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Evaluation of residual mechanical performance of damaged conductor strands due to AC fault arcs for rational repair of overhead line

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SUMMARY

Interphase short-circuit failure of overhead transmission lines may occur due to sleet jump and galloping during winter in Japan. In case of interphase short-circuit faults, the conductor strands are melted by the AC fault arc, and repairs such as replacing damaged conductors are required in general. However, some strand melting cases show only slight damage due to an AC fault on the operating overhead transmission lines.

This paper presents a way to clarify the residual strength of conductors with slight melting damage by investigating the strength of conductor strands that have experienced AC short-circuit failure arcs on-site.

First, the relationship between the damage level and the residual tensile strength was investigated in a tensile test of damaged conductor strands. Then, it was clarified that there is a linear correlation between the melting depth and the residual tensile strength of strands. Next, the residual strength of strands with slight damage that can be found in a visual inspection was determined from tensile test data, and a method for calculating the residual tensile strength of the stranded conductor was derived by replacing the tensile strength of melted strands with their residual tensile strength.

The residual strength of the melted conductor calculated based on the visual inspection correlates well with the tensile test results of the residual tensile strength of the melted conductors. This method of estimating the residual strength in a visual inspection has made it possible to estimate the residual tensile strength with high accuracy.

The new method clarified the residual strength of slightly melted damaged conductors, encouraged the application of simple repair methods for them, and led to lower maintenance costs. This method is also applicable to electrical damage (lightning damage and so on) not only to AC fault arc.

KEYWORDS

AC - Melt - Residual - Conductor - Strand - Tensile Strength - Repair - Armor Rod

1. Background and purpose

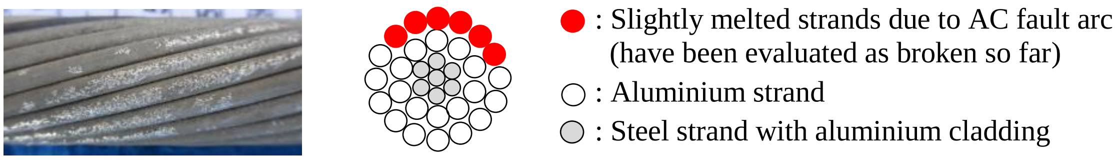
Some strands of conductor for overhead transmission lines passing through various environments are sometimes melted by an AC fault arc due to a short-circuit fault caused by galloping or sleet jump with ice/snow accretion. The tensile strength of the melted conductor is weakened due to a decrease in cross-sectional area and heating. This strength degradation can be estimated based on the residual strength of the conductor evaluated in several arc tests [1][2]. These reports only show broken level of strands, and therefore melted strands in a conventional internal rule are evaluated as being completely broken regardless of the level of melted damage. This evaluation method is not suitable for applying a simple repair method [3][4] such as an armor-rod for slight damage to conductor strands. The melted conductor in real operating conditions is often only slightly damaged, like arc spots that are spread over a wide area on the surface rather than spot damage as in laboratory tests. As a result, the residual performance of the conductor may be underestimated in deciding whether or not to replace it. For this reason, it is necessary to evaluate the residual tensile strength of strands with minor melted damage to determine an appropriate repair method. To deal with this requirment, we have developed a method for visually estimating the residual strength of a conductor by evaluating the relationship between the damage level in a visual inspection and the mechanical residual performance of the conductor that has melted due to AC short-circuit fault arcs. In addition, this evaluation method expanded the level of damage to which a simple conductor repair with an armor-rod can be applied, and made it possible to reduce the repair costs.

2. Evaluation target and test method

(1) Conductors to be evaluated
Short-circuit faults resulting from ice or snow accretion occur mainly on transmission lines of 77 kV or less in our service area. Therefore, ACSR (aluminium conductor steel-reinforced) 80–610 mm^2, which is applied to transmission lines of 77 kV or less was selected as the evaluation target. The specimens are conductors that have been actually damaged by AC fault arcs (Table I). Although there is a difference in the production method of the steel core, it does not affect the evaluation because the evaluation target is damaged aluminum strands. Figure 1 shows an example of a damaged conductor. As shown in this figure, the damage caused by an AC fault arc in the field is sometimes found to be minor.

