Research Progress on Fire Resistance of Steel-concrete Composite Structures

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Abstract. The 1930s was an important period of development in the design theory of bridge technology in Europe and the United States. Among them was the invention of welding technology, which created more favorable conditions for the development of combined structures, i.e., the connection between reinforced concrete slabs and steel girders could be welded instead of the initial connection method. In China, for more than thirty years, on the one hand, large span bridges have been able to develop rapidly and set new world records, driven by the huge technical demand seeking span breakthroughs. On the other hand, concrete bridges dominate the large number of small span bridges. In short, in China, steel-concrete (SC) structures have also developed accordingly. This paper first introduces the steel-concrete combination structure, and then analyzes the steel-ability concretes to withstand fire from both theoretical and experimental perspectives. Valid data are provided by graphs and equation analysis. Finally, a method that can measure the fire resistance of SC composite structures in fire is obtained.

Keywords: Steel-concrete structures; fire resistance, composite structure.

1. Introduction

The construction and material of bridges have undergone significant change because of advances in science and technology. The main structures of early bridges were Wooden structure and masonry structure. In the 18th century, fires often broke out in Chicago because most of the buildings were made of wood. In this case, people began to look for a new building structure to replace the wooden structure. From then on, the steel structure was born and there are several benefits of using steel structures in engineering. Firstly, the capacity of iron to span longer distances with metal ceiling joists is the first and most obvious benefit of adopting a steel framework in building. Secondly, s Second, compared to load cement or wood components, steel frame components are both stronger and lighter. Not only these three benefits, but there are also many other advantages of using steel structure [1]. In real life, there are also examples of steel structures. In China, the most famous steel structure is the Bird's Nest. During the 2008 Beijing Olympics, many people were surprised by the architectural style of the Bird's Nest. In France, the famous Eiffel Tower is also made of steel.

From the point of view of modern human engineering construction history, concrete structures are a novel kind of building as compared to masonry structures, timber structures, and steel structures. Its application is only a hundred years of history. A small “Dictionary of Science”, states that concrete is a synthetic stone-like substance used for several structural applications that is created by combining cement with different aggregates, such as sand, pebbles, gravel, or shale, and letting the mixture set. Humans have used cement throughout history: various forms of the substance date back to some 12,000 years ago, with the oldest known find being a whitewashed floor formed of burnt limestone and clay that was discovered in modern-day Turkey [2]. There is another theory about the origin of early concrete. Around 6500 BC, Nabataean traders or Bedouins who ruled several oases and established a small empire in the areas of southern Syria and northern Jordan created the first constructions that resembled concrete. After learning about the benefits of hydraulic lime, or cement that hardens in water, they began to build the kilns to produce cement for the creation of cement floors and waterproof underground cisterns about 700 BC [3]. Furthermore, using concrete has many benefits such as its highly durable and resilient ability, low maintenance, recyclable and so on.

However, concrete has disadvantages when used alone. To start with, the concrete's tensile strength is rather low in comparison to other binding materials. Also, concrete is not as ductile [4].

By the same token, there are also many defects of steel structure. Firstly, the combination of iron and other metals is called an alloy. Steel is an alloy. It is hence vulnerable to erosion. Anti-corrosion coatings could offer some assistance in resolving this problem. Second, painting is required to make it highly corrosive, increasing maintenance costs. Thirdly, because steel isn't fireproof, expensive fireproofing is necessary. High temperatures lead steel to start losing its properties. Finally, as the temperature changes, steel expands quickly. This can be bad for the whole building [5]. In this case, experts found that if the materials were combined, it might be possible to eliminate the shortcomings of individual materials. Then experts came up with the idea of composite materials. A composite component is a structural component composed of two or more different materials. The advantage of composite materials is the ability to combine the characteristics of each material and reshape them through certain operations. Thus, creating a single component whose overall function is more efficient than its individual components. Despite the availability of other material types, SC materials are the most common type of composite used in construction [4]. Buildings can use steel-concrete constructions to make up for concrete structures' lack of flexibility by taking use of the ductility of steel elements. Like how concrete's resistance to fire may be utilized to make up for steel's inability to withstand high temperatures of heating. Nowadays, combined steel-concrete structures have an irreplaceable role in most bridge construction, especially in large span bridges. Steel-concrete structure has excellent performance. Compared with steel structure, it can save steel and improve the bearing capacity; compared with concrete structure, it can reduce the building height and increase the design span, also has better shear resistance. In this context, this paper first provides an overview of steel-concrete structures, followed by the progress of research on combined steel-concrete bridge structures. The research progress is mainly about the study of material properties of steel-concrete after fire. The main goal of this paper is to find out the changes of steel-concrete structures after passing through a flame, while focusing on the properties of the material after being subjected to fire.

