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A simplified approach for fire-resistance design of steel-concrete composite beams

Guo-Qiang Li[1,2] and Wei-Yong Wang[3]*

[1]*College of Civil Engineering, Tongji University, Shanghai, 200092, P.R. China*
[2]*State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, 200092, P.R. China*
[3]*College of Civil Engineering, Chongqing University, Chongqing, 400045, P.R. China*

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Abstract. In this paper, a simplified approach based on critical temperature for fire resistance design of steel-concrete composite beams is proposed. The method for determining the critical temperature and fire protection of the composite beams is developed on the basis of load-bearing limit state method employed in current Chinese Technical Code for Fire safety of Steel Structure in Buildings. Parameters affecting the critical temperature of the composite beams are analysed. The results show that at a definite load level, section shape of steel beams, material properties, effective width of concrete slab and concrete property model have little influence on the critical temperature of composite beams. However, the fire duration and depth of concrete slab have significant influence on the critical temperature. The critical temperatures for commonly used composite beams, at various depth of concrete and fire duration, are given to provide a reference for engineers. The validity of the practical approach for predicting the critical temperature of the composite beams is conducted by comparing the prediction of a composite beam with the results from some fire design codes and full scale fire resistance tests on the composite beam.

Keywords: steel-concrete composite beam; fire-resistance design; load level; critical temperature

1. Introduction

A steel–concrete composite beam consists of a concrete slab attached to a steel beam by means of shear connectors. The use of steel–concrete composite beams has gained popularity in the last century thanks to its ability to well combine the advantages of both steel and concrete. Composite members exhibit enhanced strength and stiffness when compared to the contribution of their components acting separately, and represent a competitive structural solution in many civil engineering applications, such as bridges and high-rise buildings. However, the steel component in steel-concrete composite beams is sensitive to fire due to the fact that its strength and elastic modules will be reduced quickly when exposed to fire.

Over the last decade, many research papers have been published relevant to the behavior of composite structures in fire. Ranzi *et al.* (2007a and 2007b) presented a novel numerical model for the analysis of composite steel–concrete beams at elevated temperatures accounting for both

*Corresponding author, Associate Professor, E-mail: wwyong200@yahoo.com.cn

longitudinal and transverse interaction. The analytical model is derived by means of the principle of virtual work and its accuracy is validated against limit conditions for which analytical solutions are available in the literature.

Lamont *et al.* (2001) used an adaptive heat transfer program HADAPT to model the heat transfer to the composite steel and concrete slab. HADAPT is a 2D adaptive heat transfer code capable of carrying out a nonlinear, transient, thermal analysis. The measured concrete temperatures in Cardington Tests 1–3 have been used to calibrate the model and found that the slab temperatures in Tests 1–3 have been modeled satisfactorily. Wang *et al.* (1998) presented the results of a theoretical investigation into the effectiveness of a novel way to significantly reduce the fire protection cost to a composite beam. In the method, only the steel lower flange and a fraction of the steel web are protected.

A procedure for finite element thermal analysis of composite steel and concrete beams was described and implemented by Fakury *et al.* (2005) in a finite element based computer program, as well as a procedure for the consideration of a common type of composite connection of partial resistance in the behavior of multi-span beams when designed as semi-continuous. Benedetti *et al.* (2007) presented an analytical procedure for the incremental thermo mechanical solution of simply supported composite beams. The main feature of this procedure is the use of a series expansion of the finite stiffness temperature dependent fastening effect of the steel connectors. Hozjan *et al.* (2011) performed analysis on steel-concrete composite beams in fire condition by considering interlayer slip between concrete and connectors. Wellman *et al.* (2011) carried out test on thin composite floor assemblies (similar with steel-concrete beam) under fire loading and Kodur *et al.* (2013) conducted modelling on the response of composite beam–slab assemblies exposed to fire.

