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ABSTRACT

Steel structures take the advantages of good stability, good ductility, low construction cost, fast construction and hence high flexibility in shape with high utilization rate. With the rapid economic growth, steel structures are popularly used in modern architecture, particularly in supertall buildings of height over 300 m in China. However, the fire behaviour of steel structures should be watched because the mechanical strength of steel reduces when temperature increases.

In this paper, fire protective coatings commonly used in China for steel structures were studied by full-scale fire tests. Three types of ultra-thin, one type of thin and one type of thick coatings were evaluated. Test samples were prepared by applying the coatings on the typical H-type steel load bearing beams following standard fire resistance test. Different sets of fire protective coatings were applied on the surface of the sample as in the actual construction process. The coating thickness for the steel structural members satisfied the Chinese regulation with ultra-thin fire protective coating of 2.00 mm ± 0.02 mm, thin fire protective coating of 5.0 mm ± 0.5 mm and thick fire protective coating of 25 mm ± 2 mm. Experiments were carried out in the large-scale testing facilities at Sichuan Fire Research Institute, Dujiangyan, Sichuan, China. The transient temperatures at different positions inside and outside the steel structure, and structural distortion of the steel structural members with different fire protective coatings under the testing condition were measured.

Results on the measured temperatures, middle flexibility change values and corresponding time parameters on related parts of the test samples were then studied. A mathematical model was used for analyzing the result. The associated variables and correlation expressions among different variables were studied. Results can be taken as a reference for drafting new standards on evaluating the fire protective coatings for load bearing steel structures. For example, for the fire test of ultra-thin fire protective coating, it is possible to analyze and generalize the acquired data on temperature-time curve. For the thick-type steel structure fire protective coating, when the maximum temperature of the steel structure approaches 500°C and there is a high rate of temperature change, the fire resistance period of the structural members with protective coating can be predicted.

1. INTRODUCTION

Steel structures which are composed of several members by welding or bolting can be used for load bearing. Steel structures are particularly good for complicated designs with large span and huge space. However, the fire resistance of steel structure buildings should be watched. The steel beams, steel poles and ceiling trusses of multi-layer steel structure buildings can be severely damaged. For example, a fire occurred during construction in England in 1990 (Li *et al*., 2000); a light steel structure building of 5000 m^2 collapsed due to a fire in Kunshan, China in 1996; two 110-floor, 411 m high steel structure buildings finally collapsed due to the fire caused by the plane crash at the New York World Trade Center on September 11, 2001; and the steel structure aircraft hangar collapsed due to a fire at the Brussels International Airport of Belgium in 2006. When the temperature increases to a certain value, the steel structure will lose its load bearing capacity. This temperature is defined as the critical temperature of that particular steel. The typical critical temperature of building steel is 540^{o}C (China National Standard, 2003). The fire temperature of a building fire is usually between 700^{o}C and 1200^{o}C. The fire temperature can be over 700^{o}C within the first 10 minutes of the fire. If the temperature of the steel increases, the load on the steel structure can be over the load bearing capacity (Ryder *et al*., 2002).

Fire protective coating for the load bearing steel structure is extensively applied and highly adaptive for solving the fire resistance problem of the steel structure buildings (Knobloch *et al*., 2006). The fire resistance limit (China National Standard, 1995) of the building structures indicates the time since the structures are under fire till the structures failed in the fire resistance test according to the regulated standard temperature increase curve (generally it is in terms of hours). The failure of the structures indicates deformation of the steel members, meaning that the structures cannot continue to function.

There are many big construction projects in China with steel structures. The National Standard GB 14907-2002 (China National Standard, 2002b) “Steel structure fire protective coating” is used to determine the fire resistance limit of the fire protective coating for steel structures in Mainland China. Such methods for the fire protective coatings for steel structures are destructive tests. The test cycle is long, the cost is high and it is difficult to satisfy the environmental protection requirements if the stability and thermal insulation are evaluated. Therefore, an experimental study is proposed to test the typical steel structural members with common fire protective coatings of different thickness. The temperature of the structural member, intermediate deflection changes and corresponding time parameters are collected for data analysis. The associated factors and the corresponding relations are then deduced to evaluate the fire behavior of the load bearing steel structure applied with different fire protective coatings. The changes in maximum temperature, average temperature and intermediate deflection of the load bearing structures with time; and the comparison of the fire resistance performance for the typical load bearing steel structures with different sector factors using different fire protective coatings under the same condition can also be studied.

