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Characteristics of Downward Lightning Return Strokes Occurring on Tall Structures with Different Heights

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Abstract—*Observations for 58 natural downward negative lightning flashes with confirmed grounding points were analyzed in this paper to study the difference between the characteristics of negative lightning return strokes occurring on tall structures with different heights. The results show that the averaged difference of the number of strokes per flash and the inter-stroke intervals between the flashes occurring on structures taller than 200 m and those lower than 200 m is not obvious. But the peak currents, the 10-90% rise times and the widths from the 10% wave front to the 50% waveform tail of the optical pulses, induced by the lightning strokes occurring on structures taller than 200 m is much larger than those lower than 200 m. Futhermore, the difference between structures with different heights seem to be more significant for the first strokes rather than the subsequent strokes.*

.Keywords- downward lightning flash; tall structure; characteristics of return stroke; luminosity pulse

I. INTRODUCTION

With the development of metropolises, more and more high buildings are growing. Tall structures suffer higher probability of lightning stroke than the normal structure. The characteristics of lightning occurring on tall structures have caused extensive concerns [1-2].

Different research groups have carried out the lightning observation experiments for different tall structures in different countries for a long time [3-5]. The lightning current and the lightning electromagnetic pulse (LEMP) waveforms were measured, and the influence of tall structures on the lightning current and also the LEMP are being revealed gradually. However, most of the experiments mentioned above only focus on one tall structure, and the comparison of lightning occurring on structures with different heights in the same area are rare.

Since 2009, a Tall-Object Lightning Observatory in Guangzhou (TOLOG) was set up to get the simultaneous optical and electromagnetic observation data with high resolution for lightning occurring on the tall structures in zhujiang New Town (the central business district of Guangzhou city) [6]. In this paper, the return stroke number, the inter-stoke interval, the peak current and also the waveform of return stroke luminosity pulse for lightning return strokes occurring on tall structures with different heights are compared and analyzed, based on the observations of 58 natural downward negative lightning flashes with confirmed grounding points observed by TOLOG during 2009-2012 as well as the corresponding lightning location system records, to study the differences between the characteristics of lightning return strokes occurring on tall structures with different heights, and the difference between the influence of tall structure on the first stroke and those of the subsequent stroke are also compared.

II. FIELD EXPERIMENT AND OBSERVATION DATA

The TOLOG is situated at the top of a Building of Guangdong Meteorological Bureau (about 100m over the ground). The Zhujiang New Town lies about 2-3 km to the south-east of the observation room. Within the view of observation equipment, the International Financial Centre (with a height of 440 m) and CANTON Tower (with a height of 600 m) as well as many tall structures are included. The main observation equipments included Lightning Attachment Process Observation System (LAPOS), high-speed camera (FASTCOM SA-5, frame rate>1000fps, recording length≥1 s, pre-trigger length=20%), fast and slow electrical field change antenna, wide-band magnetic antenna, thunder acoustics recording system, etc. An oscilloscope (Yokogawa Model DL-750) was used as the primary recording system (sampling rate: 10 MHz, recording length ≥1 s, pre-trigger length=20%) to synchronously record LAPOS, electrical field change antenna, wide-band magnetic antenna, and GPS pulses per second （PPS）. The LAPOS consists of a camera, an optical fiber array, multiple photodiodes and their amplifiers. The fiber array is mounted at the camera's film plane. When a lightning occurs in the view of camera, its image formed by the camera lens is first guided by the optical fibers to the photodiodes. The spectral response of the photodiode systems is centered at 800 nm [7]. Then the output from the photodiodes is recorded by the DL-750 oscilloscope. When the DL-750 oscilloscope is triggered, it will out put trigger signal to high speed cameras, a portable oscilloscope (sampling rate: 100 kHz, recording length =35 s, pre-trigger length=14%) recording the thunder acoustical signal, and also to a GPS module which could stamp the trigger time with precision<50 ns. During 2009-2012, at least one high speed camera was set with sampling rate greater than 1,000 frames per second and recording length greater than 1 second, which could provide optical evidence with sufficient temporal resolution and duration for comparison with LLS data.