Table I Specimens

Conductor type and nominal aluminium area (mm^2)	Stranding and strand diameter (mm)		Age (years)
	Aluminium	Aluminium clad steel	
ACSR/AC 80	15/φ2.6	7/φ2.6	10
ACSR/AW 160	30/φ2.6	7/φ2.6	32
ACSR/AW 410	26/φ4.5	7/φ3.5	32
TACSR/AC 610	54/φ3.8	7/φ3.8	25



*White parts are the melted areas

Figure 1 An example of a conductor damaged by an AC fault arc (ACSR/AW 160 mm^2)

(2) Test method

The specimens collected on-site were evaluated in terms of their residual mechanical performance in the tests shown in Table II. The tests were carried out by disassembling the couductor into straighter strands. The tensile strength of the strands was measured with a tensile strength tester. The ductility characteristics of the strands with a regulation length (100 times the wire diameter) were measured with a twisting tester. As shown in Table I, the ages are different, and the initial strength in routine tests is unknown. Therefore, the tensile strength of the melted strands was estimated based on undamaged strands of the same conductor to determine mechanical performance.

Table II Test items for mechanical performance

Test items	Description
Tensile strength	The relationship between the damage level and the tensile strength of the melted strand was evaluated by measuring the molten area (width, length, depth) and doing a tensile strength test.
Ductility characteristics	The relationship between the damage level and the ductility characteristic of the melted strand was evaluated by measuring the molten area (width, length, depth) and doing a twisting test.

3. Test Results

(1) Tensile strength of the strands

Figure 2 shows an example of a damaged strand of a specimen. It is known that the tensile strength of the strand depends on the cross-sectional area. However, it is not easy to determine the cross-sectional area of the melted strand. Therefore, in order to simply index the damage level, the results of the strand tensile test were evaluated as parameters of “melt length”,“melt width” and “melt depth” respectively. When a short-circuit fault occurs, we can identify an approximate fault location using the fault location system by detecting electromagnetic change of installed sensors on towers, and detect the damaged area in visual inspection with a telescope or a drone. Therefore, if the residual tensile strength of the melted strand was well correlated with the damaged level, it makes easier to evaluate residual strength in a visual inspection. Table III shows the correlation coefficient (R^2) of the approximation for the damage level and residual strength for each strand. Figure 3 shows the tensile test results of the melted strands evaluated by each parameter. From Table III, it was confirmed that the residual tensile strength of the melted strand was well correlated with the melt depth. Figure 3 (c) shows that the deeper the melt depth, the lower the tensile strength, and the extent of strength degradation depends on each strand’s diameter.

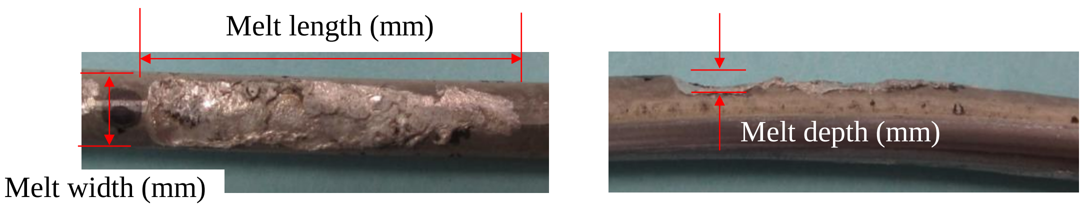


Figure 2 An example of a strand damaged by an AC fault arc

Table III Correlated variation of the relationship between damage level and tensile strength of the melted strands

Strand diameter (aluminium)	Coefficient of determination (R^2)		
	Melt length	Melt width	Melt depth
φ2.6mm	0.1572	0.2215	0.7526
φ3.8mm	0.1060	0.2690	0.2119
φ4.5mm	0.0788	0.2760	0.3492
Total strand diameter	0.0337	0.0424	0.6536