2. EXPERIMENTAL STUDIES

To carry out the fire resistance test, the selected fire protective coating is coated first on the surface of the steel structure according to certain construction process, the test part after care or shape adjustment is then obtained and placed under the regulated test conditions. The fire resistance of the test part is called the fire resistance limit of the fire protective coating of the related steel structure. Now, the National Standard “Steel structure fire protective coating” is used to determine the fire resistance limit of the fire protective coating for steel structure in Mainland China (China National standard, 2002b). This standard regulates a test base material for test and the test results (coating thickness and fire resistance test duration) are used to indicate the fire resistance performance of the fire protective coating for steel structure.

The experiments are divided into two parts, one is the main tests and the other is the verification tests. Different fire protective coatings (ultra-thin, thin, and thick) for load bearing steel structural members were selected to do the tests. H-Style steel structural members were prepared with different fire protective coatings as the test members in (Wang and Göransson, 2005). 5-6m H steel beam coated with the fire protective coating is used for the load test. The maximum deflection of the beam in a fire cannot exceed the maximum limit which can determine the fire resistance performance of the beam. After the rust of the base material is removed in the test, the antirust paint (some coatings are antirust) is painted, and the fire protective coating is painted till the test thickness. The vertical distribution load is simulated. The load is imposed according to the regulation in the standard. The load is fixed in the test. Both sides and the bottom of the steel beam catch a fire. After the test furnace is ignited, with the increase of temperature along with time, the heat gradually transfers to the base surface of the steel beam via the coating due to thermal radiation. When the steel beam reaches the critical temperature, the bearing capability starts to decrease and distort at a slow speed. At this time, the distortion is a resilient distortion and then changes to plastic distortion. With the quick increase rate of the distortion, when the span deflection of the beam and the distortion rate reach the maximum deflection, it indicates that the test part loses stability and reaches the fire resistance limit.

Details of the fire protective coatings for steel structural members used in the tests are shown in Tables 1 and 2. Based on the requirement of the test base material, the sand has to be blasted and the rust has to be removed for the selected typical steel structure members before painting the XH-1003 H epoxy zinc antirust priming. Details can be seen in Tables 3 and 4 (Spyrou and Davison, 2001).

Table 1: Fire protective coatings for steel structural members used in the tests

	Coating thickness (not more than) / mm	Fire resistance limit (not less than) / hr
Indoor and outdoor thick coating	25±2	1.0
Indoor and outdoor thin coating	5.0±0.5	1.0
Indoor and outdoor ultra-thin coating	2.00±0.2	2.0

Table 2: Detailed information of fire protective coatings for steel structural members used in the main tests and verification tests

Name of sample	Number	Sample quantity / kg	Remark
Indoor ultra-thin fire protective coating for steel structure	S-01	500	Main test
Indoor thin fire protective coating for steel structure	J-01	1000	Main test
Indoor thick fire protective coating for steel structure	ZH-01	2000	Main test
Indoor ultra-thin fire protective coating for steel structure	B-11	500	Verification test
Indoor ultra-thin fire protective coating for steel structure	LN-11	1000	Verification test

Table 3: Coating thickness for the main test

Number	Section factor (m^{-1})	Average thickness of web plate coating (mm)	Average thickness of down wing edge coating (mm)	Total average thickness of coating (mm)
H-LB B	157	6.2	6.7	6.4
H-LB B	184	6.2	7.4	6.8
H-LB B	242	6.4	6.4	6.4
H-LB H	157	27	29	28
H-LB H	184	28	32	30
H-LB H	242	27	29	28
H-LB CB	157	2.22	2.26	2.24
H-LB CB	184	2.23	2.35	2.29
H-LB CB	242	2.35	2.41	2.38