By the aid of the high speed camera records, it is convenient to classify the lightning flashes as upward or downward type. Only the downward negative lightning flashes are concerned in this paper. A total of 58 natural downward negative lightning flashes (containing 166 return strokes) occurring on 25 structures with a height ranged from 25-600 m were observed by TOLOG from 2009-06-25 to 2012-08-13.

Within the heights of the grounding points of the 58 lightning flashes, 3 ones are below 50 m, 31 ones are within a range from 90-200 m, and 24 ones are within a range from 300-600 m. Fig 1 shows the distribution of the 25 structures. In Fig1, the star signs indicate the structures with a height below 200 m, and the tower signs indicate those above 200 m. Table 1 gives the number of lightning flashes occurred on each structure showed in Fig1. Considering the distribution of the heights of the structures in the view of TOLOG and also the definition of electrically-tall structure concerning the lightning current flowing through the structure [8], we will separate the 58 lightning flashes into two groups. Group 1 is for the lightning flashes with grounding points below 200 m, and group 2 is for those above 200 m.

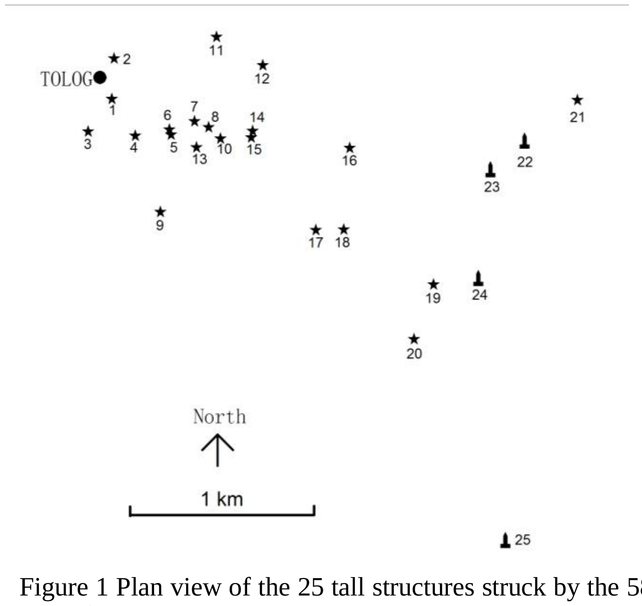

Figure 1 Plan view of the 25 tall structures struck by the 58 lightning flashes.

Table 1 Number of lightning flashes occurring on each tall structure

Order of structure	Height of structure /m	Number of flashes
1	35	1
2	115	2
3	35	1
4	110	3
5	25	1
6	90	2
7	145	3
8	100	2
9	120	1
10	100	1
11	110	1
12	105	1
13	140	1
14	105	4
15	100	1
16	140	3
17	105	1
18	160	2
19	90	1
20	140	1
21	160	1
22	340	2
23	360	6
24	440	8
25	600	8

III. STATISTICS FOR PARAMETERS OF RETURN STROKES

A. *Number of strokes per flash*

The number of strokes per flash (N_s) indicates the number of the strokes contained in one lightning flash. The N_s can be confirmed for 55 out of the 58 lightning flashes, and 3 lightning flashes could not be confirmed by far. Within the 55 lightning flashes, 33 flashes are belong to group 1, and 22 are belong to group 2. Fig 2 indicates the distribution of the N_s for group 1 and group 2.

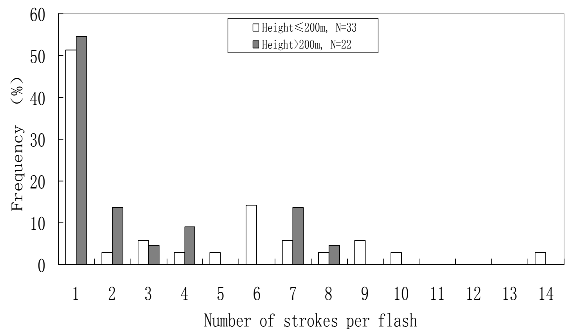

Figure 2 Distribution of N_s

The N_s are found to be ranged from 1～14 with a arithmetical mean(AM) value of 3.7 for group 1, and 1～8 with a AM value of 2.6 for group 2. The probability of single stroke lightning is found to be 51% for group 1 and 55% for group 2. In a whole, the mean N_s of group 1 is slightly higher than that of group 2.