To ensure fire-safety of steel buildings, fire protection is required to limit the temperature rise in the steel components under fire condition. The required fire protection to a steel component is traditionally determined based on the results of standard fire resistance tests. At present, analytical methods proposed in BS 5950 (1990) or ENV 1994-1-2 (1994) may also be used. In CECS200:2006 (2006), an analytical method is also provided to check the load bearing capacity of steel-concrete composite beams in fire. Nevertheless, the analytical method for calculating the ultimate moment of composite beams capacity in fire is a little complex and difficult for engineers to utilize in fire-safety evaluation and design in practice.

In this paper, a simplified approach is presented to determine the fire protection of composite beams at various load level exposed to ISO834 standard fire in required fire duration. The novelty of this approach is its convenience in determining the critical temperature and furthermore the required fire protection of composite beams. The validation has been verified by some fire design codes and experiment.

2. Material properties and temperature calculation

The strength of concrete will be reduced with the elevation of temperature, and the reduction factor of concrete cylinder compression strength at elevated temperatures proposed in CECS200:2006 (2006) can be used for this study and is listed in Table 1.

In order to conveniently use the cylinder compression strength at elevated temperatures in computer program, a fitting formula to calculate the reduction factor of concrete cylinder compression strength at elevated temperatures is given as

$$f_{cT} = f_c/(1+e^{\frac{T_c-569}{157}}) \tag{1}$$

Table 1 Strength reduction factor of concrete at elevated temperatures

Temperature (℃)	20	100	200	300	400	500	600	700	800	900	1000	1100	1200
Reduction factor	1	0.95	0.9	0.85	0.75	0.6	0.45	0.3	0.15	0.08	0.04	0.01	0

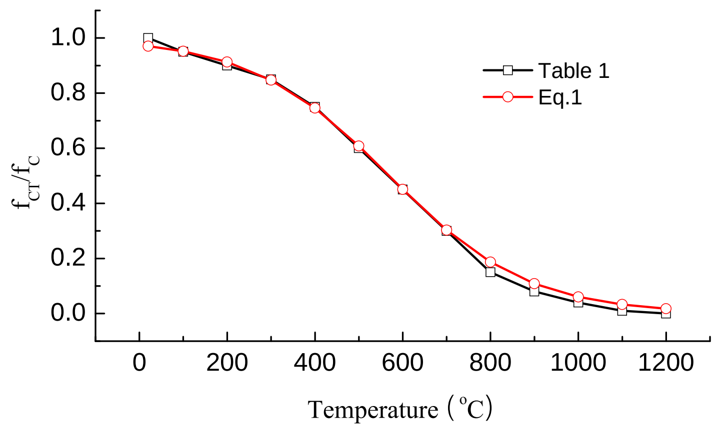


Fig 1 Comparison of Table 1 and Eq.1

where f_c is the concrete cylinder compression strength at normal temperature; f_{cT} is the concrete cylinder compression strength at elevated temperatures; and T_c is the temperature of concrete.

The comparison of Table 1 and Eq.1 is given in Fig 1. As can be seen from the Fig, there is a good fit between them.

At elevated temperatures, the yield strength of steel reduces. Although lots of recommendations may be found in the literature for various standard of steel, the following expressions recommended by CECS200:2006 (2006) may be employed for determining the reduction of the yielding strength of steel, which is given as

$$f_{yT} = \eta_T f_y \tag{2}$$

in which

$$\eta_T = \begin{cases} 1.0 & 20°C \le T_s \le 300°C \\ 1.24\times10^{-8}T_s^3 - 2.096\times10^{-5}T_s^2 & \\ +9.228\times10^{-3}T_s - 0.2168 & 300°C < T_s < 800°C \\ 0.5 - T_s/2000 & 800°C \le T_s \le 1000°C \end{cases} \tag{3}$$

where T_s is the temperature of steel; f_y is the yield strength of steel at normal temperature, and f_{yT} is the yield strength of steel at elevated temperatures.

The average temperature of concrete slabs subjected to standard fire is determined by the depth of the concrete slabs and fire duration, which can be obtained from Table 2 given in CECS200:2006 (2006).