Table 4: Coating thickness for the verification test

Number	Section factor	Average thickness of web plate coating (mm)	Average thickness of down wing edge coating (mm)	Total average thickness of coating (mm)
H-LB B	157	6.3	6.6	6.3
H-LB B	184	6.4	6.7	6.5
H-LB CB	157	2.17	2.21	2.18
H-LB CB	184	2.06	2.13	2.11

Thermocouples were used to measure the temperature of the test base material before the fire protective coating is painted. Requirements for the thermocouple setup followed the ENV 13381-4: 2002 "Test methods for determining the contribution to the fire resistance of structural members—Part 4: Applied protection to steel members" (British Standards Institution, 2002; European Committee for Standardization, 2002). Five thermocouples were located on five sections along the length of the base station, namely the 1/4, 3/8, 1/2, 5/8 and 3/4 of the fire-contact length of the base material, four thermocouples on the wing edge and one thermocouple on the web plate. Six thermocouples were placed on the upper surface of the wing edge under the beam, which means setting five thermocouples in the middle of five sections, and another one is between the outside section and the fire-contact end. Figure 1 shows two samples in the tests.

After the testing period expired, the coating thickness on the surface of each test part (Kodur and Dwaikat, 2009; Sakumoto *et al*., 2001) was measured. Eight points on 13 sections along the length of the test part (test part was divided into 14 equal parts) were measured, i.e. a total of 104 points (See Figure 2).

The coating thickness of each test part was measured and summarized in Table 1. The actual coating thickness of the test part is different from the regulated construction thickness, but only few same type base materials' coating difference between the thin coating and thick coating is too big. The difference of others is smaller. The difference is within the deviation regulated in GB 14907-2002 (China National Standard, 2002b). Each fire protective coating for steel structural member was tested five times. Each load bearing beam test part was tested separately once (Ali and O'Connor, 2001). The test part was placed in a horizontal furnace with details shown in Figure 3.

Figure 1: Structural members in the tests

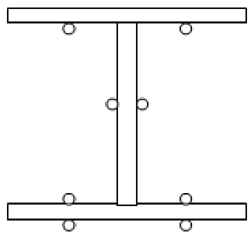

Figure 2: Measurement positions of H-type section thickness

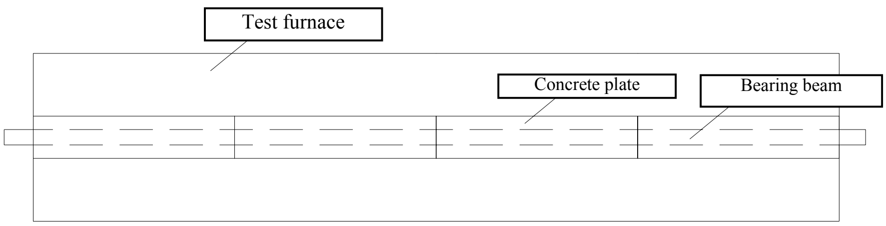

Figure 3: Layout of bearing beam test part inside the furnace

The verification test aims to verify the conclusions from the main test. The only load bearing beam test part with two section factors were used due to test cost and multiple factors. The indoor ultra-thin and indoor thin fire protective coatings for steel structural members were selected for the verification test. The load bearing beam test part was placed into the horizontal furnace.

The temperature inside the furnace was monitored by using 8 thermocouples. The thermocouples were uniformly distributed on both sides of the horizontal combustion test furnace with four thermocouples on one side. The position of the thermocouples, temperature increase inside the furnace and pressure conditions should comply with the requirements in the national standard GB/T 9978 (China National Standard, 2002a).

Prior to the test, the load was imposed on the load bearing beam according to the loading mode and actual load of the test part with different sections regulated in the national standard GB 14907-2002 (China National Standard, 2002b). The load on the test part should be kept within the deviation regulated in the national standard GB/T 9978 (China National Standard, 2002a) during the whole test. The temperature of the test base material was measured by using the thermocouple set at 2 s monitoring interval (Barnett, 2002). When the average temperature of the test base material reached 700°C, the test was terminated. When an exception occurred in the test, the test was terminated for safety.

3. RESULTS FOR THE LOAD BEARING STRUCTURE

The interior temperature increase, change rate of temperature, and structure distortion of different steel fire protective coatings for steel structural members under the test condition (Liu *et al*., 2002) were measured.

