Experimental Analysis on Mechanical Properties of Aluminum Conductor Steel-reinforced for Transmission Line

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Abstract—Under the background of "carbon neutralization", the power transmission quality of power grid transmission lines becomes more and more important. This paper discusses the mechanical properties of aluminum conductor steel reinforced (ACSR), the main medium of electric energy transmission. This test simulates the real environment, takes the stress-strain curve and elastic modulus as the starting point, divides the test process into four stages, and compares the mechanical properties of the same conductor under different loads in detail. On this basis, the data difference and performance comparison of three different sections of ACSR are obtained. Finally, the commonness and difference of different cross-section conductors are analyzed, and the precautions in the test process are given. The conclusion of this paper can promote the quality improvement of power transmission conductors.

1. Introduction
With the proposal of the "carbon peak and carbon neutralization" strategic index policy, the vigorous era of clean energy has quietly opened. During the 14th Five Year Plan period, the substitution of electric energy should be driven by clean energy. Electric energy has the advantages of high efficiency, safety and convenience. Electric energy is used to replace the energy consumption mode of bulk burning coal and oil, such as electric heating, industrial electric boilers (kilns), agricultural electric drainage and irrigation, electric vehicles, shore power of berthing ships, airport bridge equipment, electric energy storage and peak shaving. It is an important measure to promote the goal of carbon neutrality.

In modern power grid, power transmission mainly depends on overhead lines, and the most important transmission medium in overhead lines is conductors. Wires are components used to conduct current and transmit electric energy. The conductor is often tested by various natural conditions in operation. It must have the characteristics of good conductivity, high mechanical strength, light weight, low price and strong corrosion resistance. As China is richer in aluminum resources than copper, and the price difference between aluminum and copper is large, ACSR is almost used [1].

Overhead conductors are connected with poles, towers and insulators through connecting fittings, which mainly bear the tensile load in the axial direction. The conductor is affected by the natural environment in the line, and the natural environment is bad, so it must bear external loads such as conductor self weight, wind load, icing and so on [2]. Due to the importance of transmission lines, the State Grid Corporation of China lists the quality sampling inspection of conductors as the focus of its
work every year. In order to obtain the complete mechanical properties of the conductor, the stress-strain curve and elastic modulus test need to be carried out [3]. The test is listed as a class a project by the State Grid. It simulates various environmental conditions that the conductor may withstand under real operation conditions. The most complete performance data of the conductor under real load conditions can be obtained through the test.

At present, the research on the stress and strain of conductor mainly focuses on the mechanical properties of single material [1] [4], the stress distribution between conductor strands [5-11] through finite element simulation, the stress between conductor layers [2] [12] through mathematical modeling, and the influence of Aeolian fatigue vibration on conductor characteristics [13-15]. The above research mainly depends on simulation software or mathematical modeling. Limited by test conditions, there is a general lack of real test data under long-time and large load.

In this paper, the products sampled from power grid materials are taken as physical samples. The test method is in strict accordance with the national standard GB/T 1179 and the national grid enterprise standard Q/GDW 13236.2. The real stress-strain curve and elastic modulus test are carried out in the detection center, the mechanical properties of ACSR with different sections are obtained, and the elastic modulus under different conditions is quantitatively analyzed.

2. Performance characteristics of ACSR

2.1. Structure of ACSR
ACSR is a composite conductor of aluminum and steel, which belongs to concentric lay stranded conductor. It is composed of multi-layer single wires spirally twisted around a central core, and the adjacent layers are twisted in the opposite direction. Taking the common ACSR model JL/g1a-240/30-24/7 in the material sampling inspection of the State Grid as an example, G1a represents ordinary strength steel wire, 240 represents the cross-sectional area of aluminum strand is approximately 240mm², 30 represents the cross-sectional area of steel core is approximately 30mm², and 24 represents the number of aluminum strands. In fact, it is composed of two layers, 9 in the inner layer, 15 in the outer layer, and 7 represents the number of steel cores. A real section is shown in Figure 1.

![Figure 1. ACSR with 240/30 section](image1)

![Figure 2. ACSR with 400/35 section](image2)

In power transmission lines, the cross-sections of conductors are different with different voltage levels. For example, JL/g1a-400/35-48/7 for higher voltage levels will increase its cross-sectional area, the number of aluminum wire layers and the number of wires per layer, as shown in Figure 2.

