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Current Sharing of Parallel Connected Bi-2223 High-*Tc* Superconducting paths

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Abstract-- **Bi-2223 wire, the first-generation high temperature superconducting (HTS) wire, was successfully commercialized and various electrical machinery and equipment are actively being developed in many countries. Because its critical current is too small to realize the lossless conducting part of electric power system with a HTS wire, multi-HTS paths are used to enlarge the critical current of HTS system. Though the resistance generated in HTS wire by transport current is very small, the difference of it in multi-path is the additional reason which causes the non-uniform current sharing in multi-HTS path except the well known reason, the difference of inductance between each path. In this paper, experimental research on current sharing of multi-strand and multi-stacked HTS wire was implemented. The whole critical current of multi-HTS paths is not equal to sum of critical current of each path because of non-uniform current sharing occurred in this paths. It was verified experimentally that Bi-2223 wires have different resistance generated by same transport current even if they was manufactured in same progress of work. Current sharing phenomenon was affected by difference of resistance and self and mutual inductance.**

1. INTRODUCTION

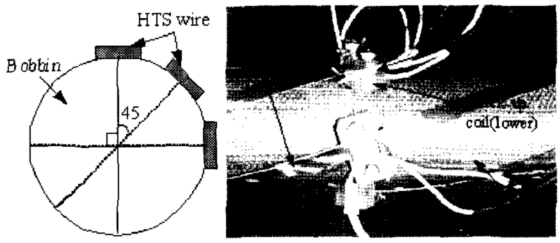
For the successful development of HTS devices applicable to high voltage electric equipment, it is necessary to have a large critical current, thermal stability, economic benefits, and so on. However, HTS coil and HTS strand wound with multi-wires enlarges the critical current, non-uniform current sharing in these structure may cause the problems in predicting of whole critical current and in the stable operation of a HTS devices [1], [2]. In this paper, two structures of multi-HTS paths were selected, which were HTS solenoid coil and HTS strand. HTS solenoid coil (HSC4) consists of multi-stacked 4 Bi-2223 wires and it also have one copper layer to protect HTS wires when it quenched. Two types of HTS multi-strand were fabricated with Bi-2223 wire. One was 2-strand (HMS2) and the other was 3-strand (HMS3). All used HTS wire was "high strength wire" of American Superconductor®. Certified minimum critical current of this wire was 115 A (@77K, self field) and it was reinforced with stainless steel. HMS2 has symmetrical structure in the aspect of mutual inductance and HMS3 and HSC4 has asymmetrical structure. The current sharing phenomena in these structures were analyzed and critical current of each path and whole structure was measured and compared.

2. PREPARING OF MULTI-HTS PATHS

2.1. Multi-HTS Strand

2 and 3-strand were fabricated for the experiment. (a) of Fig. 1 shows the cross-sectional view multi-strand. In the case of 2-strand, HTS wires were wound in a 90° gap. In the case of 3-strand, they were wound in a 45° gap. The ordinal numbers of each wound wire were given clockwise from zero at the top. In other words, in the case of 3-strand cable, the wound wire installed in the place of zero on the top was named as HTS_1 and the rest of the wires in the 45° gap were named as HTS_2, HTS_3 and so forth in the clockwise direction. The pitch of the wound wire was 180mm and the length of each wire was about 90 cm. The specification of multi-strand designed for this experiment is described in Table I.

Because the general pick-up coil used in the current measurement is designed to be adaptable for measuring the



(a) Cross-sectional view (b) HTS strand and mounted pick-up coils

Fig. 1. Fabricated HTS strand.

TABLE I.
SPECIFICATION OF MULTI-STRAND AND PICK-UP COIL

Components		Specification
Pick-up coil	dia. of wire	70 μm
	Number of turns	152 turns
	coils / strand	2 ea
Strand	diameter	25.4 mm
	length	860 mm
	pitch	180 mm
	Length of Cu	75 mm
HTS wire	Ic @ 77K, self-field	>115 A
	matrix	Ag alloy

current of the round-shape conductors and HTS wire is in the shape of thin tape the specially designed and fabricated pick-up coil was used to measure the current flows in the each path. They were installed on and below the wire and the linked magnetic field was measured and converted into the current of the conductor. The copper wire of 70 *μm* diameter was wound on the FRP bobbin to fabricate the pick-up coils. The winding numbers of one coil were 152 turns. (b) of Fig. 1 shows how the pick-up coils were mounted on each wire.