Figure 4 shows the typical testing condition for ultra-thin coating type. For the average temperature and maximum temperature, the temperature increase of the structure is divided into three phases. The temperature increase for phase I roughly meets the logarithm law. For phase II, the temperature increase meets the binomial law. For phase III, it meets the exponential function. The feature of the fire protective expansion and thermal insulation layer of the coating depends on the composition of the three temperature increase phases. The remarkable change of the deflection occurs when the maximum temperature of the structure is over 500°C. At this time, the average temperature of the structure is over 400°C. The deflection occurs when the maximum temperature of the structure reaches 700°C. At this time, the average temperature of the structure is over 500°C. For the average temperature and maximum temperature, the remarkable deflection change and bearing capability loss of the structure occur in the exponent phase of the temperature increase of the structure. The change rate of the temperature is over 10 °C/min in a unit time.

To validate the above conclusions, verification test was also performed with typical test results shown in Figure 5. The phase from remarkable deflection change and bearing capability loss of the structure is mapped with the exponent phase of the temperature increase of the structure. Especially the maximum temperature test for the structure proves that the time for temperature increase rate entry to the exponent phase approximates to the time point for remarkable deflection change. The change rate of the temperature with time in the above phase is absolutely over 10 °C/min or far higher. The verification test indicates that the conclusions of the main test for the load bearing structure with the indoor ultra-thin fire protective coating for steel structure meet the standard test and the way of testing is effective. (Auderbery, 1988).

Figure 6 shows the typical testing condition for thin type coating. For the average temperature and maximum temperature of the structure, the relation of temperature and time (pattern of temperature increase) is linear and more than two different phases of the temperature-time change rate occur. It depends on the features of the fire protective expansion thermal insulation layer of the thin coating mentioned in the theory research. The remarkable deflection change roughly occurs in phase II of the temperature increase. At this time, the average temperature of the structures reaches 400°C (or higher). The maximum temperature is over 500°C. When the deflection occurs, the average temperature of the structure is over 500 °C. The maximum temperature reaches 700°C. When the deflection remarkably changes, most change rates of the temperature with time are about 12°C/min to 16°C/min. Some change rates are higher. The maximum temperature of the structure is over 500 °C after placing in the fire for about 20 min. The fire resistance time for this phase is shorter than the time of the ultra-thin fire protective coating described before, which indicates that the performance of this thin coating is worse.

The results for the verification test for the thin coating produced by different manufacturers (6.6 mm and 6.7 mm thick coating) are shown in Figure 7. The fire resistance performance of the thin coating for the test is far higher than that of the coating for the main test. The relation of the internal temperature and time of the structure (temperature increase) is linear. Three different phases of the temperature and time change rate occurs. In the theory, the better effect of the coating thermal insulation layer indicates more different phases of the temperature-time change rate. The test proves this conclusion. The remarkable deflection change mainly occurs at the end of phase II or the initial period of phase II. At this time, the average temperature of the structure roughly reaches 400°C (or higher). The maximum temperature is over 500°C. When the deflection occurs, the average temperature of the structure is over 500°C and the maximum temperature reaches 700°C. The time from remarkable deflection change to mutation and bearing capability loss of the structure is about 10 min to 15 min. Regardless of the fire resistance performance of the coating, the fire resistance capability of the structure will become worse in this phase. The structure with a bigger section factor has a worse fire resistance performance under the same condition. This conclusion is proved in the high-performance coating test.

Figure 8 shows that under the test condition of the thick type coating, the temperature increase inside the structure (including average temperature and maximum temperature) is divided into different phases as shown in a typical case in Figure 7. The temperature increase is linear in each phase. The maximum temperature of the structural member changes remarkably. The deflection changes slowly with time during a long period when the fire resistance test starts and the change rate is far lower than that of the structure with ultra-thin and thin fire protective coating for steel structure. The intervals of the structure from the remarkable deflection change to deflection mutation and load bearing capability loss are 8.7 min, 5.0 min and 8.1 min. These intervals are shorter than those of the steel structure with thin or ultra-thin fire protective coating. In other words, for the steel structural member using the thick fire protective coating, when the internal temperature increase approximates to the yielding limit of the steel, the collapse speed of the structure is better than that of the steel structure with thin or ultra-thin fire protective coating.