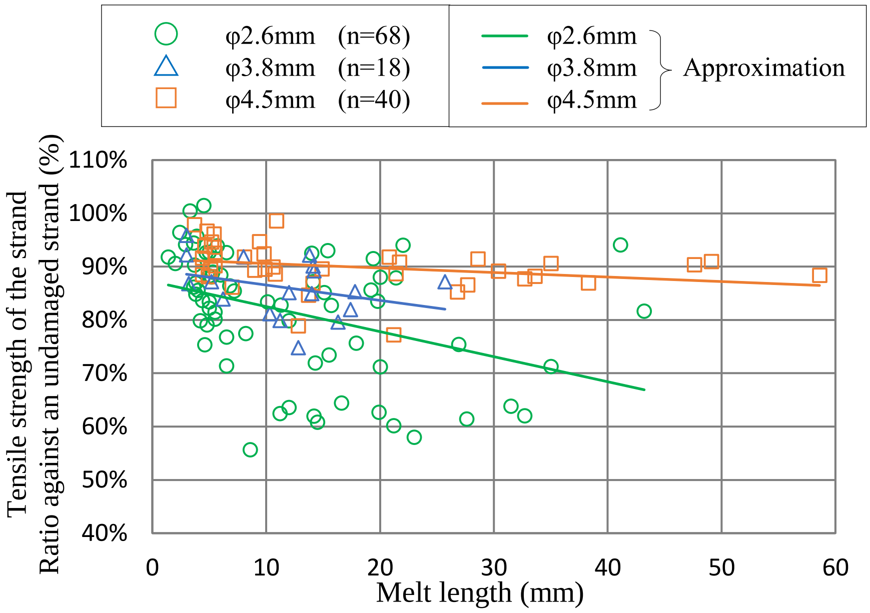


Figure 3 (a) Relationship between melt length and residual tensile strength of melted strands

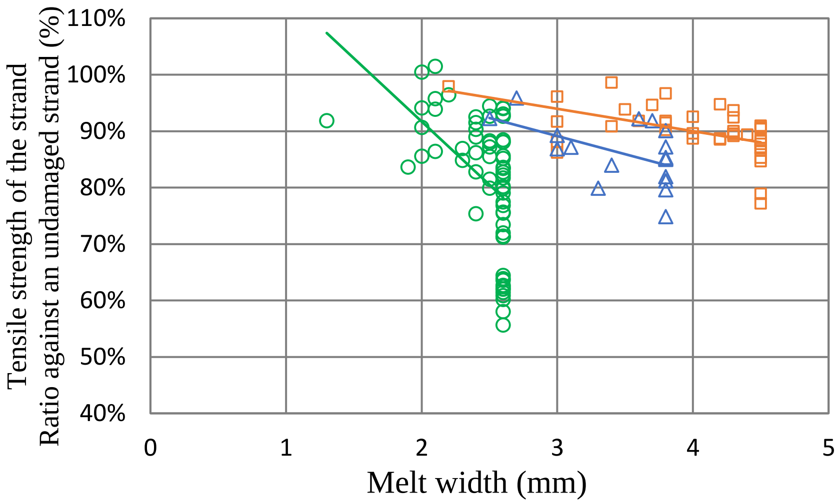


Figure 3 (b) Relationship between melt width and residual tensile strength of melted strands