2.2. Multi-stacked HTS solenoid

Table II shows the specification of HTS solenoid coil. It was wound with Bi-2223 wire insulated with polyimide tape. The HTS wire used was "high strength wire" of American Superconductor®. Certified minimum critical current of this wire was 115 A (@77K, self field) and it was reinforced with stainless steel. The solenoid coil consists of 1 copper layer and 4 HTS wire layers. Bobbins for winding were made of glass fiber reinforced plastic (GFRP). The groove, which was 4 mm width and 3 mm depth, was processed on these bobbins to stack several HTS wires. Firstly, copper with 0.8 mm thickness was wound in the groove, and then 4 layers of HTS wire were wound. Innermost HTS wire was named HTS_1 and current flowing this layer was named I_1. Outermost wire was named HTS_4. Fig. 2 shows the fabricated multi-stacked solenoid coil for the current sharing test.

3. EXPERIMENTAL SETUP

For the experiment, the current was supplied from a DC power supply and each of the signals was stored after they went through the filter and amplifier. Fig. 3 shows the experimental setup for the measurement of current sharing in multi-HTS strand. The current flowing to each path was measured by pick-up coils. Several voltage taps were made for the calculation of resistance and critical current of each path and whole strand. Fig. 4 shows experimental setup for the measurement of current sharing in multi-stacked HTS solenoid coil. Each current was measured with general current clamps of HIOKI Co. Resistance and critical current of each path and whole critical current were calculated with the measured current and voltage of 16 voltage taps mounted at each path of the coil.

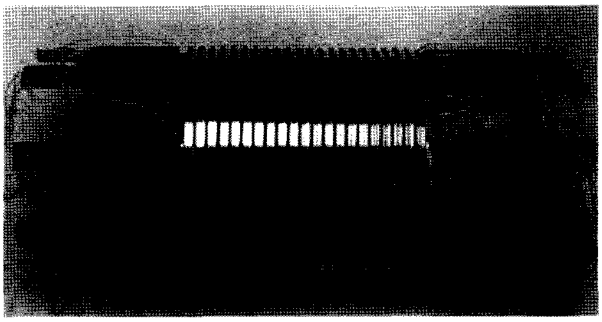


Fig. 2. Fabricated solenoid coil.

TABLE II.
SPECIFICATIONS OF HTS SOLENOID COIL

	Specification	Remarks
Number of stacked wires	5 ea	1 Cu + 4 HTS wire
Thickness of wire	0.8/0.3 mm	Cu/HTS wire
Number of turns	21 turns	
Height	129 mm	
Inner diameter	134 mm	
Outer diameter	138.8 mm	
Winding pitch	6.25 mm	
Width of groove	4 mm	
Depth of groove	3 mm	

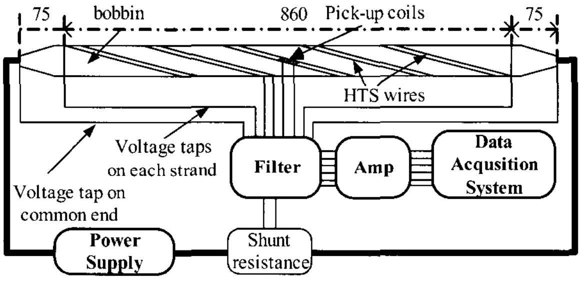


Fig. 3. Experimental setup for multi-strand.

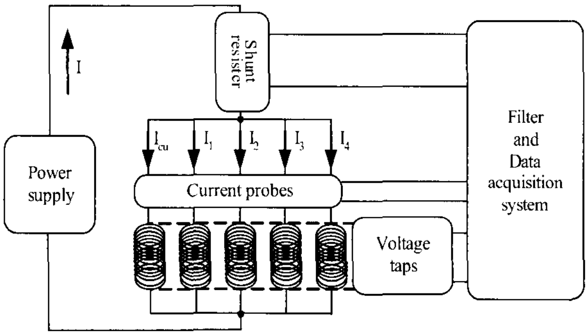


Fig. 4. Experimental setup for solenoid coil.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1. Current sharing of 2-strand (HMS2)