2.2. ACSR requirements for material procurement of State Grid Corporation
In order to ensure the quality of products connected to the grid, the State Grid Corporation of China has formulated special technical requirements for each type of materials and formed a series of enterprise standards. Among these technical requirements, several key items affecting the mechanical properties of the conductor are as follows.

- The aluminum wire shall be cold drawn aluminum wire for electrician. The cold drawn aluminum wire before stranding shall meet the bidding technical conditions and meet the requirements of GB/T 17048.
- The surface of the aluminum wire shall be smooth and free from all defects that may affect the performance of the product, such as cracks, roughness, scratches and impurities.

- The pitch diameter ratio of conductor shall be within the range specified in GB / T 1179. For conductors and aluminum stranded wires with only one layer of aluminum wire structure, the pitch diameter ratio of the outer layer shall not be greater than 14; For conductors with two or more layers of aluminum wire structure, the pitch diameter ratio of the outer layer shall not be greater than 12. The twist direction of adjacent layers shall be opposite, and the twist direction of the outer layer shall be right. For stranded wires with multiple layers, the pitch diameter ratio of any layer shall not be greater than that of the immediately adjacent inner layer.

- During stranding, the steel core of the conductor and the strand to be strangled shall be placed in the factory for a long enough time to ensure that the steel core and the strand to be strangled should be at the same temperature, and the same temperature should be maintained during the whole stranding process.

2.3. Test items of conductor

Material sampling inspection mainly includes sampling test and type test items.

Sampling test is to ensure that the quality of conductor and ground wire meets the requirements of procurement standards. The test samples shall be randomly selected from the batch. The sampling test items include single wire performance, cross-sectional area, outer diameter, linear density, surface condition, pitch diameter ratio and twist direction, DC resistance at 20 ℃ and strand breaking force, etc.

The type test is to check whether the performance of conductor and ground wire meets the design requirements. The type test shall be carried out in a quality inspection institution with corresponding qualification. The conductor type test items include single wire performance, rated tensile strength of stranded wire, elastic modulus, DC resistance, pitch diameter ratio, mass per unit length, stress-strain curve, creep curve, linear expansion coefficient, ampacity, fatigue performance, tightness and flatness, etc.

3. Test setup of stress-strain curve

3.1. Selection of test samples

Three kinds of cross-section ACSR commonly used in material sampling inspection(Figure 3) are selected, which are hereinafter referred to as sample 1, sample 2 and sample 3. Their models are JL / G1a 240 / 30-24 / 7, JL / g1a-300 / 40-24 / 7 and JL / g1a-400 / 35-48 / 7 respectively.

![Figure 3. ACSR for test](image1)

![Figure 4. Strain gauge with large deformation](image2)

The mechanical property parameters of the three samples are shown in Table 1.

| Sample | Number of galvanized steel wires / diameter (PCs. / mm) |
|--------|--------------------------------------------------------|
| 1      | 7/2.40                                                  |
| 2      | 7/2.66                                                  |
| 3      | 7/2.50                                                  |

Table 1. Comparison of key parameters of three different specifications of ACSR
3.2. Configuration of software and hardware

According to GB / T 1179-2008, the sample length shall not be less than 400 times of the outer diameter of the conductor and not less than 10m. Here, the maximum diameter of the sample is 26.8mm, 26.8mm * 400 = 10720mm, so 11m long sample is selected. Use a large deformation strain gauge (Fig. 4) with a length of 1m and place it in the middle of the sample. The strain gauge is 5m away from both ends. The strain gauge shall be fixed when the sample is in a natural state, that is, after the prestress is removed. The horizontal tensile machine with the maximum bearing capacity of 2000kN (Fig. 5) is used, and the nondestructive fixture is configured. The automatic test software is customized, which can automatically record the test process data (Fig. 6).