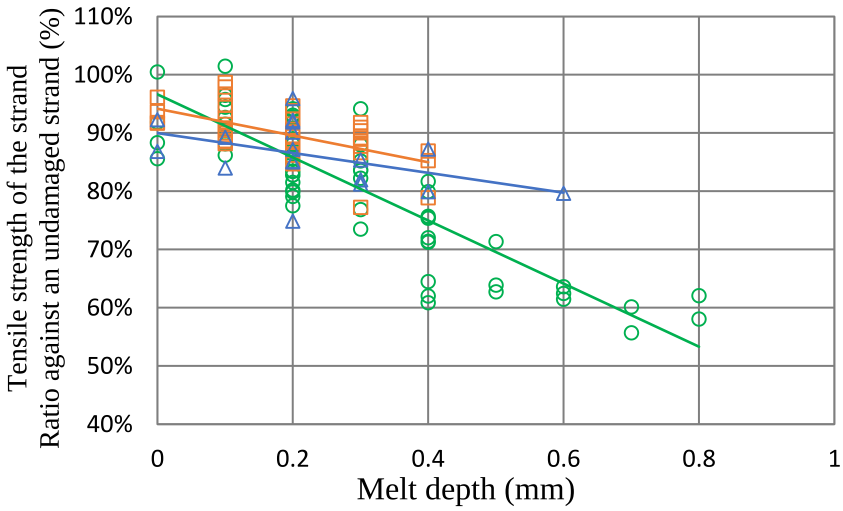


Figure 3 (c) Relationship between melt depth and residual tensile strength of melted strands

(2) Ductility characteristics of the strand
Figure 4 shows the ductility characteristics of the melted strands. The ductility characteristics were verified in a twisting test. The ductility performance decreases in proportion to the melt depth and the degradation level is large even with slight damage. Since a worsening of twisting characteristics lead to a worsening of fatigue characteristics, there is a fear that the melted strands could break due to long-term vibration fatigue regardless of the damage level without an appropriate repair. Therefore, the test result suggests that damaged strands should be evaluated carefully.