Fig. 5 shows the current sharing of 2-strand (HMS2). HMS2 consists of two wound HTS wires by 90° gap. The current has been increased to 300A with the ramping rate of 100A/s. At the beginning state of ramping-up, the current-increasing rate of HTS_2 was higher than that of

HTS_1. This current concentration phenomenon becomes more and more severe but, after the critical current value, the two values become similar. Especially, the current which flows to HTS_1 was bigger than that of HTS_2 after the quench. The final currents which flow on HTS_1 and HTS_2 were 151.7 A and 148.3 A respectively. As shown in Fig. 6, the critical current of HTS_1 HTS_2 and whole strand were 103.6 A, 108.7 A and 203.7 A respectively. This phenomenon can be analyzed in the relation to the resistance generated by the transport current shown in Fig. 7. It shows the generated resistance by transport current and contact resistance between HTS wire and copper block in each end of strand. The factors occurring the current sharing of multi-HTS paths are difference of contact resistance, inductance, and the resistance generated in HTS wire by transport current, and so on. HMS2 has symmetrical structure in the aspect of mutual inductance. When the transport current was below the critical current, the resistance of HTS_1 was larger than that of HTS_2. This difference increased in proportion to the increase of transport current so the current concentration into HTS_2 became larger. But, in the state of transport current after the critical current, the resistance generated in HTS_2 was larger so the distribution of the current which flows to each strand was changed. This phenomenon takes place because of the resistance difference generated in the wire after the quench. The wire of American Superconductor® consists of Bi-2223 multi-filament and Ag alloy matrix. Though the same-lot-produced wires were used, the current re-distribution phenomenon by the increase of transport current was observed because of the resistance difference generated by the matrix and Bi-2223 filaments. From these experimental analyses, as shown in Fig. 5 and 7, current sharing is more affected by resistance generated in HTS wire by transport current than contact resistance which is larger than generated resistance by transport current below the critical current area. In the state below the critical current, the difference of maximum transport current was about 17.5 A. When the transport current of300 A, the maximum transport current, was transported, the difference of the transport current was 3.4 A and current imbalance distribution occurred.

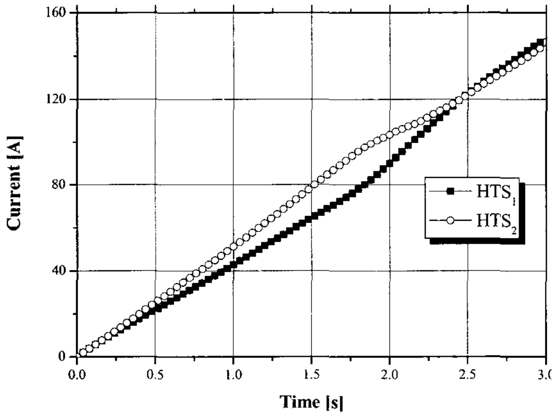


Fig. 5. Current sharing of 2-strand.

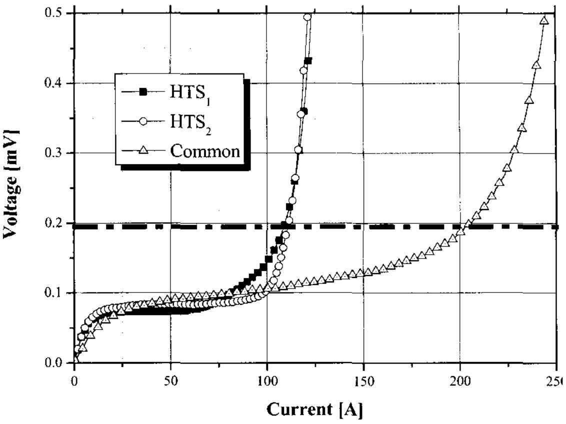


Fig. 6. V-I characteristic of 2-strand.