2. Overview of Steel-concrete Structures

2.1. Composite Structure in Foreign Countries

In foreign countries, various methods of shear connection between steel beams and concrete flanges were introduced in the mid-1930's. In the 1950's, pressed steel plates began to be used in construction projects. In 1960, the federal court building project in Brooklyn, the first use of nail fusion welding of the pressed steel plate concrete combination floor system. With the popularization and application of the combined structure, steel-concrete structure is also gradually developed [6].

2.2. Composite Structure in China

The design idea for composite beam was first mentioned in China in 1974. For the first time in the content of "steel and concrete composite beam," the design code of our nation's steel structure was included in 1988, indicating that the combination structure had received more attention. With the continuous and steady growth of the world economy, the transportation infrastructure has also been developed rapidly. However, there are more and more traffic accidents due to overloading of vehicles, speeding and drivers' fatigue. With the flying start of the transportation industry, the transport vehicles of fuel and dangerous goods are significantly increasing, and the resulting bridge fire is also increasing year by year. Bridge fires can cause serious economic losses and even casualties. The steel - concrete structure will be seriously deteriorated under the action of high temperature in fire, especially when the concrete occurs after high temperature burst, the thickness of the concrete protective layer becomes smaller. When the steel bar is exposed directly, the attenuation degree of bridge pier bearing capacity will be aggravated and the safety of bridge superstructure will be seriously threatened. Therefore, it is very important to study the properties of steel - concrete structures after fire.

2.3. Material Properties after High Temperature

For steel-concrete hybrid structures, under the action of fire and high temperatures, steel will suffer greater damage than ordinary concrete girder bridges because of its poorer ability to resist fire than concrete. Specifically, the strength and modulus of elasticity of steel are reduced as temperatures increase, resulting in cross-sectional damage and excessive deformation leading to failure and collapse. To study the basic material automatic properties and characteristics of composite girder bridges after high temperature (fire), some useful conclusions have been made through data collection and material comparison, which can provide some useful information for the basic material properties of composite girder bridge design against fire [7].

3. Theoretical Studies- Methods of Fire Resistance Analysis of Structural

3.1. The Finite Element Software

Zhou et al. [8] argued in their paper that using the specific kind of software ANSYS, which is popular in engineering, to analyze the fire rebellion of the SC beam, also the parameters about concrete slab, SC beam and pegs, the parameters of the longitudinal strengthening in the concrete slab, and the load parameters that affect the fire rebellion ability of the synthetic beam. The final study shows that the loading ability and the concentration of the fire protection layer are the two main data influencing the fire rebellion ability of the SC synthetic beam. Zhou et al. [9] argued that the ANSYS was used to carry out the fire resistance analysis of the SC beam, and the finite element model was used to analyze the fire environment of the SC beam with different types of compression iron plates. This study shows that: different types of compression steel plates have little influence on the fire resistance (FR) of the composite beam. The composite beam with four typical boundary conditions can be reduced to simply supported and solidly supported composite beams for fire resistance calculation. The additional curving moment caused by the force is smaller when the fully solidly supported SC beam is in the hot temperature state, the lower flange of the steel beam in the negative moment zone is more likely to be locally buckled, and finally the plastic hinge is generated at the end of the beam and in the span and destroyed. Zha [10] used DYNA3D finite element software to analyze the FR of axially pressed columns of round steel pipe concrete in his research. Ding and Wang [11] argued in his paper that ANSYS and ABAQUS software were used to study the FR of round SC pipe and square SC pipe columns, respectively.

3.2. Neural Networks

Abdullateef and Mohammad [12] argued that the neural network model was used to train the neural network and predict the fire resistance limit by using the learning samples with the determination of each test parameter and fire resistance limit of the steel pipe concrete axial compression column.