Table 2 Average temperature in concrete slabs subjected to standard fire

Depth of slab（mm）	Fire duration(min)			
	30	60	90	120
≤50	405	635	805	910
≥100	265	400	510	600

The temperature of H-shaped steel beam consisting of a steel-concrete composite beam subjected to standard fire can be obtained by dividing the steel beam into two parts, i.e. the upper flange, which is exposed to fire with three sides, and the inversed T shape part including the web and lower flange, which is exposed to fire with all sides. According to the section shape coefficient defined as F/V, where F is the area per length of steel beam exposed to fire; V is the volume per length of steel beam; the temperature of the steel parts can be obtained from Table 3 at different time exposed to fire, given in CECS200:2006 (2006).

Table 3 Temperature of bare steel members exposed to ISO834 Standard fire

time (min)	Temperature of atmosphere (℃)	Section shape coefficient F/V(m^{-1})									
		10	20	30	40	50	100	150	200	250	300
0	20	20	20	20	20	20	20	20	20	20	20
5	576	32	44	56	67	78	133	183	229	271	309
10	678	54	86	118	148	178	311	416	496	552	590
15	739	81	138	193	246	295	491	609	669	697	711
20	781	112	197	277	350	416	638	724	752	763	767
25	815	146	261	365	456	533	737	786	798	802	805
30	842	182	327	453	556	636	799	824	830	833	834
35	865	221	396	538	646	721	838	852	856	858	859
40	885	261	464	618	723	787	866	874	877	879	880
45	902	302	531	690	785	835	888	893	896	897	898
50	918	345	595	752	834	871	906	911	913	914	915
55	932	388	655	805	871	898	922	926	928	929	929
60	945	432	711	848	900	919	936	940	941	942	943
65	957	475	762	883	923	936	949	952	954	954	955
70	968	518	807	911	941	951	961	964	965	966	966
75	979	561	846	933	956	963	972	974	976	976	977
80	988	603	880	952	969	975	982	984	986	986	987
85	997	643	908	968	981	985	992	994	995	995	996
90	1006	683	933	981	991	995	1001	1003	1004	1004	1004

3. Fire resistance capacity of composite beams

At the elevated temperatures, the load bearing capacity of the composite beam will reduced. To insure the safety of the beam, the working load should be no more than the load bearing capacity of the composite beam in fire, represented as
for simply-supported composite beams

$$M \le M_{uT}^{+} \tag{4}$$

and for rigidly-supported composite beams

$$M \le M_{uT}^{-} + M_{uT}^{+} \tag{5}$$

where M is the moment induced by load on the composite beam in fire, which may be determined as $M = ql^2/8$; q is the distributed load on the beam; l is the span of the beam; M_{uT}^{+} and M_{uT}^{-} are the positive and negative moment bearing capacity of the composite beam at elevated temperatures respectively.

Plastic approach with using the yielding strength distribution over the cross section of composite beams can be employed to determine the positive and negative moment bearing capacity. The cylinder compression stress of concrete and yield strength of steel in fire can be obtained with Eq. (1) and Eq. (2) when the temperature of the concrete slab and steel beam of the composite beam is determined.

4. Critical temperature of composite beams

The ultimate load bearing capacity of composite beams can be obtained based on the shape dimension and material properties. Accordingly, the load level of composite beams can be defined as

$$R = M / M_u \tag{6}$$

where M_u is ultimate moment capacity of composite beams at normal temperature. For simply-supported composite beams (the rib of the steel deck is perpendicular to the steel beam), M_u is the positive moment bearing capacity, and for rigidly-supported composite beams (the rib of steel deck is parallel to the steel beam), is the total of positive and negative moment bearing capacity.

According to the required fire duration of composite beams, the temperature of concrete slabs T_c can be obtained in Table.2. Given an initial time of steel beams exposed to fire (usually 10minutes), the temperature of steel beam can be obtained by Table 3. Then the ultimate moment capacity of composite beam at elevated temperature M_u^T can be obtained at the given temperatures. If M_u^T is bigger than M, then increase the time for steel beam exposed to fire, until the temperature of lower flange reach a temperature T_{cr} at which M_u^T is equal to M. T_{cr} is defined as critical temperature of composite beams. Fig 2 shows the flowchart of the steps associated with the critical temperature calculation.