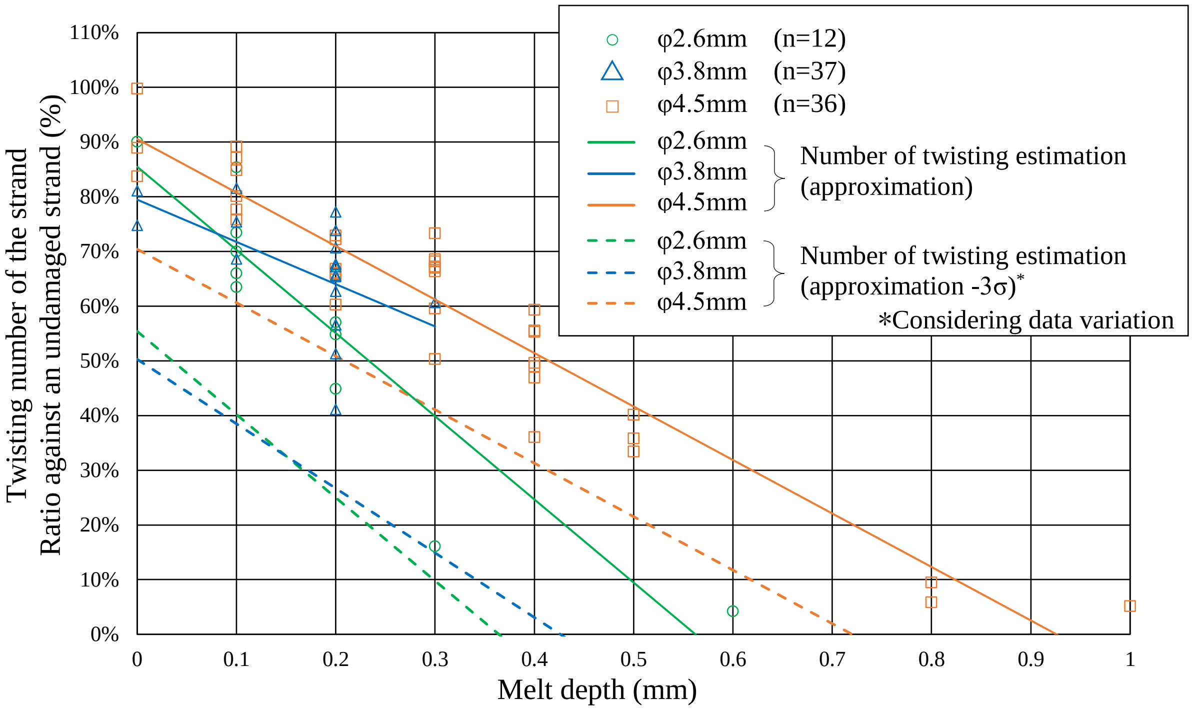


Figure 4 Ductility characteristics of the melted strand

4. Consideration on estimation of residual tensile strength in visual inspection

(1) Estimation of residual tensile strength of melted strands
In order to evaluate the residual tensile strength visually, it is necessary to measure the damage depth in a visual inspection on a live line. However, it is difficult to measure the melting depth of strands even in a visual inspection with a telescope or a drone in the field. Here, if the melting depth is not found even for damaged strands, it is deemed that there is certain residual tensile strength. The melt depth that was considered to not be recognized was set at 0.5 mm in considration of variations in visual inspection. The tensile strength with a melt depth of 0.5 mm was set at a value of approximately -3σ (σ: standard deviation) in consideration of the variations in the test as shown in Figure 5. Table IV shows the residual tensile strength of the melted strands summarized by strand diameter, and Figure 6 shows a comparison of the appearance of damage level. The results of the studies make it easier to evaluate residual strengh in a visual inspection.

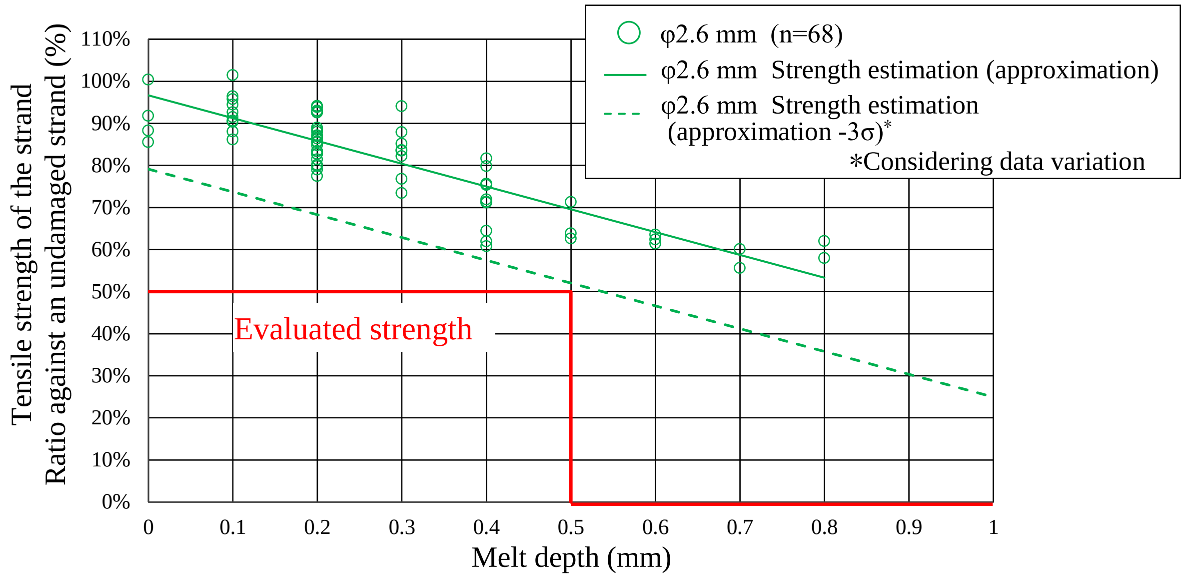


Figure 5 (a) Tensile strength of the melted strand (φ2.6 mm)