3.3. Parsing method, Semi-analytic Semi-numerical Value Method

Ranzi and Bradford [13] gave an analytical calculation method for the loading ability of SC beams with partial shear connection under high temperature in his paper. Benedetti and Mangoni [14] proposed that an analytical calculation way for the mechanical properties of SC beams under fire is given based on Fourier series expansion. Li [15] argued that the loading capacity of steel pipe (reinforced) concrete axial and biased columns under standard fire is analyzed by Rankin's method, and a method for solving the plastic compression bending loading capacity of SC pipe under fire is proposed.

3.4. Fiber Model Method and Conjugate Beam Method

Lie and Stringer [18] argued in his research that a simplified formula for figuring the FR of round SC pipe and square SC pipe was proposed using the fiber model method. Kodur [19] argued that further proposed a simple way that can calculate the FR limit of round SC pipe and square SC pipe by using the fiber model method. The effects of the magnitude of the load acting on the member under fire, the type of concrete aggregate, the effective calculated length of the insider, the section created by a plane cutting a solid perpendicular to its longest axis dimensions and the concrete strength were considered in this formula.

4. Experimental Analysis

4.1. Standard Temperature-time Curve

To accurately assess the FC of SC under fire, the degree of damage, and to give reasonable measures for the repair of the structure after fire. In recent years, many experimental studies and theoretical analyses of the stress performance of reinforced concrete materials and their members under high-temperature fires have been carried out at home and abroad. The high temperature effect of fire on the structure is mainly reflected in the temperature rise - time curve, and the force performance of reinforced concrete under high temperature mainly depends on the thermal properties of its material and the temperature assignment of the members. Therefore, determining the fire heating curve is the basis for studying the fire resistance of structures. Shi [16] argued in his research on force performance of steel-concrete structures at high temperatures. A standard temperature-time curve given by the International Organization for Standardization (ISO) in 1990 was used as follows.

$$T = 3451g(8t + 1) + 20 \quad (1)$$

where T is the average temperature in the test furnace (℃); t is the time experienced by the fire (min).

Using this equation, the temperature rise curve and temperature field are calculated and combined with experimental studies. By pre-installing temperature sensors inside and on the outface of the SC frame experimental equipment, the temperature of each point is measured with the temperature inside the furnace after the experimental equipment is heated up, providing images of various temperature field curves. In this case it is possible to derive a general picture about the performance of the steel-concrete structure at high temperatures.

4.2. In-furnace Test Analysis

Zhang [17] provided actual heating curves inside the furnace, steel beams, heating processes inside the concrete slab and vertical displacement-time relationship curves in the span of the combined beams.

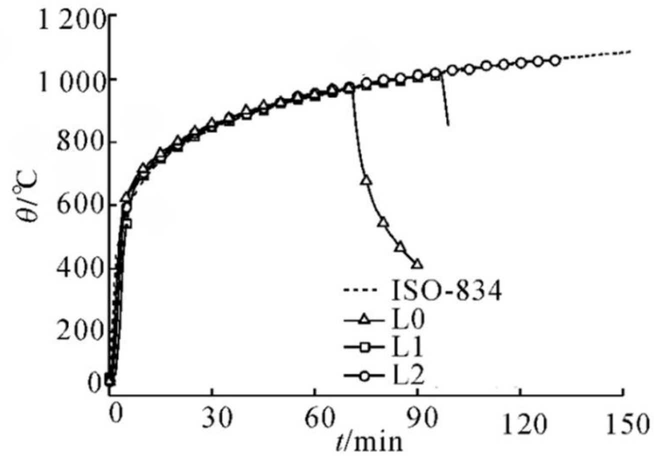

Fig. 1 Temperature-time curve [19]

Figure 1 provides a visualization of the deformation and load relationships of the three materials under continuous heating. The mid-span deflection reaches its ultimate deflection value after five minutes of continuous heating. Table 1 provides the main parameters of specimens to help readers better understand the material properties of the curve in the Figure 1.