B. Inter-stroke interval.

Inter-stroke interval (T_{int}) indicates the time interval between two sequential return strokes in one lightning flash. 25 out of the 55 lightning flashes are found to be multi-strokes lightning flashes. There are 15 multi-strokes lightning flashes (containing 95 strokes) are belong to group 1, and the other 10 ones (containing 41 strokes)are belong to group 2. Fig 3 indicates the distribution of the Tint for group 1 and group 2.

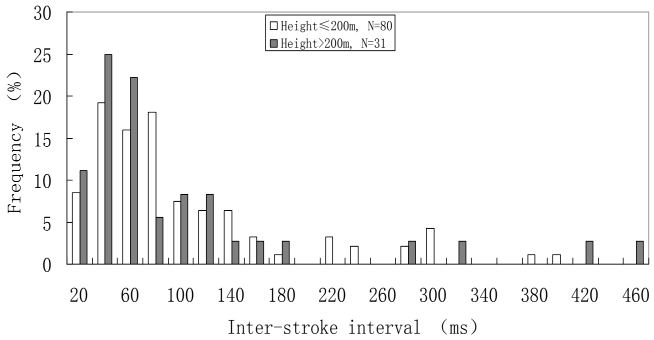

Figure 3 Distribution of T_{int}

The T_{int} are found to be ranged from 4～392 ms with a AM value of 95 ms for group 1, and 11-446 ms with a AM value of 94 ms for group 2. The geometrical mean(GM) value is 66 ms for group 1, while 57 ms for group 2.

C. Peak current of return stroke

Due to the fact that the peak current of return stroke (I_{peak}) are practically difficult to measure directly. The records of the lightning location system of Guangdong Power Grid (GDLLS) are used instead in this paper. Chen et al evaluated the performance characteristics of GDLLS based on the observation obtained during the 2007-2011 triggered lightning experiment, and found that the AM value of the absolute percentage errors of I_{peak} estimation was about 16.3% [9]. Note that the I_{peak} from LLS data for tall-tower strikes can be affected by the height and the geometry of the stricken object, but no correction is taken into account in this paper yet.

For group 1, there are 30 first strokes were detected by GDLLS, and the I_{peak} were found to be ranged from -13.8～-320.1kA with a AM (GM) value of -57.9 (-43.8) kA. For group 2, there are 24 first strokes were detected by GDLLS, and the I_{peak} were found to be ranged from -31.6～-234.8 kA with a AM (GM) value of -104.3 (-92.9) kA. The distribution of I_{peak} is shown in Fig 4.

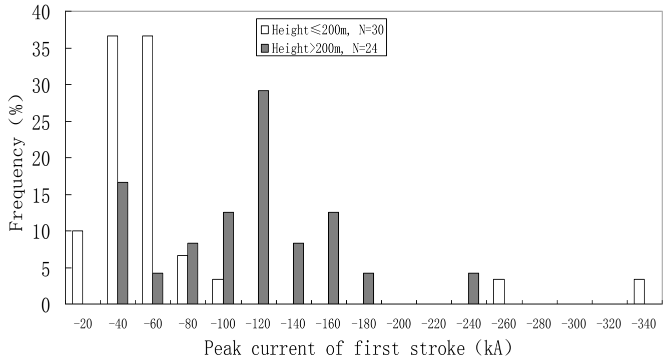

Figure 4 Distribution of I_{peak} for the first strokes

For group 1, there are 68 subsequent strokes were detected by GDLLS, and the I_{peak} were found to be ranged from -12.5～-98.6 kA with a AM (GM) value of -34.1 (-30.8) kA. For group 2, there are 32 subsequent strokes were detected by GDLLS, and the I_{peak} were found to be ranged from -12.9～-151.4 kA with a AM (GM) value of -50.1 (-42.6) kA. The distribution of I_{peak} is shown in Fig 5.

