Experimental Study of Round Steel Damage Caused by Lightning

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***Abstract*—The surface of round steel often suffers from serious ablation under direct lightning stroke. The change in the internal structure and mechanical property of round steel at the ablation point is a topic deserving of study. In this study, we performed a simulated lightning stroke test on the round steel samples using impulse current generator, and conducted a tension test and a metallographic analysis on the samples afterwards. We found that in comparison with short stroke, long stroke is the real main cause for internal structure change and mechanical property impairment of round steel at the ablation point. After long stroke, the tensile strength of the samples decreased by 7.86%-13.68%, and obvious lightning stroke features like pores and cracks were observed at the internal structure. Therefore, high temperature effect of arc discharge by lightning stroke may damage the structure of metallic material and influence the structure safety of buildings (structures) under the joint action of building (structures) load and other factors. The metallic damage features can be taken as hidden forms of lightning hazard, which must be given due academic concern and is worth of extensive study.**

Keywords- round steel; lightning stroke; damage; test

I. Introduction

Modern buildings are mostly made of reinforced concrete, steelwork and metal structure. When a building is struck by direct lightning, lightning current will discharge to the ground through building metals, causing minor personal injuries and equipment damages. But high temperature and impact induced by lightning arc may partially alter the mechanical property and internal structure of metallic material to some extent, thereby impairing the strength of metal structure and reducing building life [1-3].In this study, we performed a laboratory simulated lightning stroke test on metal material along with subsequent tension test and metallographic analysis [4-6] to investigate the influences of high temperature and impact induced by lightning arc discharge on metal material, which provides a reference for researches on safety and reliability of metal materials used in buildings that are vulnerable to lightning stroke.

II. Methodology

We performed a simulated lightning stroke test using impulse current testing system to examine the damages of metal material structure caused by lightning arc discharge; and then we conducted a tension test and a metallographic analysis to probe into the change of mechanical property and internal structure of metallic material associated with lightning stroke.

Pretreatment test – simulated lightning impulse test: perform laboratory simulated lightning stroke test on metallic material in two scenarios including short stroke and long time lightning.

Mechanical property test – tension test: perform tension test on the metallic material before and after the pretreatment test using an electronic tension tester and analyze the change of metal material’s tensile strength before and after the simulated lightning stroke test.

Metallographic analysis – study of lightning damages: conduct a metallographic analysis on the metal material after the pretreatment test using metallographic analytical system to examine the internal structure changes of the metal material before and after lightning stroke.

III. Test Information

A. Test Instruments and Equipment

1) Impulse Current Test System

For the purpose of simulated lightning stroke test, we employed the impulse current testy system developed by Chongqing Engineering Research Center of Lightning Disasters Identification and Prevention for pretreatment of the metal material sampled for this study. The test system can produce impulse current with 200kA amplitude and 8/20μs waveform and that with 20kA amplitude and 10/350μs waveform[7,8] as well as A+C component current waveform used to measure the direct impacts of lightning on structures. A+C component current waveform, that is the test waveform composed of initial peak current waveform (A component) + sustained current waveform (C component), was selected according to the definition of the waveform used for measuring the direct impacts on metal material structure prescribed in GJB3567-99 *Lightning Protection Qualification Test Techniques for Military Aircraft* [9] and the definition of the test waveform prescribed in GJB2639-96 *Lightning Protection of Military Aircraft* [10]. And the impulse current generator applied is shown in Fig. 1.

Figure 1. Impulse current generator

2) Electronic Tension Tester

The metal material properly pretreated for simulated lightning stroke test must go through mechanical property test to examine the change of its mechanical property after lightning stroke. And we used an electronic tension tester with a max. test force of 100kN, force measuring range of 2kN-100kN and beam travelling speed of 0.05-500mm/min for that purpose. The tension tester was connected to a computer so that test parameters can be calculated using system software, and such parameters as test force, displacement, peak value, running state, running velocity, test force range and tensile strength-displacement curve can be displayed clearly. The electronic tension tester is illustrated in Fig. 2.

