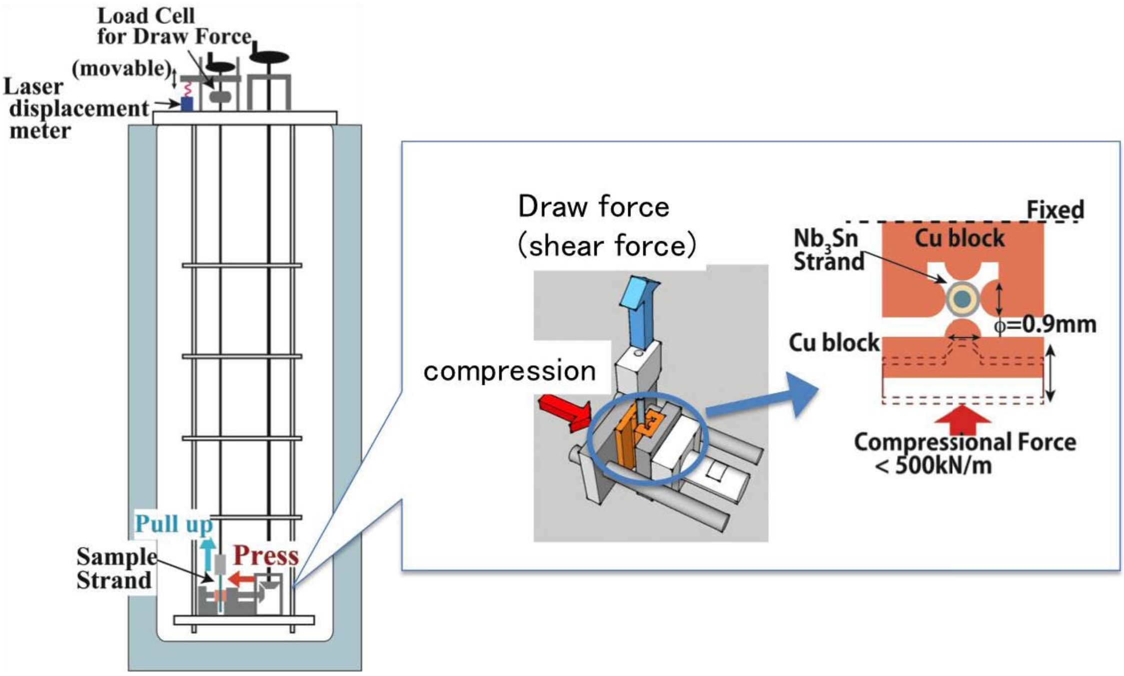

Fig. 4 Schematic view of experimental setup. A detailed view of the sample strand compression and the draw force are also shown in the enlarged square. The compression force is up to 500 kN/m, and the draw force is 200 N, which is much larger than the shrinkage stress due to the thermal contraction.

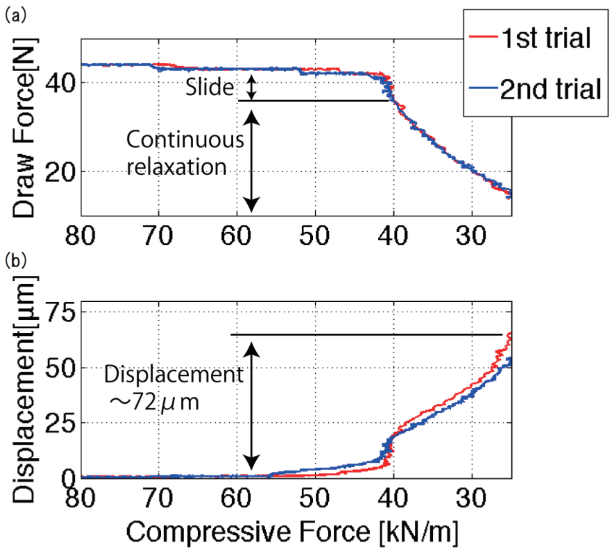

Fig. 5 Typical waveforms draw force along relaxation of compressive force. (b) Typical waveforms of strand displacement along relaxation of compressive force. A slip of 3 μm is observed at a press load of approximately 40 kN/m.

(ii) During operation, LF is applied. The strands are moved to one direction. Deformation doesn't occur because strands on the side with low void fraction can't move due to highly compression. Strands on the area with high void fraction also can't move because strands still make contact with each other and friction force exists.

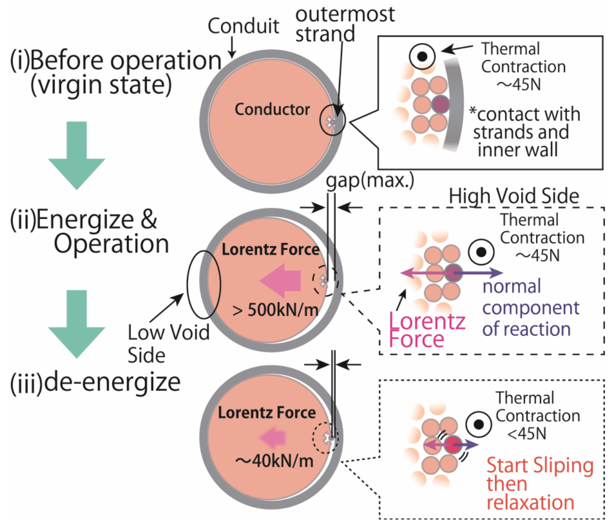

Fig. 6 Typical waveforms of (a) 45 N shear force applied initially and (b) displacement of sample strand vs. compression force. A slip of 3 μm is observed at a press load of approximately 40 kN/m.

(iii) When coil is discharged and LF is reduced, strands which are contacted apart from each other. Slipping starts and buckling occurs when LF is discharged and friction force between strands is released.

4. Conclusion

The slide at the crossover of strands is the main factor of buckling. The slide starts when LF is reduced to one tenth of maximum LF of several hundred kN/m. The amount of the slide was verified by the experiment. Thermal contraction force of 45 N causes the 53 μm slide under the condition of decreasing LF (coil-discharging process). It agrees our previously calculated result.

Acknowledgments

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