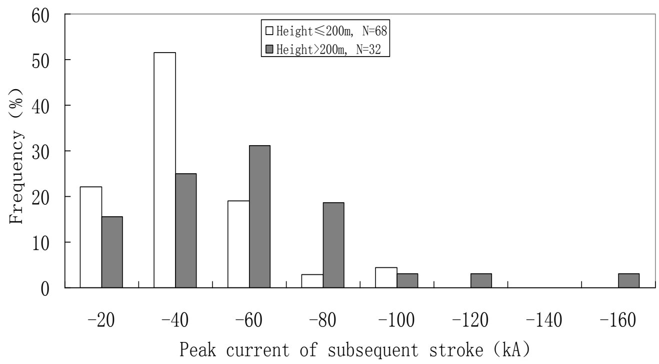

Figure 5 Distribution of I_{peak} for the subsequent strokes

D. luminosity pulse waveform of return stroke

In this paper, we define T_1 as the 10-90% rise time, and T_2 as the widths from the 10% wave front to the 50% wave tail of the lightning return stroke luminosity pulses observed by the LAPOS. Fig 6 shows the illustration for the waveform parameters of luminosity pulse induced by a downward single-stroke lightning return stroke.

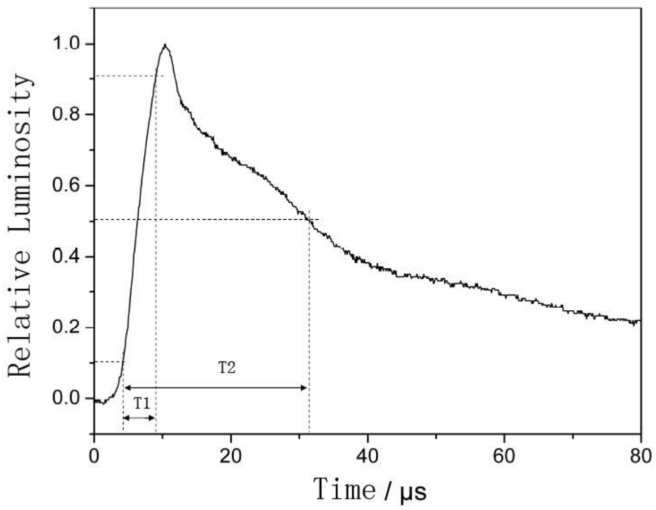

Figure 6 Illustration for the waveform parameters of luminosity pulse induced by lightning return stroke

Fig 7 shows the T_1 and the T_2 versus the heights of the grounding points. A total of 30 first return strokes (17 belong to group1 and 13 belong to group2) and 23 subsequent return strokes (19 belong to group1 and 4 belong to group2) have the available LAPOS observation. It could be found that both T_1 and the T_2 exhibit an increasing trend with the height. Table 2 presents the statistical value for the T_1 and the T_2.

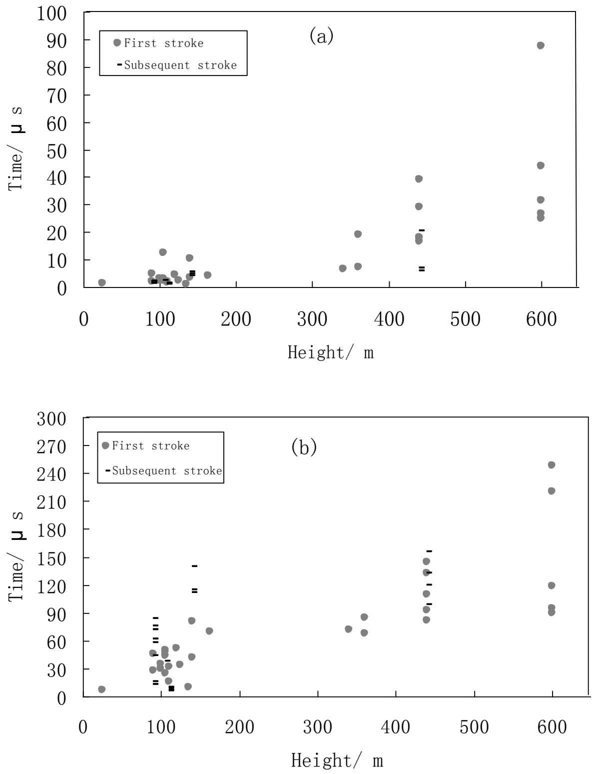

Figure 7 The T_1 (a) and the T_2 (b) of the luminosity pulses waveform induced by the return strokes versus the heights of the grounding points.

