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Experimental Study on Fire Resistance of Building Steel Structure Fireproofing Material

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The definition and connotation of the steel structure fire protection material are briefly given, and the relationship between the fire resistance and the HP/A is analyzed and summarized according to the domestic refractory test data of the typical laboratory exposed steel structure. According to the existing specification, the necessity of fireproof protection, the application and basic requirements of the steel structure fire protection material and the necessity of adopting the steel structure fire protection material are put forward, pointing out the existing problems of fire protection technology, exploring other fire protection materials. Reasonable proposal have been given for the fire resistance test standard system, the relevant standards and norms of the system: Develop different fire resistance test methods should be made for different fire situations, and the corresponding assessment methods should be made for practical engineering application. And then the further content that needs to be studied in this field has been pointed out. Although there are many deficiencies that the steel structure fire protection materials transfers from the development, product characteristics, test methods or standard systems and test data to the actual application of the transition, but the actual demand decisions the broad prospects of this area, so it is of great significance to carry out its fire performance test.

1. Introduction

In recent years, steel structure has played a unique and increasingly important role in construction projects. Large steel structure construction has short construction period and quick return. It is one of the preferred building structures for building factories, warehouses, shopping malls and so on. It can be predicted that the steel structure in our country has a very broad prospects for development. However, steel, as a construction material, has some inevitable defects in fire protection. In the case of no fire prevention processing, steel will not be on fire, but the intensity will decline rapidly in the fire.

According to the theoretical calculation, in full load condition, the critical temperature making the steel structure lose stability of static balance is 500 DEG C or so, while in general, the temperature of fire site reaches 800 to 1000 DEG C. Under such as high temperature, the exposed steel structure will soon appear plastic deformation, resulting in local damage, and even lead to failure of the overall collapse of the steel structure. On 5th, May, 1998, a fire broke out in the furniture city around Yuquanying of Beijing. Because the fire prevention of original structure was not up to standard, it resulted in 13 thousand square meter steel structures collapsed, resulting in direct economic losses amounting to 20.87 million yuan (Bilotta, et al., 2016; Zhang et al., 2016; Mi and Liu, 2016; Sanabria et al., 2017).

In order that the steel materials can overcome the lack of fire prevention in practical applications, it is necessary to make a fire protection processing. So far, using the method of fire retardant coatings for steel structure fire protection is still considered one of the most effective measures in the industry. The fire retardant coating for steel structure plays an important role in 90% of the steel structure engineering. The fire retardant coating (also called flame retardant coating) is coated on the surface of steel structure. In addition to the decoration and protection functions of ordinary paint, it also has anti-corrosion, anti rust, acid and alkali resistance, salt fog resistance and so on performances. More importantly, in that the paint itself has no burning or flame retardant, it can prevent the spread of fire flame and delay the expansion of fire. In this way, it

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better protects the substrate and avoids the building collapse caused by steel structure losing the support capability.
Fire protection material is coated on the surface of components for structure protection. Fire protection materials are materials that can improve the fire resistance of structures or components, including inorganic fiber sheet, plate or sheet, coating and other materials (Puri & Khanna, 2016), which can meet fire, physical and chemical mechanical and environmental requirements. According to the use, it can be divided into wood structure, concrete structure, reinforced concrete structure, steel structure fire protection and other types of materials.The fire protection material can be used for fire protection of the steel structure to improve the fire resistance limit of the steel member, and prolong the bearing time of the steel member or structure (which does not collapse during the specified time). The corresponding fire protection materials are coated or coated on the surface of steel members according to certain construction technology to form the test specimen after maintenance or conditioning (Christke, et al., 2016), then, it will carried out refractory experimental after being put in the specified experimental condition, which can obtain the fire resistance of the test specimen, known as fire resistance of steel structure fire protection materials. It is related to the structure of the specimen, the material structure level, the construction technology, the maintenance condition or the state regulation, and the fire resistance test conditions.

2. Necessity of using steel structure fire protection material

2.1 Experiments of bare steel structure in typical laboratory in China

2.1.1 Basic conditions and general requirements
At the beginning of 90s, the fire resistance limit of bare steel beam was verified in the revision of the steel structure fire retardant coating standard GB 14907-94 (Carosio, et al., 2016), and it is confirmed that the fire resistance limit of I36b and I40b two kinds of hot rolled ordinary I-beam is 15, 16min, which is taken as the basic data of standard fire resistance test for fire retardant coatings for steel structures. In the experiment, the critical value of the internal temperature of steel and the maximum allowable deflection of midspan are taken as the judging conditions (Bilotta, et al., 2016). The internal temperature of steel to the critical value and maximum allowable deflection value as the load conditions. Based on probability theory, the limit state design method is adopted in the design, and there is no combination section between concrete slab and steel beam (Puri, et al., 2016).