Remarks: In Figures 4 to 8, Curve A represents the change of maximum temperature for the steel structure, Curve B represents the change of average temperature for the steel structure, and Curve C represents the deflection change for the steel structure, where every 100°C equal to 10 mm in y axis.

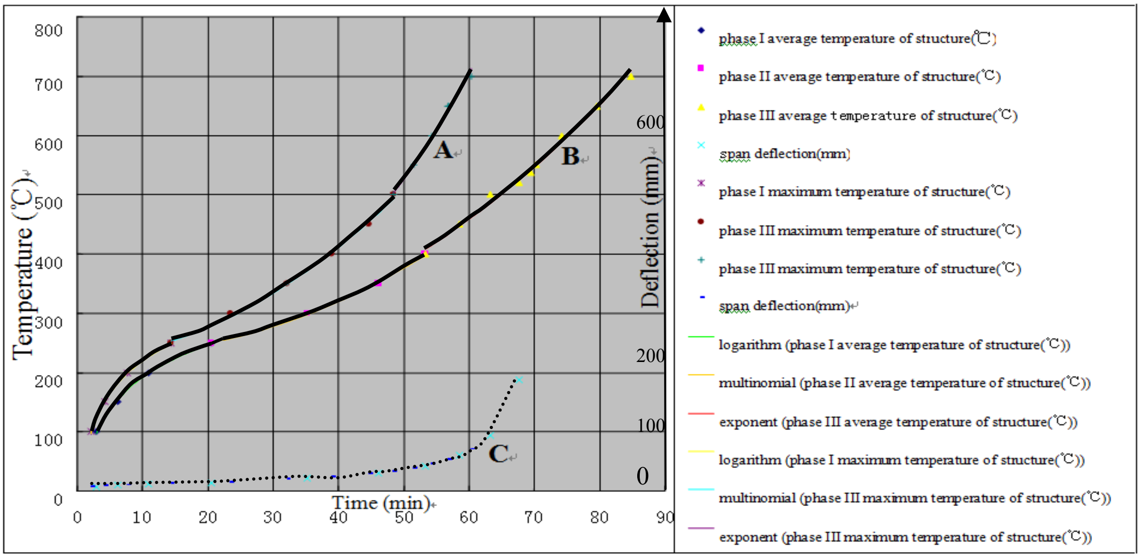

Figure 4: Temperature-time-deflection curve of main test on ultra-thin coating

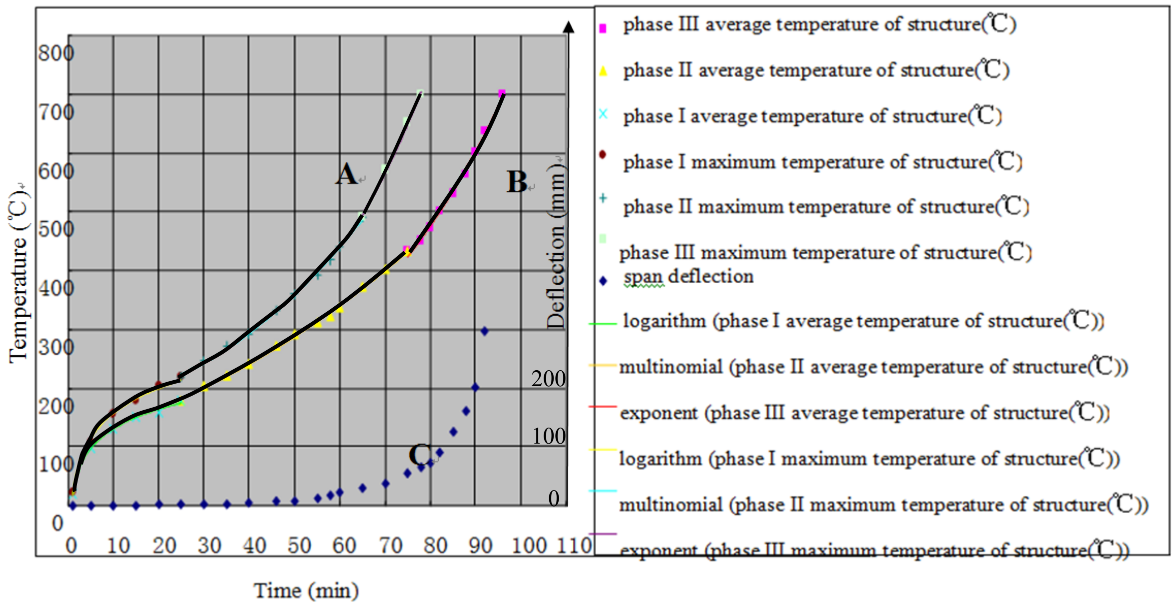

Figure 5: Temperature-time-deflection curve of verification test on ultra-thin coating