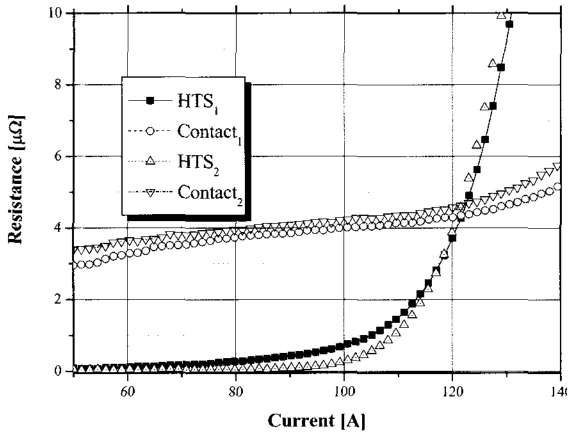


Fig. 7. Resistance of each strand generated by the transport current.

4.2. Current sharing of 3-strand (HMS3)

Fig. 8 shows the current sharing of 3-strand with HTS wires wound in a 45° gap. The final current of HTS_1, HTS_2, and HTS_3 were 156.7 A, 143.2 A, and 150.1 A respectively. Fig. 9 shows that the critical current of HTS_1, HTS_2, HTS_3 and whole 3-strand was 103.6 A, 106.3 A, 108.7 A, and 317.6 A respectively. 3-strand was asymmetrical structure in the aspect of mutual inductance. The inductance of each strand is the sum of its self inductance and mutual inductance. As each strand has the same length and pitch structure, its self inductance will be same. In the case of mutual inductance, which is proportional to the distance between windings, HTS_2 has the largest mutual inductance among three paths. This is the reason why 3-strand is asymmetrical structure in the aspect of mutual inductance. So, the current of HTS_2 was expected to be the smallest and it was experimentally proved as shown in Fig. 8. Impedance of Fig. 10 was the calculated value with each transport and ramping rate and it shows that the biggest impedance generated before it quenched was that of HTS_2. Impedance of HTS_2 around 2.3 s was smaller than others because this path was not quenched but other paths were already quenched around 2 s. In other words, impedance of HTS_1 and HTS_3 at 2.3 s includes the resistance of matrix by quench of HTS wires but that of HTS_2 doesn't. So the current increasing rate increased around this time. After all quench of three paths, increasing rate of each path was almost same.

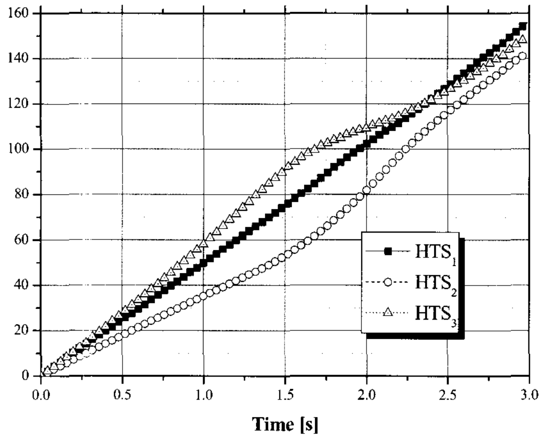


Fig. 8. Current sharing of 3-strand.

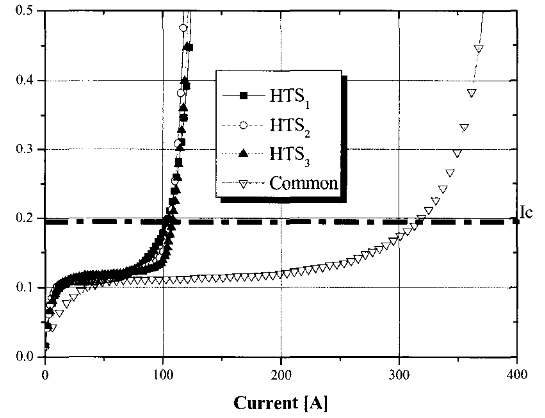


Fig. 9. V-I characteristic of 3-strand.

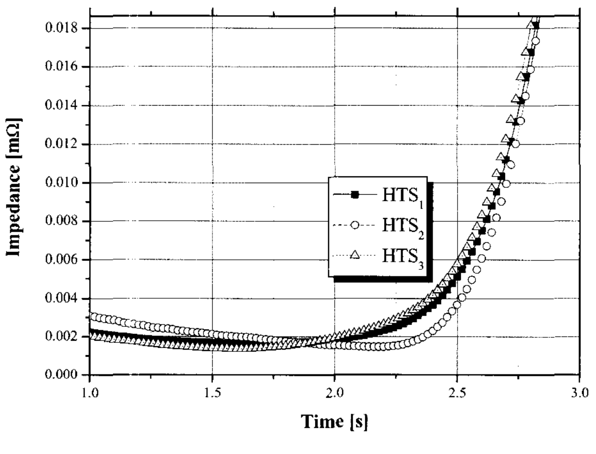


Fig. 10. Impedance of each path generated by current ramping-up.