Table 1. Parameters of specimens [19]

Specimen number	h_c/mm	d_i/mm	F/kN	Steel beam cross section/mm	Type of steel
L_0	100	15	100	H400*150*10*10	Q345B
L_1	100	15	100	H400*150*10*10	Q345-FR
L2	100	25	100	H400*150*10*10	Q345-FR

4.3. Simplification of Numerical Analysis Method

For further study the fire resistance of SC frame, separate analyses of steel and concrete are required. In this thesis a simplified numerical approach will be presented to analyze the thermodynamic properties of steel materials and its coefficients, and the thermodynamic properties of concrete materials and its coefficients.

4.3.1 Thermodynamic properties of steel

Coefficient of thermal expansion of steel α_s [20]

The coefficient of thermal expansion recommended by ECCS and adopted by European norms is:

$$\alpha_s = 1.4 * 10^{-5} m/(m \cdot ℃) \tag{2}$$

Thermal conductivity of steel λ_s [21]

The thermal conductivity of steel decreases with increasing temperature

UK specification takes a constant：

$$\lambda_s = 37.5 W/(m \cdot ℃) \tag{3}$$

Density of steel ρ_s [22]

The density of steel varies very little with temperature and can be taken as a constant:

$$\rho_s = 7850 kg/m^3 \tag{4}$$

4.3.2. Thermodynamic properties of concrete

Coefficient of thermal expansion of concrete α_c [22]

In order to facilitate the calculation, Lie gives the relationship between the coefficient of thermal expansion of concrete and temperature as

$$\alpha = (0.008T + 6) * 10^{-6} \tag{5}$$

Thermal conductivity of concrete λ_c [23]

The thermal conductivity is the rate of heat flow per unit area through an isothermal surface per unit temperature gradient. The type of orthopedics has a large effect on it. A simplified formula is provided:

$$\lambda_c = 1.9 - 0.0085T \qquad 0℃ \le T \le 800℃ \tag{6}$$

$$\lambda_c = 1.22 \qquad T \ge 800℃ \tag{7}$$

Density of concrete ρ_c

The density of concrete can be viewed as a constant: the

$$\rho_c = 2400 kg/m^3 \tag{8}$$

4.3.3 Solution of the heat conduction equation

When a fire occurs, the fire field temperature and the properties of the components change with time, so the temperature field within the build is a non-linear transient problem, and to simplify the analysis process, the thermal properties of concrete and steel are usually considered to be uniform and homogeneous. The above-mentioned equations and constants concerning the thermodynamic properties of steel and concrete are introduced into mathematical calculations, such as the two-dimensional temperature field derived differential equation and the three-dimensional temperature field derived differential equation. In his thesis, Cha [23] used the nonlinear finite element method to consider the thermal propagation within the cell and the thermal propagation on the boundary surface and completed the study of the steel-concrete fire bearing capacity using computer programming and matrices.

5. Conclusion

(1) By changing the parameters of steel beam cross-sectional size, steel grade, concrete strength grade, and coefficient of thermal expansion of materials, it was analyzed that the height of steel beam, thickness of combined floor slab, load ratio, and data of thermodynamic inflation of iron were the mainly factors influencing the fire rebellion of high performance fire-resistant weathering steel-concrete simply supported combined beam.

(2) The material and mechanical property parameters of suitable high-temperature thermal performance were selected, and the fire resistance analysis model of high-performance fire-resistant weathering steel-concrete composite beam was established by using ABAQUS general software, and the precise of the model was verified by involved tests.

(3) The outcome of this paper provide a theoretical analysis of the fire resistance of refractory steel-concrete composite beams, which can be used as a reference for the design and application of refractory SC composite beams, and provide a basis for the development of standards and codes for the fire rebellion design of refractory SC composite beams.