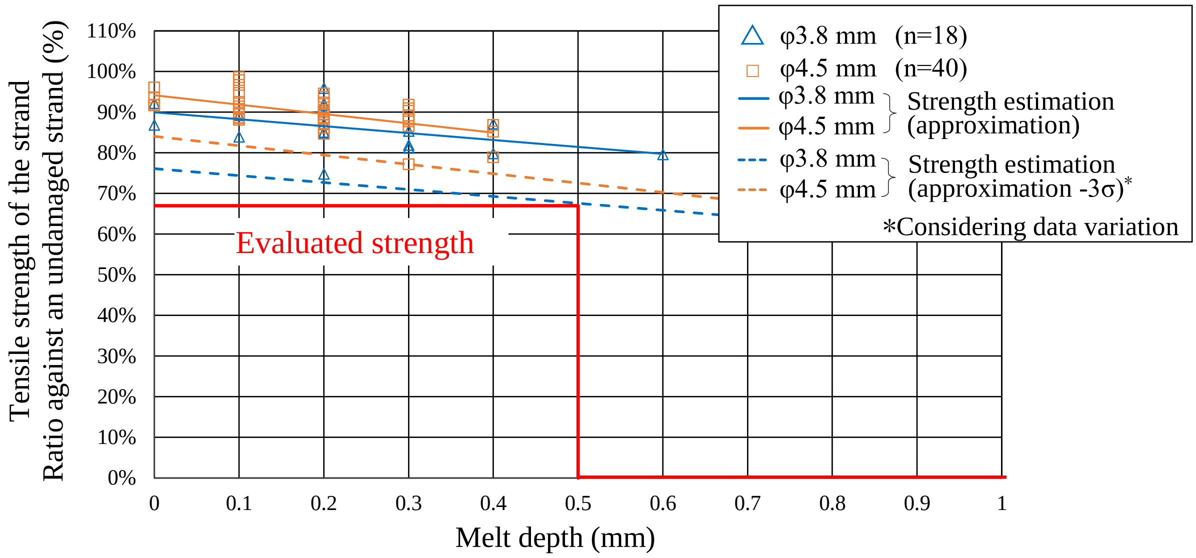


Figure 5 (b) Tensile strength of the melted strand (φ3.8 mm, φ4.5 mm)

Table IV Criterion for determining the residual strength of the melted strand

Damage level	Melt depth to estimate strength	Strand diameter	Evaluation of strength ratio	Number of strands evaluated as broken
Major	Depth > 0.5mm	All strand diameter	0%	1
Minor	Depth ≤ 0.5mm	Diameter < φ3.8mm	50%	1/2
		Diameter ≥ φ3.8mm	66%	1/3

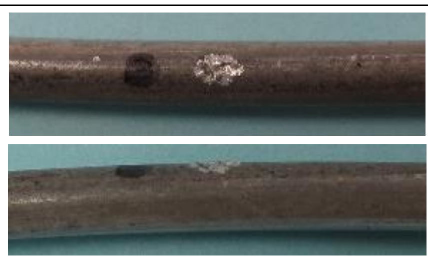
Melt depth	Major	Minor
State of melted strand		

Figure 6 Comparison of appearance of damage level

(2) Estimation of residual tensile strength of the stranded conductor

The residual strength of the conductor can be calculated by using the criterion in Table IV. However, the position of damage of each strand is not always on the same strand cross section. Therefore, the following two kinds of strength estimation methods were examined. Figure 7 shows the concept of estimating the residual strength.

Ⅰ. Counting the number of deemed broken strands in each melt cross section of damage area and determining the residual strength from the minimum strength cross section.
Ⅱ. Calculating the residual strength by excluding the sum of deemed broken strands within 1 pitch.

Table V shows a comparison of the residual strength estimated with the above methods and the results of testing tensile strength. As shown in the table, the calculated residual tensile strength of the strand generally agreed with the test results in both methods. However, in order to meet the strength required by safety regulations without fail, method Ⅱ which calculated the residual strength as being lower than the test results, was applied. ACSR/AC 80 mm^2 was excluded from the application of this evaluation method because the calculated residual tensile strength is overestimated compared with both methods. Small conductors have fewer strands than large ones. Therefore, it is considered that AC fault arc heating more greatly affects small conductors than large ones, and the residual strength becomes lower.