4.3. Current sharing of multi-stacked solenoid coil (HSC4)

Because multi-stacked solenoid coil is also asymmetrical structure in the aspect of mutual inductance, it is necessary to check the resistance and self and mutual inductance of each path. Fabricated solenoid coil has one copper wire path and 4 HTS wire paths, and the measured electrical parameters are as shown in Table III. Subscript “cu” means copper path and “4” means outermost HTS path. L means self inductance and $M_{ab}=M_{ba}$ means the mutual inductance between L_a and L_b. Mutual inductance was calculated with following equation (1). L_t means total inductance.

$$\frac{(L_1+M)(L_2+M)}{L_1+L_2+2M}=L_t \qquad (1)$$

Fig. 11 shows the current sharing of multi-stacked HTS solenoid coil. Transport current was increased to 300 A with a ramping rate of 50 A/s. The final current of each path were 0.003, 79.27, 80.60, 71.68, 67.12 A respectively.

Table IV and Fig. 12 show the critical current of each path and whole coil with ramping rate of 50A/s and a final current of 500A. 1 μV/cm criterion was used to determine critical current. The sum of the critical current of each wire was 402.1 A and whole critical current was 399 A. Difference between these two values was 3.1 A. HTS_2 was quenched at 7.79 s firstly, and HTS_3 was quenched at 8.34 s lastly. The whole coil was quenched at 8.13 s. It shows that, though one or more paths of coil is/are not quenched, resistance of the whole coil could be reach the same level as all the coil were quenched. Current increasing ratio of I_3 began to arise after about 7.8 s. It was because of the quench of HTS_2. The ratio of transport current of copper increased according to the quench of each HTS path. Because the critical current of I_4 was the smallest as shown in Table 4, though it was quenched at 8.09 s, its increasing ratio of was not raised as that of HTS_3 did. The ratio of the final current of each path changed, which signifies that the resistance generated in HTS wire by transport current was changed after quench. The largest current flowed into HTS_1.

As this coil contain a normal conducting part to settle current probes, several joint resistances and different resistances generated by the same transport current [3], each path of coils has different resistances. The current sharing of this coil was mostly affected by difference resistance of normal conducting parts, not superconducting part. To check this result follows the rule, which current sharing affected the difference of impedance including inductance and resistance, numerical simulation about current sharing was implemented. Fig. 13 shows the simulated current sharing of multi-stacked solenoid coil. Agreement between simulation (Fig. 13) and experiment (Fig. 11) was quite good. FDM is used as a simulation method and governing equation of the simulation is equation (2). Used electrical parameters for the simulation were from Table 3. Simulation results coincided well to the experimental result.

$$\begin{bmatrix} V_{cu} \\ V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} L_{cu} & M_{cu1} & M_{cu2} & M_{cu3} & M_{cu4} \\ M_{1cu} & L_1 & M_{12} & M_{13} & M_{14} \\ M_{2cu} & M_{21} & L_2 & M_{23} & M_{24} \\ M_{3cu} & M_{31} & M_{32} & L_3 & M_{34} \\ M_{4cu} & M_{41} & M_{42} & M_{43} & L_4 \end{bmatrix} \begin{bmatrix} di_{cu}/dt \\ di_1/dt \\ di_2/dt \\ di_3/dt \\ di_4/dt \end{bmatrix} + \begin{bmatrix} R_{cu} i_{cu} \\ R_1 i_1 \\ R_2 i_2 \\ R_3 i_3 \\ R_4 i_4 \end{bmatrix} \tag{2}$$

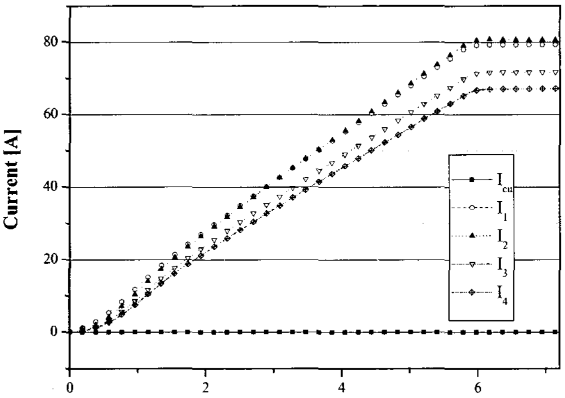


Fig. 11. Current sharing of multi-stacked solenoid coil.