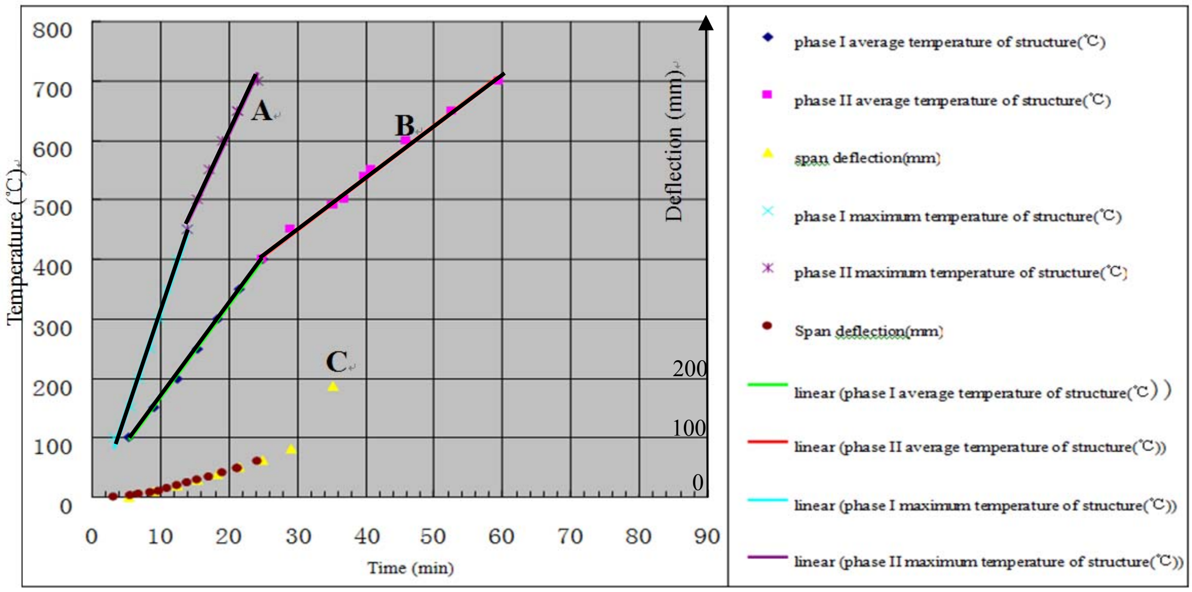

Figure 6: Temperature-time-deflection curve of main test on thin coating

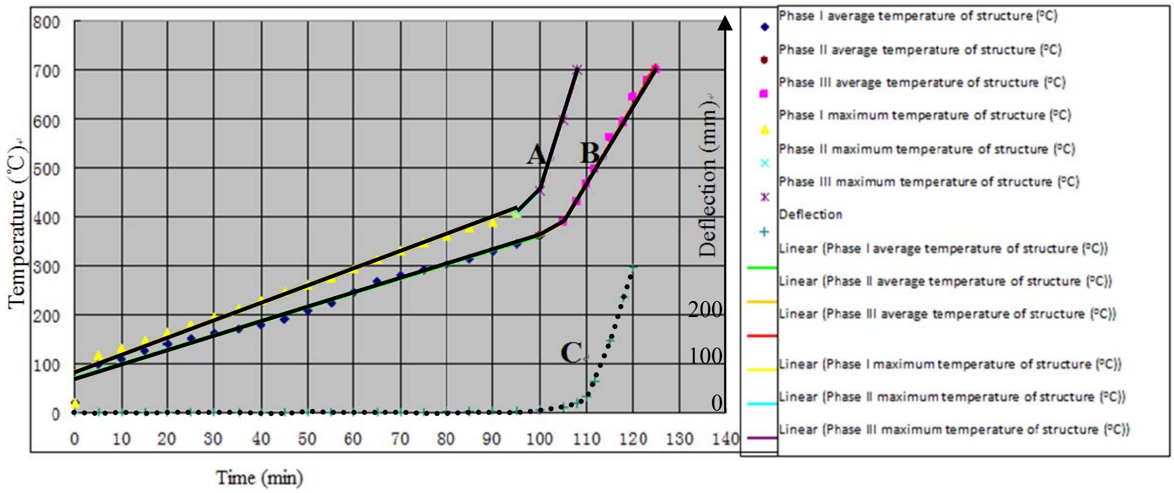

Figure 7: Temperature-time-deflection curve of verification test on thin coating

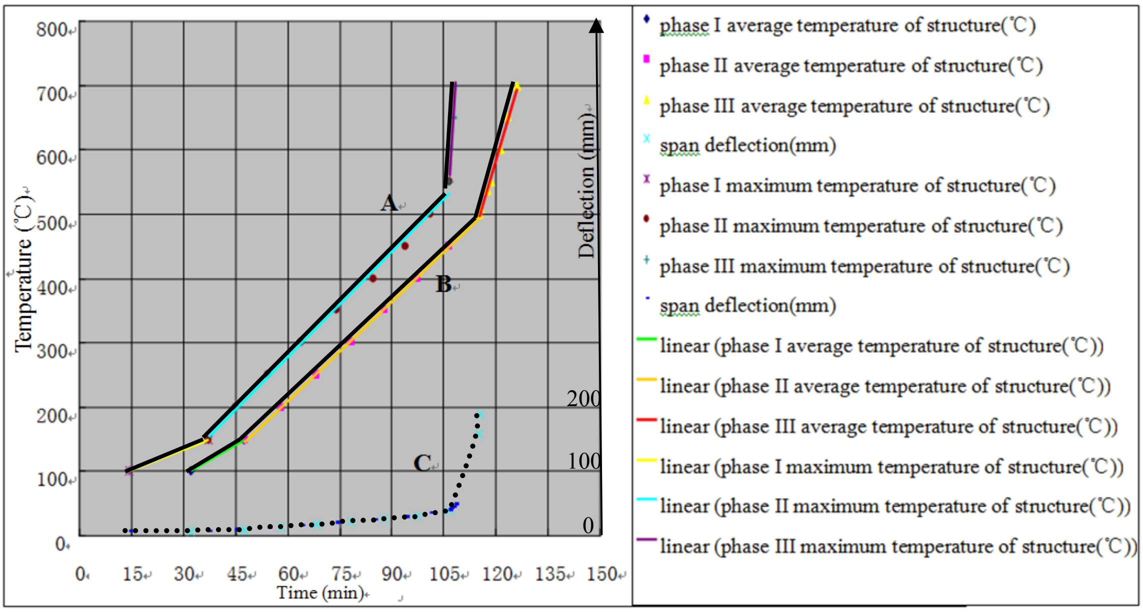

Figure 8: Temperature-time-deflection curve of verification test on thick coating

5. CONCLUSION

It is known that when the fire protective coating for steel structure is used in different building structures, the fire resistance limit of the imposed part is related to the structure of the test part, construction and structure of materials, coating construction process, maintenance conditions or status adjustment for the same type of steel structure fire protective coating, the same process and the same coating thickness. The fire protection performance might be different when the cross-sectional shape, dimensions and construction of steel structures are different. Taking Mainland China as an example, the data acquired from tests conducted according to the current fire protective coating standard for steel structure in China must be applied in the construction projects according to the regular rules in line with the actual circumstances in order to meet the safety requirements. The purpose of the related tests is to find the regular pattern within a certain scope and to a certain extent.