The formula of engineering stress and strain is:

\[
\sigma = \frac{P}{A_0}
\]

\[
\varepsilon = \frac{L - L_0}{L_0}
\]

In the above formula, P is the load, \(A_0\) is the original cross-sectional area of the sample, \(L\) is the length of the sample after deformation, and \(L_0\) is the original gauge length of the sample. The stress-strain curve is abbreviated as \(\sigma-\varepsilon\) Curve. When to strain \(\varepsilon\) is independent variable, stress \(\sigma\) When you draw a graph for a function, you get \(\sigma-\varepsilon\) Curve. Here, because the cross-sectional area is fixed and the gauge distance is 1m, it is also constant. In order to eliminate irrelevant interference and facilitate the comparison between different models, the load deformation curve is used to replace the stress-strain curve in this paper.

Slope \(\tan \alpha = \frac{P}{A_0}\) is the elastic modulus or young's modulus of the material. The elastic modulus reflects the deformation resistance of the conductor in the elastic stage.
3.3. Method and process
The initial load is 2% RTS (rated breaking force), which is used to straighten the conductor, remove the load after straightening, and then install the strain gauge without tension. For discontinuous stress-strain data records, take a strain reading every 2.5% RTS, in kN.

The experiment is divided into four stages. ① The load applied to 30% RTS shall be maintained for 0.5h. During the test, the readings shall be taken after 5, 10, 15 and 30min, and unloaded to the initial load. ② Reapply the load to 50% RTS for 1 h, take readings after 5, 10, 15, 30, 45 and 60min, and unload to the initial load. ③ Reapply the load to 70% RTS for 1 h, take readings after 5, 10, 15, 30, 45 and 60min, and unload to the initial load. ④ Reapply the load to 85% RTS for 1 h, take readings after 5, 10, 15, 30, 45 and 60 min, and unload to the initial load.

During the test, the load growth rate shall be uniform, and the time to reach 30% RTS shall not be less than 1 min nor more than 2 min. the same load growth rate shall be maintained throughout the test.

Applying a certain prestress can make the conductor obtain a straight initial state and prevent abnormal points at the beginning of the test. The significance of keeping it for a period of time is that it can simulate the mechanical properties of the conductor under continuous stress in the overhead line. When the wedge clamp is used for the test, the removal of load may loosen the grip of the wedge clamp. Therefore, in this case, the initial load of 2% RTS shall be maintained when the strain gauge is reset to zero.

4. Test Results and Discussions

4.1. Acquisition of load deformation curve
The load deformation test data of three samples are shown in Table 2.

|            | Sample 1 | Sample 2 | Sample 3 |
|------------|----------|----------|----------|
|            | 30%RTS   | 50%RTS   | 70%RTS   | 85%RTS   |
|            | 30%RTS   | 50%RTS   | 70%RTS   | 85%RTS   |
|            | 30%RTS   | 50%RTS   | 70%RTS   | 85%RTS   |
|            | 30%RTS   | 50%RTS   | 70%RTS   | 85%RTS   |