Figure 2. Electronic tension tester

3) Metallographic Analytical System

Metallographic analysis must be conducted on the metal material properly pretreated for simulated lightning stroke test to investigate its internal structure change after lightning stroke. And we used metallographic analytical system for that purpose. The system consists of a cutting machine and a polishing machine for metallographic sample preparation, an electron microscope and analysis software. The cutting machine is equipped with a grinding wheel for cutting out metallographic specimen and a cooling installation for cooling down in cutting. The max cutting sectional area is 55mm × 55mm and rotational speed 2,860rad/min; the polishing machine is provided with two abrasive wheels and configured with two velocity slabs, having a diameter of 250mm and rotational speed 500/1,000 rad/min adjustable; and the electron microscope is of trinocular inverted type, with 30° inclination and 100-1,000× magnification. The metallographic analytical system is shown in Fig. 3.

Figure 3. Metallographic analytical system

B. Test Procedures

As stated in GB50057-2010 *Building Lightning Protection Design Code* [11] with respect to lightning current waveform, lightning stroke falls into two categories, one is short stroke (also known as initial component of lightning current) and the other is long stroke (also known as continuous component of lightning current). The waveforms of short stroke and long stroke are shown in Fig. 4. We performed the simulated lightning stroke test on the metal material under such two waveforms of lighting current respectively. Considering the engineering practice in Chongqing district, we selected Φ12mm galvanized round steel as metal material for the test, the steel specifications summarized in Table I. In the test, we mounted the galvanized round steel samples cut into 1m long strips horizontally onto the test stand of the impulse current generator, with the trigger carbon rod positioned perpendicular to and at the center of the samples. See Fig. 5 for test schematic diagram and Fig. 6 for site layout. After the simulated lightning stroke test, allow the round steel samples to cool down to room temperature and then conduct a tension test to examine the change of their tensile strength. Select the initial tensile strength of round steel without any pretreatment as control parameter, and take cross-cut sections of the pretreated round steel samples for observing their internal structures under microscope.

According to lightning location data 2008-2012 of Chongqing, the average strength and frequency of negative lightning discharges were -38.3kA and 96.6% respectively. So we selected negative impulse current with 40kA amplitude for 13 groups of simulated short lightning stroke test. Later, we carried out 12 groups of long stroke test by imposing quantity of electric charge varying from 49C to 212C on the samples.

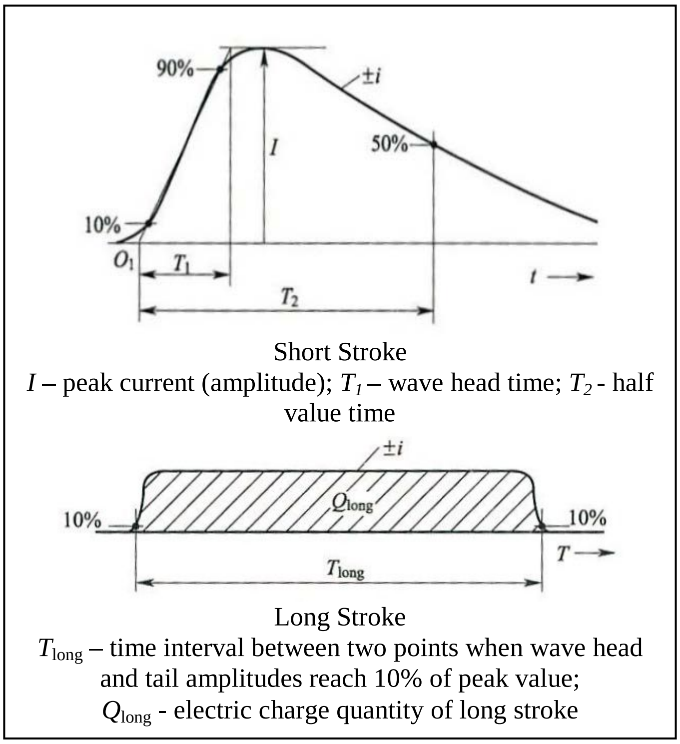


Figure 4. Short stroke (typical value T2<2ms) and long stroke (typical value 2ms<Tlong<1s)