2.1.2 Load calculation of simply supported slab beam with three faces

2.1.2.1 Known conditions
The steel is Q235 steel, the design strength is f(N/mm^2), and the strength reduction factor is k. The beam calculated span is L_0(m), and the installation method is level. The weight is g(N/m); the silicon plate is two blocks with same length and same section, and the weight is q_0(N/m), which uniformly covers the upper flange of the steel beam, and has no contact with steel structure.

2.1.2.2 Checking calculation of overall stability
(Referred to 4.2.1 in the second of GBJ17-1988) L/b_1, the L is the free length of the compression flange of the steel beam; b_1 is the width of the compression flange. If $L/b_1>13$, it should be calculated according to the overall stability; if the $L/b_1<13$ or rigid plank is paved on compressed flange beam, and can prevent the torsion beam section, then it should be calculated according to the strength.

2.1.2.3 Calculation of coefficient Ψ_b of stability factor according to overall stability
a. for steel girders, the Ψ_b shall be determined according to the load distribution, the type of the joist beam and the free length of the compression flange.
b. For the welded steel beam with composite section, the calculation should be carried out according to the following formula:

$$\Psi_b = \beta_b(4320/\lambda_y^2)\cdot(Ah/Wx)[\sqrt{1+(\lambda_y t_1/4.4n}+\eta b]\cdot 235/fv \tag{1}$$

If $\Psi_b>0.6$ is calculated, the corresponding Ψ_b' value should be found for the calculation of B

2.1.2.4 Calculation of the uniformly distributed load of steel beam q_{max}

$$M_{max}/(\Psi_b\cdot Wx) = k\cdot f \tag{2}$$

$$M_{\max} = 1/8 \cdot q_{\max} \cdot L_0^2 \tag{3}$$

It can be introduced from (2) (3) that $q_{\max} = 8 \cdot k \cdot \Psi_b \cdot Wx / L_0^2$

2.1.2.5 Calculation of external load q

$$q = q_{\max} - g - q_0 \tag{4}$$

2.1.2.6 Calculation of total external load p

$$p = q \cdot L_0 \tag{5}$$

2.1.3 Calculation examples

I40b hot rolled ordinary steel i-beam: L0=5630mm, f=215N/mm$_2$. Wx=1140000mm$_3$, k=0.9
Section size of concrete slab:550mm X 150mm. Alkali grade of concrete: C30.
Total external load p will be calculated.
Calculation procedural:
a. Ψ_b is calculated:
L/b_1=5630/144=39.1>13 should be calculated according to the overall stability.
After looking up in the table: L=5, L=6 are corresponding to Ψ_b =0.073, Ψ_b=0.6
When L_0 = 5.63m, Ψ_b= [(0.6-0.73)/(6-5)] X 0.63+0.73=0.65>0.6;
After looking up in the table: Ψ_b'=0.63
b Uniform load design value q_{max} is calculated:

$$\begin{aligned} q_{\max} &= 8 \cdot k \cdot f \cdot \Psi_b \cdot Wx / L_0^2 \\ &= 2 \times 0.9 \times 215 \times 0.63 \times 1140000 / 5630^2 \\ &= 35.0 (N/mm) \end{aligned} \tag{6}$$

c. q External load P is calculated:

$$\begin{aligned} q &= q_{\max} - g - q_0 = 35000 - 724 - 186 \\ &= 32416 N/m \end{aligned} \tag{7}$$

d. Total external load P is calculated:

$$p = qL_0 = 32416 \times 5.63 = 182502(N) = 183kN \tag{8}$$

Table 1: The tested data for unprotected steel beam in GB

Numbers	H mm	B mm	D mm	T mm	A mm^2	Hp mm	Hp/A 1/mm	Span (mm)	Fire endurance
1	360	138	12.0	15.8	8368.0	1086	0.1298	5630	14min
2	400	144	12.5	16.5	9411.2	1182	0.1256	5630	16min

2.2 Experimental results

Statistical data show that the bigger the HP/A of the component is, the smaller the fire resistance limit and the bigger fire risk, as shown in Figure 1. According to the standard of nation, such as the GB 50045 "fire protection design of tall buildings", GB50016 “Code for fire protection design of buildings”, the requirements for the fire resistance of the relevant components are also specified, and the highest value is 240min, which is the bare steel structure can not meet the. Therefore, it is necessary to carry out fire protection to the steel structure, in order to meet the requirements of the corresponding fire resistance grade.