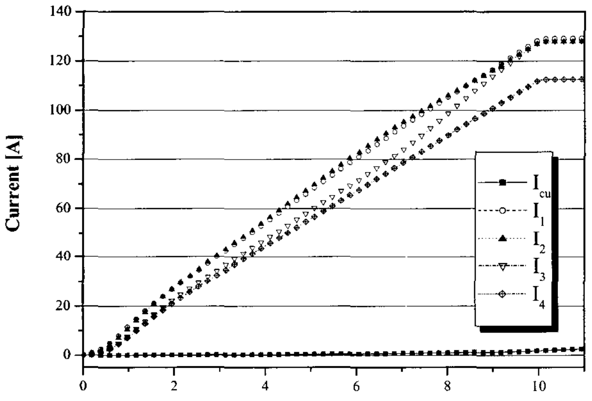


Fig. 12. Experimental current sharing result of insulated and multi-Stacked HTS solenoid coil with ramping rate of 50A/s and final current of 500A.

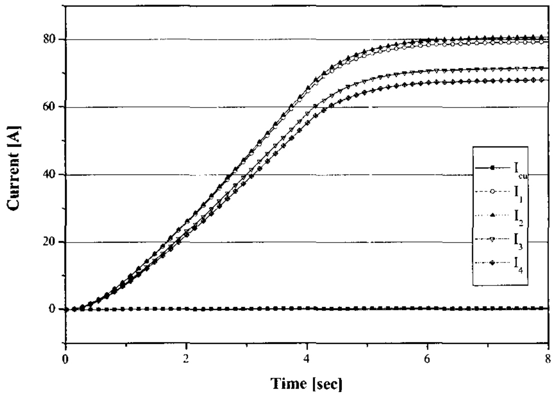


Fig. 13. Simulated current sharing of multi-stacked solenoid coil.

TABLE III.
ELECTRICAL PARAMETERS OF SOLENOID COIL

	Value $\mu\Omega$		Value μH		Value μH		Value μH
R_{cu}	11×10^3	L_{cu}	37	$M_{cu1}=M_{1cu}$	36	$M_{13}=M_{31}$	38.02
R_1	144	L_1	38.2	$M_{cu2}=M_{2cu}$	35.61	$M_{14}=M_{41}$	38.24
R_2	141	L_2	39	$M_{cu3}=M_{3cu}$	34.85	$M_{23}=M_{32}$	39.61
R_3	160	L_3	41	$M_{cu4}=M_{4cu}$	34.68	$M_{24}=M_{42}$	39.22
R_4	168	L_4	41.8	$M_{12}=M_{21}$	38.8	$M_{34}=M_{43}$	39.6

TABLE IV.
CRITICAL CURRENT OF EACH STACK AND COIL

	HTS$_1$	HTS$_2$	HTS$_3$	HTS$_4$	Whole
Critical current A	104.0	103.5	103.9	90.7	399
Quench time s	7.92	7.79	8.34	8.09	8.13

5. CONCLUSION

In this paper, current sharing phenomenon of multi-HTS paths was analyzed experimentally. The conclusion of this paper is as follows.

1. Characteristics of current sharing in multi- HTS paths were mostly affected by the different inductance of each path.
2. The critical current of the whole multi-HTS path decreases because of the difference of the characteristics and the critical currents among paths.
3. When there is an asymmetrical structure in the mutual inductance among multi paths, the non-uniform current distribution became severe but the decrease rate of total critical current was the smallest in this experiment.
4. Current re-distribution phenomenon among multi-paths also takes place according to the difference of impedance occurrence rate as the current rises in the symmetry multi-strand structure.

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