References

[1] Monalisa Patel. Advantages and disadvantages of Steel Structures. August 2, 2019. Retrieved on September 13, 2022. Retrieved from: https://gharpedia.com/blog/advantages-and-disadvantages-of-steel-structures/

[2] Rainer Nobis. Illustrated History of Cement and Concrete. Retrieved on September 13, 2022. Retrieved from: https://www.worldcementassociation.org/about-cement/our-history

[3] Nick Gromicko, CMI and Kenton Shepard. The History of Concrete. Retrieved on September 13, 2022. Retrieved from:https://www.nachi.org/history-of-concrete.htm#ixzz31V47Zuuj

[4] Dan. Concrete-steel composite structures. Last edited Oct 27, 2021. Retrieved on September 13, 2022. Retrieved from: https://www.designingbuildings.co.uk/wiki/Concrete-steel_composite_structures

[5] Family-run Business. Advantages and Disadvantages of Structural Steel Structures. January 04, 2018. Retrieved on September 14, 2022. Retrieved from: https://northern-weldarc.com/advantages-disadvantages-structural-steel-structures/

[6] Zihai Shi, Hajime Kubo, Structural analysis theories and experimental studies on sewer renovation. Retrieved on September 15, 2022. Retrieved from: https://www.sciencedirect.com/topics/engineering/shear-connection

[7] Astaneh-Asl A, Noble C, Son J, Wemhoff AP, Thomas M, & McMichael LD. Fire Protection of Steel Bridges and the Case of the MacArthur Maze Fire Collapse. June 24, 2009. Retrieved on September 16,2022. Retrieved from: https://www.semanticscholar.org/paper/Fire-Protection-of-Steel-Bridges-and-the-Case-of-Astaneh-Asl-Noble/fdb1f979f44ecaf78aba00040d8239c4252f581c

[8] Zhou Hongyu, Li Guoqiang, Wang Yinzhi. Parametric studies on fire resistance of simply supported steel concrete composite beams. Steel Construction, 2005, 20(6): 92-96.

[9] Zhou Hongyu, Li Guoqiang, Wand Yinzhi. Analysis of two factors influencing the fire-resistance of composite beams. Progress in Steel Building Structures, 2006, 8(5): 40-45.

[10] Zha Xiaoxiong. FE analysis of fire resistance of concrete filled CHS columns. Journal of Constructional Steel Research, 2003, 59(7): 767-799.

[11] Ding J, Wang YC. Realistic modelling of thermal and structural behavior of unprotected concrete filled tubular columns in fire. Journal of Constructional Steel Research, 2008, 64(10): 1086-1102 .

[12] Abdullateef MA, Mohammad JT. Prediction of fire 108resistance of concrete filled tubular steel columns using neural networks. Fire Safety Journal, 2002, 37(4): 339-352 .

[13] Ranzi G, Bradford MA. Analytical solutions for elevated-temperature behavior of composite beams with partial interaction. Journal of Structural Engineering, ASCE, 2007, 133(6): 788-799 .

[14] Benedetti Andrea, Mangoni Enrico. Analytical prediction of composite beams response in fire situate[J]. Journal of Constructional Steel Research, 2007, 63(2): 221-228 .

[15] Li Guoqiang, Wang Yinzhi, Wang Kongfan. Research on fire resistance capacity of composite beams with considering axial restrains. Chinese Quarterly of Mechanics, 2006, 27(4): 726-732.

[16] Shi Xudong, Crossing Zhenhai.Reinforced concrete under high temperature stress performance test research. Journal of civil engineering, 2000, (6): 6-16.

[17] Jiang X, Tong GS, Zhang L. Experiments on fire-resistance performance of fire-resistant steel-concrete composite beams. Journal of Zhejiang University (Engineering Science), 2016.

[18] Lie TT. Stringer DC. Calculation of the fire resistance of steel hollow structural section columns filled with plain concrete. Canada Journal of Civil Engineering, 1994, 21(3): 382-385 .

[19] Kodur VKR. Performance-based fire resistance design of concrete-filled steel columns. Journal of Constructional Steel Research, 1999, 51(1):21-36.

[20] Elsevier Science Pub. Co. Recommendations for the Fire Safety of steel structures. Elsevier Scientific Publishing Company, 1983.

[21] BSI. Structural Use of Steel work in building. Part8. Code of Practice for Fire Resistance Design, 1990 .

[22] LieTT. A Procedure to Calculate Fire Resistance of Structural Members. International Seminar on Three Decades of Structural Fire Safety, 1983, 22, 139-153.

[23] Zha Xiaoxiong and Zhong shantung. Calculation of temperature distributions in steel, concrete and composite member under different fires. Journal of Harbin architecture University. 2002,35(2):5.