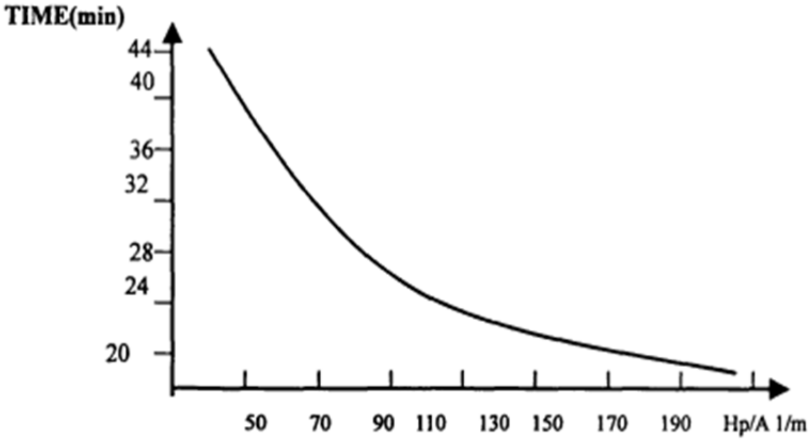

Figure 1: Section factor and fire endurance

3. Specific performance of fire protection materials

For the fire protection of steel structure, the main existing protective measures or materials used have the following six types: Fireproof Coatings for depositing steel structure, stickup inorganic fireproof board, spraying inorganic fiber, pasting inorganic fiber board paste, pasting flexible material, and the internal structure can go through water.

3.1 Depositing steel structure fire retardant coating

It is a kind of coating that can be costed in the surface of steel structure of the buildings, and usually, it plays the role of decoration, but it can form a fireproof heat insulation protective layer when fire. It can improve the fire resistance of steel structure to meet the requirements of code for fire protection design of buildings. Steel structure fire retardant coating according to its thickness is divided into three categories. H class is the fire retardant coating of thick coating steel structure that is mainly composed of inorganic materials and binder composition (Li, et al., 2016). The coating thickness is 7mm~45mm, and its surface is granular, the density is small, the thermal conductivity is low, and the coating will not expand under fire. The fire resistance limit can be 0.5h~3.0h, known as the steel structure fireproof heat insulation coatings. The B class is thin fire retardant coating for steel structure. The coating thickness is about 3mm~7mm, and it has a certain decorative effect. It will expand to thermal-protective coating under high temperature, and the fire resistance limit can be 0.5~1.5h, known as the expansion fire retardant coating for steel structure. The CB class is the ultra-thin fireproof coating for steel structure, and the coating thickness is below 3mm. It has better decorative effect, and will expand to thermal-protective coating under high temperature (Fan, et al., 2016). The fire resistance limit can be 0.5~1.5h. Indoor steel structure fire retardant coatings (NH, NB, NCB) are applied in the steel structure in the industrial and civil buildings. The outdoor fire retardant coatings for steel structures (WH, WB, WCB) are applied to the steel structure in petrochemical enterprises, has good durability, and can meet the requirements for outdoor use. The fire resistance limit can be up to 0.5h~3.0h. Among them, the ultra thin steel structure fire retardant coatings developed rapidly in the past 5 years, and has been widely used. Its fireproof and heat insulation is as following:

①The coating does not burn or does not support combustion, which can shield and prevent the heat radiation for the steel base, isolate the flame and avoid the direct exposure of the steel structure to the flame or high temperature;

②Some of the material in the coating absorbs heat and decomposes the water vapor, carbon dioxide, ammonia gas and other non combustible gases, which plays an important role in the consumption of heat, the decrease of the flame temperature and the burning speed, and the dilution of oxygen;

③The role of the fire protection layer is the formation of carbonized foam layer after coating thermal expansion, and the thermal conductivity is very low, so it can effectively prevent heat transfer, postpone the time that the steel reaches the critical temperature, so as to improve the fire resistance of steel (Puri & Khanna, 2016).

Fireproof principle thin steel construction fire retardant coating is the same as the ultra-thin fireproof coating for steel structure, usually, the coating of the thin fire retardant coating for steel structure is strong because contains fiber, but the foaming rate is far less than the ultra-thin fireproof coating for steel structure.