An example of evaluating a damaged conductor (ACSR/AC160 mm^2)

Method Ⅰ Equivalent number of broken strands：$\underbrace{1.0}_{\text{A (minimum strength section in damage area)}}$

Method Ⅱ Equivalent number of broken strands：$\underbrace{1}_{A} + \underbrace{1/2}_{B} + \underbrace{1/2}_{C} = \underbrace{2.0}_{\text{Sum of broken strands in 1 pitch}}$

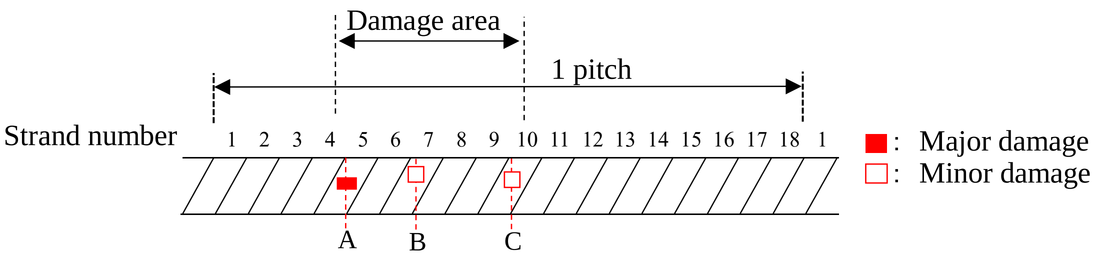


Figure 7 Concept of the estimating the residual strength

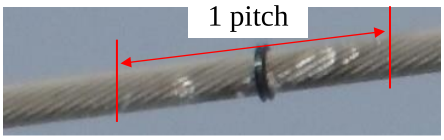
Table V Comparsion of methods to estimate tensile strength of a damaged stranded conductor

Conductor type	Test value	Estimated value			
		Method Ⅰ		Method Ⅱ	
	Strength	Strength (Comparison to test value)	Validity*	Strength (Comparison to test value)	Validity*
ACSR/AC 80 mm^2	36.2 kN	39.7 kN (+3.5kN)	×	36.3 kN (+0.1kN)	×
ACSR/AW 160 mm^2	76.5 kN	77.0 kN (+0.5kN)	×	68.2 kN (-8.3kN)	○
ACSR/AW 410 mm^2	144.5 kN	145.9 kN (+1.4kN)	×	133.2 kN (-11.3kN)	○

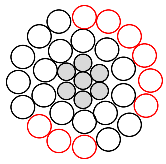
*○ : Test value ≥ Estimated value × : Test value < Estimated value

5. Evaluation of repair method for damaged conductor using new method

Figure 8 and Table VI show a comparison of the new method and the conventional method for estimating residual strength. In the conventional method, a strand is evaulated as broken even if there is only minor damage. On the other hand, according to the new method as shown in Table IV, minor damage to a strand is estimated to reduce the tensile strength by 1/3. Therefore, the equivalent number of broken strands is 20% or less of the total number, and a simple repair can be applied based on technical internal rules.



*White parts are melted areas



○: Slightly melted strands due to AC fault arc (minor damage)
○: Aluminium strand
○: Steel strand

Figure 8 An example of appearance of a damaged conductor for evaluating repair method (ACSR410 mm^2)

Table VI Comparison of repair methods (ACSR410 mm^2)

Category	Damage level	Number of strands evaluated as broken by damage level	Number of melted strands	Equivalent total number of broken strands	Repair methods*
Conventional method	Minor	1	9	9	Conductor replacement
New method	Minor	1/3	9	3	Repair with armor-rod

*Internal rule in a simple repair test with an armor-rod

･Equivalent number of broken strands is within 6 (within 20% of the total number of aluminium strands)
⇒ Repair with armor-rod

･Equivalent number of broken strands is 7 or more (over 20% of the total number of aluminium strands)
⇒ Replace conductor

･Total number of aluminium strands of ACSR 410 mm^2 is 26

6. Conclusion

This paper shows a simple method by which the residual tensile strength of an (T)ACSR that has melted due to an AC fault arc can be estimated by looking at the strand damage level in a visual inspection. The applicable conductor size for this method is 160 mm^2 and over (including conductors that are not specimen in this paper), and this method is also applicable to electrical damage (lightning damage and so on) not only to AC fault arc. The new method has achieved significant results such as paving the way for expanding simple repairs of damaged conductors and reducing the costs of replacing damaged conductors.

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