2.50% 0.09 0.51 1.05 1.59 0.48 0.71 1.16 2.02 0.05 0.2 0.71 1.35
5.00% 0.2 0.58 1.12 1.83 0.46 0.72 1.19 2.15 0.06 0.26 0.81 1.67
7.50% 0.3 0.67 1.21 2.08 0.5 0.76 1.24 2.25 0.1 0.33 0.87 1.88
10.00% 0.41 0.75 1.29 2.18 0.57 0.81 1.29 2.32 0.12 0.4 0.93 1.95
12.50% 0.51 0.84 1.38 2.27 0.65 0.87 1.36 2.39 0.15 0.48 1.01 2.03
15.00% 0.62 0.93 1.46 2.36 0.74 0.95 1.43 2.46 0.26 0.56 1.1 2.11
17.50% 0.74 1.02 1.55 2.44 0.83 1.02 1.51 2.54 0.38 0.64 1.18 2.2
20.00% 0.86 1.11 1.64 2.53 0.93 1.1 1.59 2.62 0.5 0.73 1.27 2.28
22.50% 0.96 1.2 1.73 2.63 1.03 1.19 1.68 2.71 0.61 0.81 1.36 2.37
25.00% 1.07 1.29 1.83 2.73 1.14 1.28 1.76 2.79 0.72 0.9 1.44 2.46
27.50% 1.2 1.39 1.92 2.82 1.26 1.37 1.85 2.88 0.84 0.98 1.53 2.55
30.00% 1.34 1.48 2.01 2.92 1.39 1.45 1.94 2.96 0.97 1.07 1.62 2.65
|        | 32.50% | 35.00% | 37.50% | 40.00% | 42.50% | 45.00% | 47.50% | 50.00% | 52.50% | 55.00% | 57.50% | 60.00% | 62.50% | 65.00% | 67.50% | 70.00% | 72.50% | 75.00% | 77.50% | 80.00% | 82.50% | 85.00% |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|        | 1.58   | 1.68   | 1.8    | 1.92   | 2.06   | 2.2    | 2.37   | 2.55   | 2.87   | 2.99   | 3.11   | 3.22   | 3.37   | 3.56   | 3.8    | 4.12   | 4.62   | 4.76   | 4.9    | 5.1    | 5.36   | 5.9    |
|        | 2.11   | 2.2    | 2.3    | 2.39   | 2.48   | 2.58   | 2.67   | 2.77   | 3.79   | 3.88   | 3.98   | 4.09   | 4.18   | 4.29   | 4.39   | 4.5   | 4.62   | 4.76   | 4.9    | 5.1    | 5.36   | 5.9    |
|        | 3.01   | 3.1    | 3.2    | 3.29   | 3.39   | 3.49   | 3.59   | 3.68   | 3.79   | 3.88   | 3.98   | 4.09   | 4.18   | 4.29   | 4.39   | 4.5   | 4.62   | 4.76   | 4.9    | 5.1    | 5.36   | 5.9    |
|        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|        | 1.54   | 1.65   | 1.77   | 1.89   | 2.01   | 2.15   | 2.31   | 2.51   | 2.79   | 2.97   | 3.11   | 3.25   | 3.42   | 3.62   | 3.82   | 4.13   | 4.62   | 4.76   | 4.9    | 5.1    | 5.36   | 5.9    |
|        | 2.02   | 2.12   | 2.21   | 2.3    | 2.4    | 2.5    | 2.59   | 2.68   | 3.79   | 3.88   | 3.97   | 4.07   | 4.17   | 4.27   | 4.36   | 4.47   | 4.58   | 4.65   | 4.79   | 4.99   | 5.22   | 5.62   |
|        | 3.05   | 3.14   | 3.23   | 3.32   | 3.41   | 3.5    | 3.59   | 3.69   | 3.78   | 3.88   | 3.97   | 4.07   | 4.17   | 4.27   | 4.36   | 4.47   | 4.58   | 4.65   | 4.79   | 4.99   | 5.22   | 5.62   |
|        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|        | 1.17   | 1.28   | 1.39   | 1.52   | 1.65   | 1.79   | 1.96   | 2.14   | 2.46   | 2.55   | 2.69   | 2.85   | 3.03   | 3.24   | 3.45   | 3.72   | 4.23   | 4.37   | 4.55   | 4.8    | 5.12   | 5.83   |
|        | 1.7    | 1.79   | 1.88   | 1.97   | 2.06   | 2.16   | 2.26   | 2.35   | 3.48   | 3.57   | 3.6   | 3.7    | 3.8    | 3.9    | 4      | 4.12   | 4.23   | 4.37   | 4.55   | 4.8    | 5.12   | 6.08   |
|        | 2.73   | 2.82   | 2.91   | 3.01   | 3.09   | 3.19   | 3.28   | 3.38   | 4.48   | 3.57   | 3.6    | 3.7    | 3.8    | 3.9    | 4      | 4.12   | 4.23   | 4.37   | 4.55   | 4.8    | 5.12   | 6.08   |
| 5min   | 1.41   | 1.44   | 1.45   | 1.45   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   | 1.46   |
| 10min  | 1.24   | 1.44   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   | 1.45   |
| 15min  | 1.03   | 1.04   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   | 1.05   |
| 30min  | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   | 0.82   |
|        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
According to Section 3.3, the test is divided into four stages, 30% RTS, 50% RTS, 70% RTs and 85% RTs. In each stage, several points will be obtained to obtain an independent load deformation curve. Taking sample 1 as an example, the load deformation curves of its four stages are shown in Fig. 7-10.