Table 2 Statistical value for the parameter of luminosity pulse waveform induced by return strokes

Lightning flash group	Statistical value for the parameter of luminosity pulse waveform			
	First stroke		Subsequent stroke	
	T_1/ μs	T_2/ μs	T_1/ μs	T_2/ μs
Group 1(AM)	3.8	38.1	2.2	52.9
Group 2(AM)	28.3	22.7	10.1	126.5
Group 1(GM)	3.1	32.5	2.0	35.0
Group 2(GM)	119.8	110.5	8.8	124.8

IV. Discussion

The difference of the N_s and the T_{int} between group 1 and group 2 is not too obvious, which infer that for the downward lightning flashes, the N_s and the T_{int} may be mostly infected by the electrical situation inside the thunder storm rather than the height of structure struck by the lightning.

Diendorfer and Pichler, Baba and Rakov pointed out that significant wave process of lightning current will occur when a tall structure exists in the lightning channel, and then enhance the amplitude of the LEMP [10-11]. Lafkovici et al compared 21 I_{peak} measured directly on the CN tower and those reported by the North American Lightning Detection Network (NALDN), and pointed out that the I_{peak} reported by the NALDN are about 2.6 times of the value measured directly [12]. In our study, the I_{peak} of the first and also the subsequent strokes of group 2 are significantly higher than those of group 1, which also shows that taller structures may lead to bigger enhancement effect on the LEMP.

Hussein compared the maximum steepness of lightning current measured on CN tower, Empire State Building and Peissenberg tower, and found that the maximum steepness of lightning current exhibit a down trend when the height of the structure increase [13]. Though the waveforms of lightning current are not available in this study, however, to some extent, the luminosity pulse waveform can also reflect the change of the current flowing through the lightning channel [14-15]. In our study, the T_1 and T_2 of the first and also the subsequent strokes of group 2 are significantly bigger than those of group 1, which shows that taller structures may further mitigate the maximum steepness and lead to longer duration of the “wave hump” of the of lightning current.

It is worth to note that the AM(GM) value of the I_{peak}, T_1 and T_2 of group 2 are 1.8（2.1）, 7.4（7.4）and 4.6（4.3）times of those of group 1 for the first return strokes, while 1.5（1.4）, 3.1（3.4）and 2.4（3.6）times for the subsequent return strokes. It seem that for the downward lightning flashes, the difference of heights of structures may cause greater impact on the characteristics of the first return strokes than those of the subsequent return strokes.

V. Summary and Conclusion

In this paper, comprehensive observations for 58 natural downward negative lightning flashes with confirmed grounding points are analyzed, to study the difference between the characteristics of lightning return strokes occurring on tall structures with different heights. The results show that:

1) The AM value of the N_s is about 3.7 for the lightning flashes occurring on structures lower than 200 m, while 2.6 for those taller than 200 m.

2) The AM(GM) value of the T_{int} is about 95(66) ms for the lightning flashes occurring on structures lower than 200 m, while 94(57) ms for those taller than 200 m.

3) The AM(GM) value of the I_{peak} of the first strokes and the subsequent strokes is about -57.9（-43.8） kA and -34.1（-30.8）kA for the lightning flashes occurring on structures lower than 200 m, while -104.3（-92.9） kA and-50.1（-42.6） kA for those taller than 200 m.

4) The AM(GM) value of the T_1 of the first strokes, T_2 of the first strokes, T_1 of the subsequent strokes and T_2 of the subsequent strokes is about 3.8（3.1）μs, 38.1（32.5）μs, 2.2（2.0）μs and 52.9（35.0）μs respectively for the lightning flashes occurring on structures lower than 200 m, while 28.3（22.7）μs, 119.2（110.5）μs, 10.1（8.8）μs, and 126.5（124.8）μs for those taller than 200 m.

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