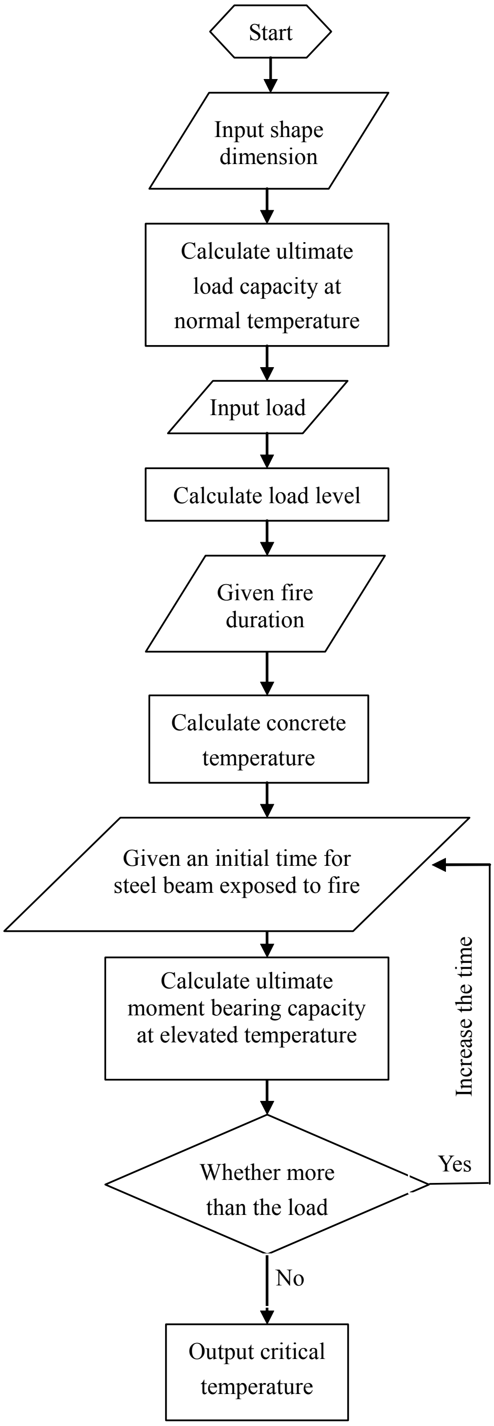


Fig.2 Flowchart showing the steps associated with the critical temperature calculation

5. Parametric study

In order to investigate the parameters affecting the critical temperature of composite beams, parametric study is carried out. The parameters include dimension of beams, strength of concrete and steel, depth of slabs, effective width of concrete slab, required fire duration and concrete property model.

There are variety dimension of composite beams in practice. It is impossible to calculate the critical temperature for all the dimension of composite beams. In this paper, some dimensions widely used in buildings are analyzed. The rib height for steel decks is 75mm. The thickness of concrete slab is within the range of 50mm-100mm and the effective width of the concrete slab is from 1200mm to 1800mm. The required fire duration is often 30 minutes, 60 minutes, 90 minutes or 120 minutes.

5.1 Dimension of beams

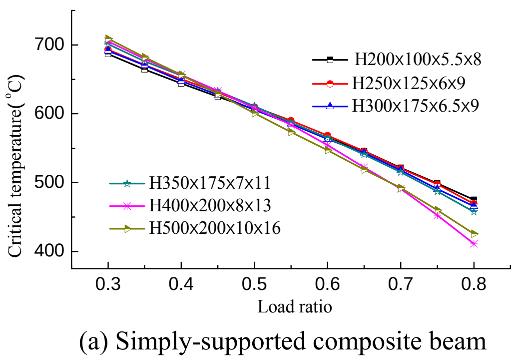
The critical temperatures of composite beams for six kinds of dimensions of steel beams are analyzed at different load level and are plotted in Fig 3. In the analysis, the fire duration is fixed in 60min. The slab depth and effective width of concrete slab are 80mm and 1500 respectively, the steel and concrete grades are Q235 and C35 respectively.

From the Fig 3, it is shown that the steel beam shape has little influence on the critical temperature of composite beams no matter simply-supported or rigidly-supported at the ends of the composite beams.