All points of the above four stages are depicted on a graph, which can represent the complete test process of nearly 4 hours, so as to obtain our target load deformation curve. The target load deformation curves of the three samples are shown in Figure 11-13 respectively.
4.2. Results and analysis

According to the test data and curves, the following conclusions are drawn:

(1) It can be seen from figure 7-10 that the deformation of the conductor will change after it is maintained for a period of time under a certain load. The change rate is different under different loads. The greater the load, the greater the change rate. The maximum change rate of deformation after holding for 1 hour at fourth stage (85% RTS) is close to 5%.

(2) It can be seen from figure 7-10 that the performance of the combined conductor is different from that of a single material. It is basically linear in the first and second stages, plastic deformation begins in the third stage, and yield begins in the fourth stage. After the third stage of force relief, the conductor is still elastic when it is stretched again.

(3) It can be seen from Fig. 11-13 that, different from the short-term tensile properties of a single material, after the ACSR is unloaded to the initial load (2% RTS), the sample does not return to the initial state, but has a certain amount of deformation, resulting in the right deviation of the starting point of the next stage in the graph. The maximum deformation of the previous stage is very close to the instantaneous deformation of the same load in the next stage. On the graph, these two points almost coincide. It seems that the curve of the latter stage intersects the curve of the previous stage. This intersection point indicates that the wire cannot remain elastic all the time, and local permanent deformation will occur.

(4) According to figure 11-13, the elastic modulus of the conductor at different stages can be calculated. When calculating the elastic modulus, select the appropriate starting point and end point. Due to the influence of compression joint, the curve is unstable in the initial stage, so the linear region of the curve is anchored here, and the starting point and end point of the linear region are selected to
calculate the elastic modulus. For example, for the first stage of sample 1, the elastic modulus \( E = \frac{(0.275-0.075)}{276} / (1.2-0.3) \times 10^5 = 80.5 \text{GPa} \). According to this method, the true elastic modulus of each sample at each stage is calculated successively, and the results are shown in Table 3.

### Table 3. Calculated elastic modulus of each sample at each phase

| Elastic modulus     | Sample 1 | Sample 2 | Sample 3 |
|---------------------|----------|----------|----------|
| Phase I (30.00% RTS)| 80.5     | 95.3     | 97.9     |
| Phase II (50.00% RTS)| 85.3    | 93.5     | 102.5    |
| Phase III (70.00% RTS)| 92.9    | 90.5     | 95.9     |
| Phase IV (85.00% RTS)| 90.0    | 94.7     | 96.6     |

It can be seen that the distribution range of the maximum elastic modulus of conductors with different sections is different. This is related to the cross-sectional area of the conductor, stranding process and raw material properties. The real deformation resistance needs to be determined according to the actual situation.

(5) By observing the graph of each sample in the fourth stage in Fig. 11-13, it can be found that there is an obvious fault in the graph of sample 2 and sample 3 in the fourth stage (85% RTS), that is, the load suddenly increases and the deformation remains unchanged, indicating that this stage has separated from yield, began to appear hardening and entered the strengthening stage. The relative change of sample 1 is not obvious.

(6) The deformation of sample 1 and sample 2 before the third stage is larger than that of sample 3, but it is exceeded by sample 3 in the fourth stage. It shows that the large section sample 3 has relatively strong deformation resistance in the elastic stage, but once its elasticity is destroyed, its performance is even weaker than that of the small section sample.

(7) The load deformation curve in the image does not pass through 0 point in the first stage, which is related to the crimping end. Here, several factors affecting the test are analyzed. First, the end shall be crimped with wedge-shaped wire clamp to ensure that the end is not loose and the conductor does not slip in the tensile and unloading stages, and prevent the fracture of the conductor at the end due to uneven stress. Second, different rated tensile breaking force and elastic modulus of aluminum and galvanized steel lead to relative displacement between steel core and aluminum strand, which will affect the overall mechanical properties.

### 5. Conclusion

This paper discusses the mechanical properties of ACSR, the main medium of electric energy transmission, in the test. A series of comparative tests were set up to simulate the real environment. The mechanical properties of ACSR under different loads and the performance differences of ACSR with different sections were analyzed in detail, and the complete curve of ACSR load deformation with time was given. The precautions in the test process are suggested. This paper can not only provide test method guidance for power grid conductor quality sampling inspection, but also provide data reference for transmission line fault analysis. At the same time, it can be used as the evaluation basis for bad suppliers and provide support for conductor bidding and selection.

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