Three typical steel structures commonly used with thick, thin, and ultra-thin-type fire protective coatings were tested. The selection gives a more realistic picture of the construction industry. Test samples were prepared by applying the coatings on the typical steel structures according to the test plan and fire protection performance test. The temperature, middle flexibility change values and corresponding time parameters on related parts of the test samples under the test conditions were acquired and a suitable mathematical model was used for data analysis before drawing a temperature-time characteristic curve. On this basis, the associated variables and correlations were summarized and explored.

As described earlier, accurate assessment of the thermal insulation performance of fire protective coating depends upon the changes of internal temperature of steel structures. Whether it is thick, thin or ultra-thin fire protective coating, the temperature change of related parts of a steel structure is closely related to the change of fire protection and thermal insulating properties and fire resistance stability (Newman *et al*., 2006).

For steel structures coated with ultra-thin fire protective coating, the relation between temperature rise of load bearing structures and time is divided into three stages, with the regular pattern of temperature rise as the first stage basically in the form of logarithm, the second stage basically in the form of binomial and the third stage in the form of exponential function. For a steel structure coated with thin-type fire protective coating, the relation between the temperature rise of typical load bearing steel structural members (average temperature and maximum temperature) is linear and at least two stages will occur where temperature-time rate of change is different. The period from the time when the flexibility of the typical load bearing structure changes substantially to the time when the steel structure loses the load bearing capacity occurs at the second or third stage of the linear temperature rise of the steel structure. The rate of temperature change within a unit time all exceeds 10^{o}C /min, and the period from the occurrence of significant change of flexibility to the loss of fire resistance stability is also about 10 minutes (Li and Jiang, 1999). For a steel structure with thick-type fire protective coating, the temperature rise of typical load bearing steel structure is also divided into different stages, and the change of the maximum temperature of the steel structure is always linear among three different rates of change. The change of average temperature of the steel structure sometimes reflects the linear relation between two different rates of change, sometimes the linear relation among three different rates of change. The change of flexibility over time is very slow during a quite long period of time from the beginning of the fire protective test of typical load bearing structure, far below that of the steel structure with ultra-thin or thin-type fire protective coating, but the rate of temperature change within a unit time is extremely high from the occurrence of significant change to sudden change in flexibility, so high that it takes only several minutes for the structure to lose its load bearing capacity. That is to say, for a steel structure with thick-type fire protective coating, when the internal temperature rise approaches the yield limit of the steel, the steel structure will collapse much faster than the steel structure with thin-type or ultra-thin fire protective coating.

It can be seen that accurate control of the temperature change inside a steel structure is very important for assessing the fire protection performance of steel structure fire protective coating. Given the fact that there is no provision in the current Chinese national standard for measurement of temperature rise of steel structure, it is indeed necessary to fill the gap as soon as possible.

The results give some guides on the fire behavior of steel structure fire protective coating based on the regular pattern of temperature rise and rate of temperature change of steel structure. For example, for the fire protective test of ultra-thin fire protective coating for steel structure, it is possible to analyze and generalize the acquired data on time-temperature relation. When the maximum temperature of the steel structure reaches 500^{o}C, the regular pattern of temperature rise within a certain period (about three minutes) is basically in the form of exponential function and the rate of temperature change within a unit time exceeds 10^{o}C/min. It is possible to forecast that the coating in question will reach its fire resistance limit after more than ten minutes. Moreover, for the thick-type steel structure fire protective coating, when the maximum temperature of the steel structure approaches 500^{o}C and the rate of temperature change within a unit time increases suddenly, it is possible to forecast that the coating will reach its fire resistance limit after several minutes (Bartholmai and Schriever, 2003).

The aforesaid method is important to understand the quality characteristics of steel structure fire protective coating, avoid falsification effectively in the test process, conserve energy and promote environmental protection. Related tests demonstrate that under the same coating thickness and type, the steel structure with a higher cross-section coefficient has a lower fire protection performance. This characteristic is especially evident with load bearing steel structures (Kirby, 1986). The tests further reveal that, whether the coating is of superior or inferior fire protection performance, the effect on the repeatability of test process and test conclusion is basically the same. This also indicates the universality and suitability of the test pattern.

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