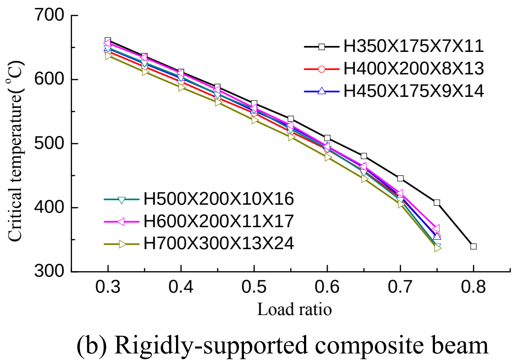
5.2 Grade of concrete and steel

The critical temperatures of composite beams for various grades of steel and concrete are analyzed at different load level and are plotted in Fig 4 and Fig 5. In the analysis, the steel beam shape is H350 X 175 X 7 X 11, the fire duration is 60min and the slab depth and effective width are 80mm and 1500 respectively.

From Figs. 4 and 5, it is observed that the grade of steel and concrete has little effect on the critical temperature of both simply and rigidly supported composite beams.



(a) Simply-supported composite beam

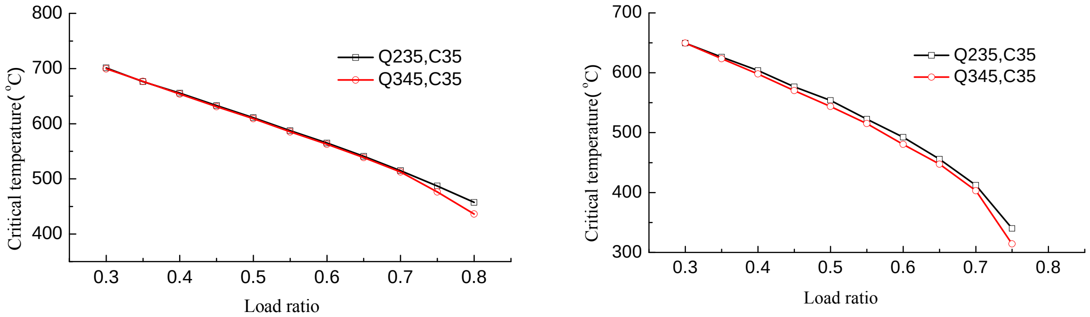


(b) Rigidly-supported composite beam

Fig.3 Influence of steel beam shape on critical temperature at various load level

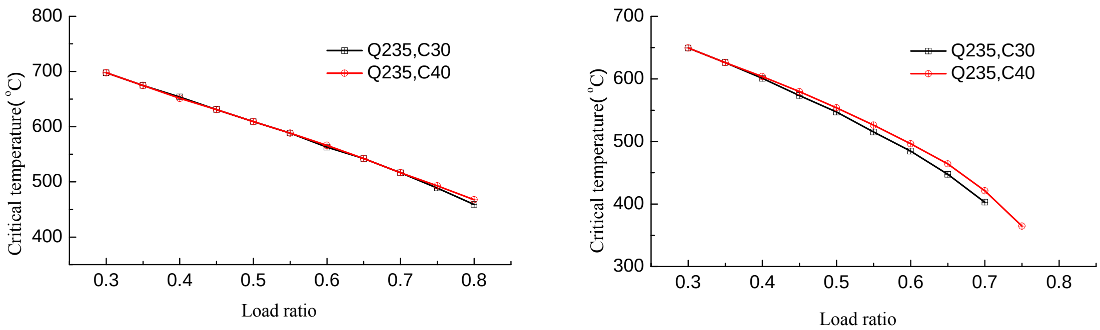
5.3 Depth of slabs

The critical temperatures of composite beams for different depth of slabs are analyzed at various load levels and are plotted in Fig 6. In the analysis, the steel beam shape is H350 x 175 x 7 x11, the fire duration is 60min, the effective width of slab is 1500mm and the steel and concrete grades are Q235 and C35 respectively.