TABLE I. ROUND STEEL SPECIFICATIONS

Hot-rolled round steel bar	Grade	HRB335
	Nominal diameter	12mm
Chemical composition %	C	0.17
	S_i	0.42
	M_n	1.21
	P	0.045
	S	0.045
	Carbon equivalent C_{eq}	0.38
Mechanical property	Yield strength R_{eL} N/mm^2	365
	Tension strength R_m N/mm^2	380

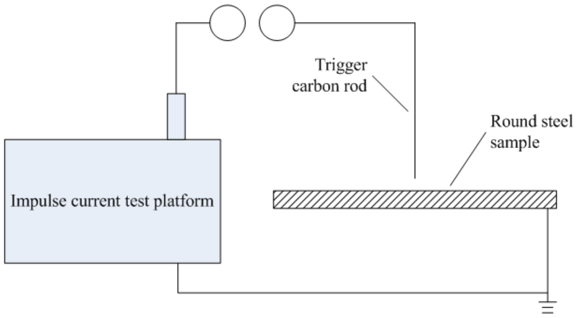


Figure 5. Schematic diagram of simulated lightning stroke test

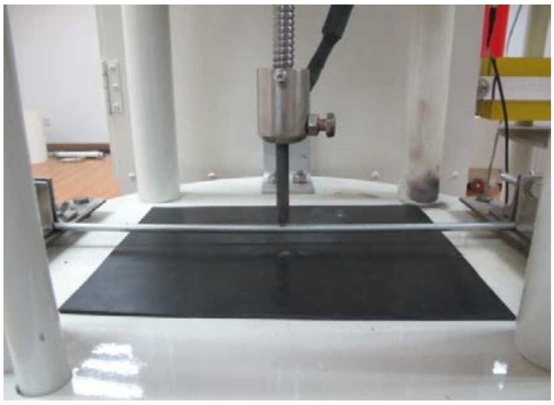


Figure 6. Test site layout

C. *Test Results*

1) *Tension Test*

The results and analysis of tension test following the simulated lightning stroke test are summarized in Tables II & III and Fig. 7-11. The figure inserted in each sample number as shown in Table II denotes the number of lightning stroke on the sample. For example, A0 indicates the sample was struck by 0 lighting stroke, namely it was an untreated round steel; and A18 indicates that sample was struck by 18 lightning strokes. We selected 13 samples with different numbers of lightning stroke for the short stroke scenario.