3.2 Pasting inorganic fireproof board

The sheet is pasted in the steel substrate surface with a predetermined shape according to the section properties. Because the inorganic fireproof board itself thermal conductivity is low, but has good heat insulation, so part of the crystal water will be lost under high temperature, which makes the steel temperature rise slowly, improveing the fire resistance of steel plate. The plate thickness is about 10-50mm, fire resistance limit can be up to 60--240min, and has a good decorative effect (Fan, et al., 2016). However, the plate is fixed and it needs fixing block and the binder when paste it, and there is crystal water between the plate and the steel substrate surface. So the adhesive quality will greatly affect the fire-resistant properties, and its construction only can play the efficiency when the steel substrate has the regular surface. In addition, the component works with deformation, so it has higher requirements on the plates and bonded (Naik, et al., 2016). At present, only the majority of projects using this method, there is no industry standards or national standards, only the enterprise standard.

3.3 Spraying inorganic fiber

After crushing, the fiber board (rock wool, aluminum silicate fiber cotton) is added a small amount of binder and solvent (water), and mixed and sprayed by spray gun to attached to the steel surface to form a protective layer. It can be divided into dry spray and wet spray. When the fire occurs, it has good thermal insulation performance, so that the temperature of steel rises slowly, and the fire resistance of steel structure is improved (Zhang, et al., 2016). The thickness is generally 10~50mm, and the fire endurance can reach 60~240min. Because the main body is inorganic fibers, so the protective layer has low strength, the surface is rough, and it is vulnerable to be destroyed by the external force. It has no decoration effect; but its cost is low, the construction is quick, and is suitable for the irregular component surface of various hidden engineering. This method is used in some projects.

Although there are certain advantages in the pasting fiber board, pasting flexible material, but there are certain shortcomings and difficulties in the practical application. Therefore, in the current domestic engineering, these three methods are almost not be used.

4. Application status and defects

The above six kinds of fire protection measures or materials can play its effectiveness in the steel structure fire protection. The steel structure fire retardant coating plays a major role in most of the steel structure fire protection project, and shows great value in the steel structure engineering in our country, but it still has defectiveness. For example, a fixed standard steel structural member or commonly used beams or columns are adopted in the inspection of the steel structure fire protection system in laboratory, whether it is fire retardant coating, spray inorganic fiber or fire board and other materials. However, there is difference in the size, structure, cross-sectional shape and the fire surface of the structural member in the practical engineering (Akaa, et al., 2016). As a result, the data obtained by a standard component test used by the laboratory cannot be directly applied to the different structural components in the practical engineering. The refractory test data of the same product of each manufacturer are less, the cross-sectional shape, size and structure of the steel member are quite different from those of the refractory test. The thickness of the coating must be calculated to reach the same fire resistance, otherwise, protective layer cannot plays the actual effect.

5. Conclusion

By participating in a variety of fire protection tests that mainly takes the fire-resistant protective materials of steel structure, the following conclusions can be obtained after a large number of experimental data have been collected and the relevant norms and engineering applications have been discussed.

①Whether it is the development of norms, the implementation of the test method, or the effect considered in the design of the building, first of all, fire characteristics should be distinguished in the possible fire scene. For different fire occasions, the corresponding fire protection will be designed, and the proper meaning of the fire endurance should be give. Then, the failure of the component caused by the effect of water on the integrity of the component and the strength of the components should be taken into consider. Then, the pad value of the fire endurance caused by the burn-in of the materials and components should be considered.

②When developing a fire resistance evaluation method standard, it is necessary to introduce an assessment of the attenuation of the fire resistance caused by the aging of the material, especially the fire protection of the structure, so that the fire test conditions are more in line with the actual fire situation. After such a refractory test, the qualified components can provide a basic guarantee for reliable fire protection design.

③With the emergence of new materials and new structures, it is necessary to confirm the new protective measures and the fire resistance limits of the new structure, and provide the basic data for the standardized revision. Such as steel-silicon beam and plate combination structure, steel grid structure, steel pipe structure, and lattice components, etc. Although theoretically, the strength of the steel is force to express the fire resistance limit when reaches a certain extent (generally 50%, reach the critical temperature of steel), but because of the changes of the standard structure design method and the different characteristics of the structure, the refractory limits will be given the different limits, which needs to further develop the basic test of fire resistance test, and then provide basic data for carrying out the fire protection of steel structure fire protection material.

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