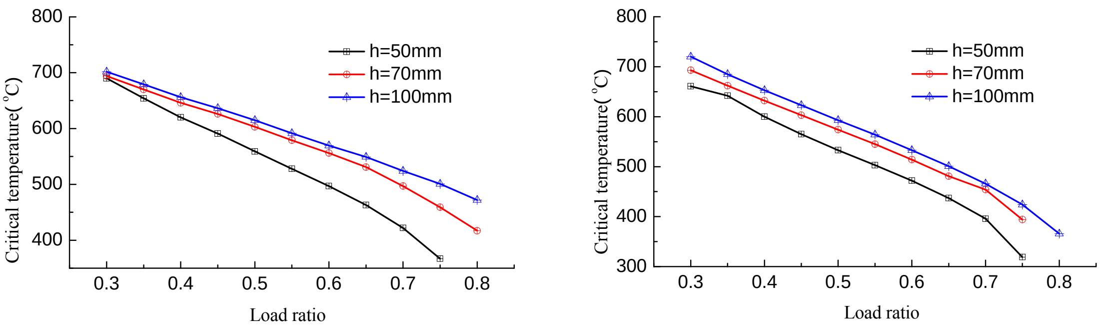
(a) Simply-supported composite beam (b) Rigidly-supported composite beam

Fig.4 Influence of steel strength on critical temperature at various load level



(a) Simply-supported composite beam (b) Rigidly-supported composite beam

Fig.5 Influence of concrete strength on critical temperature at various load level



(a) Simply-supported composite beam (b) Rigidly-supported composite beam

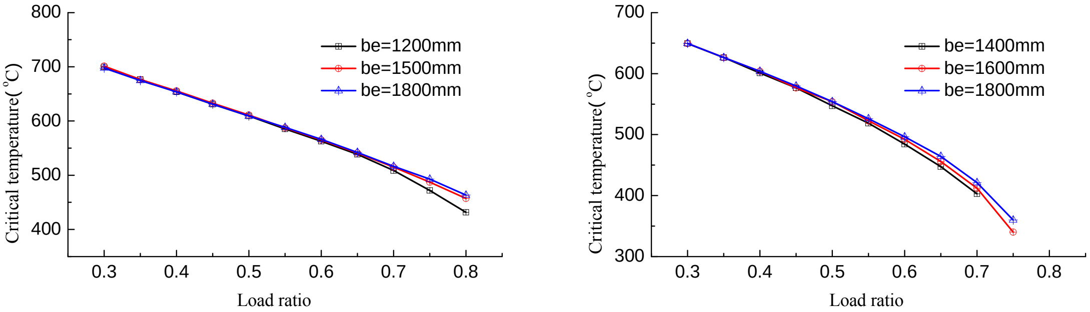
Fig.6 Influence of slab depth on critical temperature at various load level

Fig 6 clearly shows that the depth of slab has significant influence on the critical temperature of both simply and rigidly-supported composite beams. At a particular load level, the thicker the slabs, the higher the critical temperature due to the slab temperature has great relation with the depth at certain fire duration.

5.4 Effective width of concrete slab

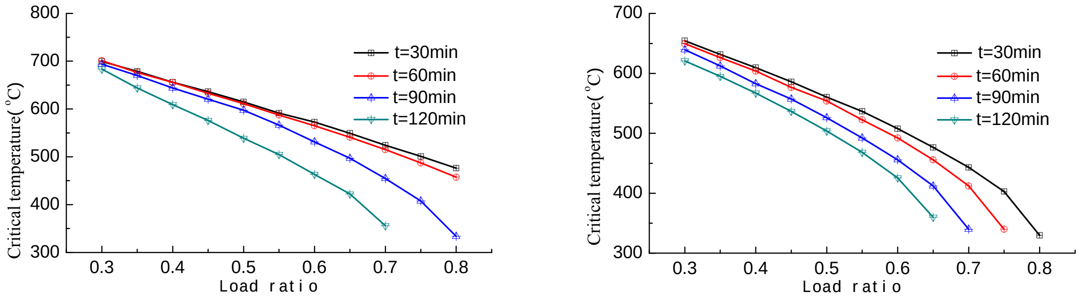
The critical temperatures of composite beams for different effective width of slabs are analyzed at various load levels and are plotted in Fig 7. In the analysis, the steel beam shape is H350×175×7×11, the fire duration is 60min, the depth of slab is 80mm and the steel and concrete grades are Q235 and C35 respectively.