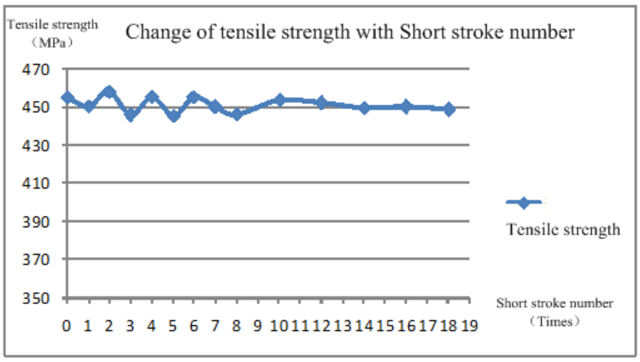


Figure 7. Short stroke test results

TABLE II. SHORT STROKE TEST RESULTS

Sample	Tension strength R_m/MPa	Short stroke parameters	Description	Remarks
A0	455.640	/	Untreated round steel	/
A1	450.441	NEG, 40kA	1 short stroke	Breakpoint ≠ lightning strike point
A2	458.439	NEG, 40kA	2 short strokes	Breakpoint ≠ lightning strike point
A3	445.971	NEG, 40kA	3 short strokes	Breakpoint ≠ lightning strike point
A4	455.301	NEG, 40kA	4 short strokes	Breakpoint ≠ lightning strike point
A5	445.462	NEG, 40kA	5 short strokes	Breakpoint ≠ lightning strike point
A6	445.182	NEG, 40kA	6 short strokes	Breakpoint ≠ lightning strike point
A7	450.231	NEG, 40kA	7 short strokes	Breakpoint ≠ lightning strike point
A8	446.209	NEG, 40kA	8 short strokes	Breakpoint ≠ lightning strike point
A10	453.842	NEG, 40kA	10 short strokes	Breakpoint ≠ lightning strike point
A12	452.316	NEG, 40kA	12 short strokes	Breakpoint ≠ lightning strike point
A14	449.678	NEG, 40kA	14 short strokes	Breakpoint ≠ lightning strike point
A16	450.102	NEG, 40kA	16 short strokes	Breakpoint ≠ lightning strike point
A18	448.668	NEG, 40kA	18 short strokes	Breakpoint ≠ lightning strike point

As shown in Fig. 7, the ordinate value of X_0 stands for the initial tensile strength of the round steel; the rate of tensile strength change in the round steel subject to varying short strokes was lower than 2.12%. So we can conclude that the tensile strength of the galvanized round steel was not affected by short stroke within the permissible range of tensile strength error. We also noted in the tension test that the breakpoints of round steel struck by short stroke were distributed randomly throughout the steel instead of coinciding with the lightning strike point. As illustrated in Fig. 8, the red circles denote lightning strike points, while the black ones denote breakpoints of tension test. The round steel samples were struck by more short strokes from left to right; despite of that, the breakpoints still did not coincide with the lightning strike points. It suggests that short stroke only causes damage to the zinc coating on the round steel surface but not any structural damage to the steel. In the contrast, the breakpoints on the round steel struck by long stroke coincided with lightning strike points, as shown in Fig. 9, indicating that long stroke would cause damage to steel structure.

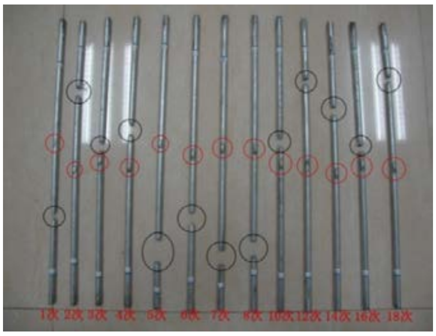


Figure 8. Results of tension test following short stroke

Figure 9. Comparison of tension test results following short stroke and long stroke

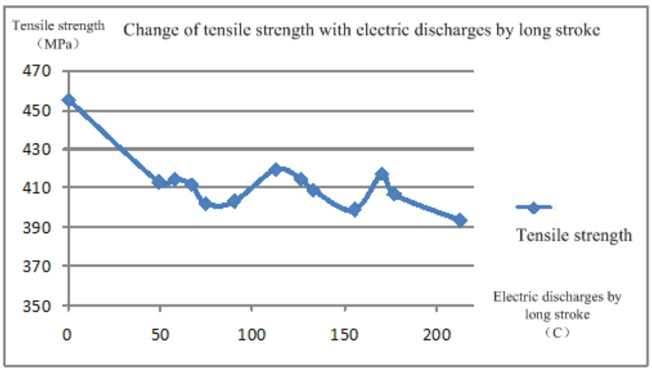


Figure 10. Long stroke test results

TABLE III. LONG STROKE TEST RESULTS

Sample	Tension strength R_m/MPa	Long stroke parameters	Description	Remarks
A0	455.640	/	Untreated round steel	/
AC1	412.977	49C	1 long stroke	Breakpoint ≠ lightning strike point
AC2	414.673	58C	1 long stroke	Breakpoint ≠ lightning strike point
AC3	412.129	67C	1 long stroke	Breakpoint = lightning strike point
AC4	402.290	74C	1 long stroke	Breakpoint = lightning strike point
AC5	403.138	90C	1 long stroke	Breakpoint = lightning strike point
AC6	419.847	112C	1 long stroke	Breakpoint = lightning strike point
AC7	415.013	126C	1 long stroke	Breakpoint = lightning strike point
AC8	409.160	133C	1 long stroke	Breakpoint = lightning strike point
AC9	398.897	155C	1 long stroke	Breakpoint = lightning strike point
AC10	417.812	170C	1 long stroke	Breakpoint = lightning strike point
AC11	406.870	177C	1 long stroke	Breakpoint = lightning strike point
AC12	393.299	212C	1 long stroke	Breakpoint = lightning strike point

As shown in Fig. 10, the ordinate value of X_0 stands for the initial tensile strength of the round steel; and the tensile strength changed after application of long stroke current with varying quantities of electric discharge. As can be seen from Table III and Fig. 10, the tensile strength of the galvanized round steel after application of long stroke current decreased by 7.86%-13.68%. The test results showed that the breakpoints of tension test did not coincide with lightning strike points when a small quantity of electric discharges were applied; but when the electric discharges added up to a certain level, the breakpoints coincided with the points of strike, as illustrated in Fig. 11. As shown in Fig. 11, the red circles stand for lightning strike points, and more electric discharges of long stroke were applied on the round steel samples from left to right. When 49C and 58C electric discharges were applied on the round steel, the breakpoints did not coincide with the lightning strike points; when 67C and higher electric discharges were applied, the breakpoints coincided with the lightning strike points.

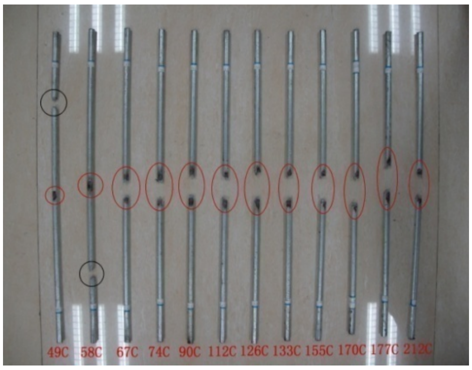


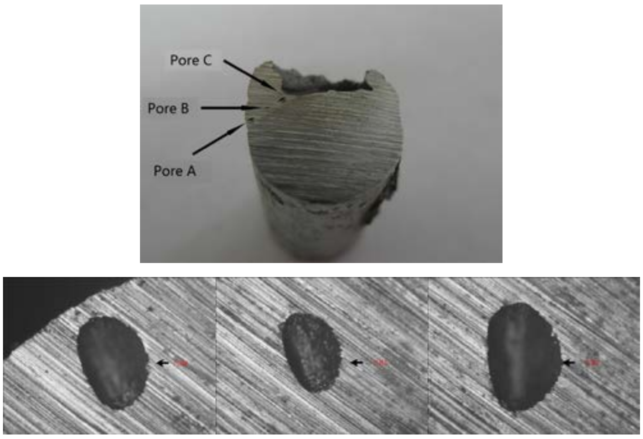
Figure 11. Breakpoints of tension test coincided with light strike points when electric discharges of long stroke added up to a certain level

2) Metallographic Analysis

We conducted metallographic analysis respectively on the round steel samples struck by short and long strokes by taking the vertically cut-out and polished sections of round steel for observing their internal structures under electron microscope. The analysis results showed that short stroke only impaired the zinc coating on the surface of the metal material but not the internal structure. In the contrast, long stroke caused ablation-induced craters (as shown in Fig. 12) on the surface along with pores and cracks (as shown in Fig. 13 and Fig. 14) on the internal structure of the metal material. The reason is that in the course of arc discharge by long stroke, the surface of metal heats up and melts under the action of arc, forming a liquid molten bath that triggers intensive evaporation or ejection of metallics. The metallic vapour ejects from the surface of metal parts at a certain rate, and craters are created on the surface of metal parts at the end of arc discharge by long stroke. Meanwhile, the metal parts melt down at the points of strike under the action of heat generated by lightning arc. When in cooling crystallization of molten metal, some gases fail to escape timely and then stay in the solidification zone of craters formed by molten metal, thereby pores are created on the surface of metal. Besides, the generation and termination of lightning arc discharge results in drastic change of temperature within the arc thermofusion zone (incl. solidification zone and partial heat affected zone), thus causing cracks on the internal structure of metal. Fig. 15 illustrates the craters, pores and cracks formed on the metal under the action of long stroke. Increasingly lowering cross sectional area of metal in the craters leads to narrowing of the stress surface, and the compactness of the metal internal structure is damaged under the presence of pores and cracks, all of which operate to impair the mechanical property of the metal material.

Short Stroke Long Stroke

Figure 12. Comparison of damages occurred to galvanized round steel (Φ12mm) surface under short stroke and long stroke



Pore A Pore B Pore C

Figure 13. Pores created on cross section of lightning strike point (under 100× magnification)

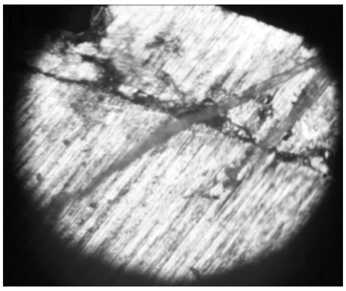


Figure 14. Cracks observed on cross section of lightning strike point at high-tensile steel wires (Φ8mm) of bridge cable (under 100× magnification)

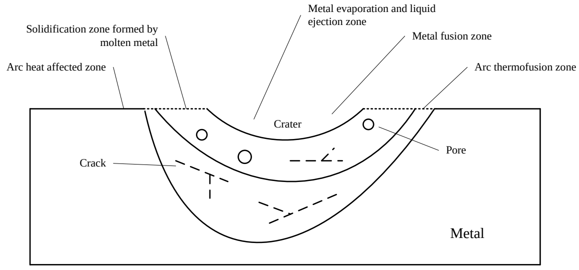


Figure 15. Schematic diagram of craters, pores and cracks created on metal under action of long stroke

IV. CONCLUSIONS

We find through test that: a) in comparison with short stroke, long stroke is the real main cause for damage of metal material; b) arc discharges by long stroke causes metal damages by creating craters on the surface along with pores and cracks on the internal structure; c) the mechanical property of metal material is impaired under the presence of craters, pores and cracks created by long stroke, as evidenced by reduction of tensile strength by 7.86%-13.68%; d) the impairment of mechanical property of steel bars under the action of long stroke is a safety hazard for the buildings made of steelwork.

REFERENCES

[1] A . Rousseau, L. Boutillon, A. Huynh, “Lightning Protection of a Cable-Stayed Bridge” C. 28th International Conference on Lightning Protection, 2006, pp. 1410-1413.

[2] Liang-fu LI. “Lightning Arc Discharge and Its Damage Mechanism” M. Beijing: China Meteorological Press, 2014.

[3] Xiang MI, Zhong-nan XIAO et al. “Analysis of lightning stroke test on bridge cables” J. Municipal Engineering Technology, 2014, 32(4), pp. 59-62.

[4] Bin WANG. “Mechanical Property Test” M. Beijing: China Metrology Publishing House, 2008.

[5] Hong-wei CAI. “Metallographic Test” M. Beijing: China Metrology Publishing House, 2008.

[6] Lan WANG, Ping YANG, Chang-rong LI. “Metallographic Test Technologies” M. Beijing: Metallurgical Industry Press, 2010.

[7] Protection Against Lightning –Part 3: Physical Damage to Structures and Life Hazard S. IEC 62305-3.

[8] Lightning Protection System Components (LPSC) –Part 2: Requirements for Conductors and Earth Electrodes. IEC 62561-2.

[9] Hefei Hangtai Electrophysics Institute, AVIC Research Institute 301, China Flight Test Establishment et al. GJB 3567-1999 Lightning Protection Qualification Test Techniques for Military Aircraft S. Beijing: Standard Press of China, 1999.

[10] AVIC China Flight Test Establishment, AVIC Research Institute 301, PLA Air Force No. 1 Aviation University. GJB2639-1996 Lightning Protection of Military Aircraft S. Beijing: Standard Press of China, 1996.

[11] China Machinery Industry Federation. GB50057-2010 Design Code for Protection of Structures against Lightning S. Beijing: China Planning Press, 2011.