It is shown that, in Fig 7, effective width of slabs has little effect on the critical temperature for composite beams. The effective width only has some influence on the critical temperature at high load level.



(a) Simply-supported composite beam (b) Rigidly- supported composite beam

Fig.7 Influence of effective width on critical temperature at various load level



(a) Simply-supported composite beam (b) Rigidly-supported composite beam

Fig.8 Influence of fire duration on critical temperature at various load level

5.5 Fire duration of composite beams

The critical temperatures of composite beams for different required fire duration are analyzed at various load levels and are plotted in Fig 8. In the analysis, the steel beam shape is H350 X 175 X 7 X 11, the depth and effective width of slab are 80mm and 1500 respectively and the steel and concrete grades are Q235 and C35 respectively.

From Fig 8, it is shown that the required fire duration has great influence on the critical temperature of composite beams. For simply-supported composite beams, the fire duration has little influence on the critical temperature when the fire duration is lower than 60min.

5.6 The effect of temperature in the concrete slab

To understand the effect of temperature in the concrete slabs on the critical temperature of the composite beam, an analysis has been made on a typical concrete-steel composite beam. The steel beam shape is H350 X 175 X 7 X 11.The rib height for steel decks is 75mm. The thickness of concrete slab is 100mm and the effective width of which is 1500mm. The steel and concrete grades are Q235 and C30 respectively. The critical temperature of the composite beam is obtained at various load ratios which is drawn in Fig 9. As can be seen from the figure, at a definite load ratio, the temperature of concrete slab has little impact on the critical temperature of the composite beam when the temperature of concrete slab is low. However, the impact becomes significant when the temperature of concrete slab is high.

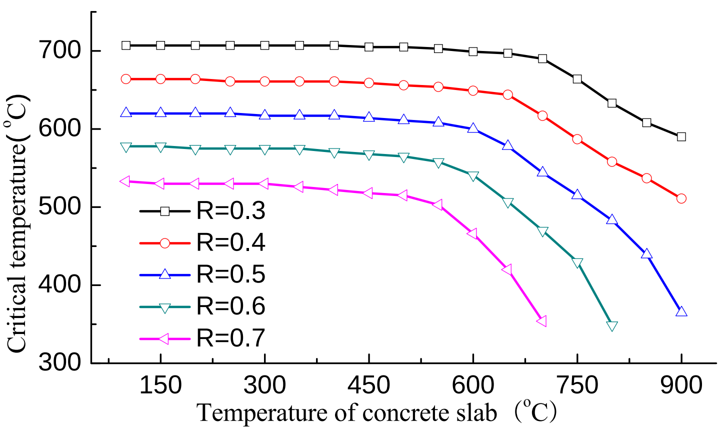


Fig 9 Relationship of temperature of concrete slab and critical temperature of composite beam

5.7 The influence of concrete mechanical property model

The effect of high temperature in concrete slab on fire resistance of composite beams is invariably linked to the high temperature concrete mechanical property model. In order to understand the influence of concrete strength at elevated temperature on the critical temperature, some concrete property models (Lu (1989), Lie *et al.*(1993) and ENV 1994-1-2(1994)) presented in Fig 10 are adopted in the analysis. The critical temperatures are calculated for a typical steel-concrete composite beam at various load ratios. The depth and effective width of the concrete slab is 100mm and 1500mm. The steel deck is GH-344 and the rib height is 76mm. The grade of concrete is C30, with the cylinder compression strength of 14.3MPa. The shape of steel beam is H350 × 200 × 7 ×11, with the steel grade to be Q235. The span of the composite beam is 4m.

The critical temperatures of the composite beam obtained with using various concrete property models are plotted in Fig 11. It is shown that the concrete property model has little influence on the critical temperature of the composite beam.

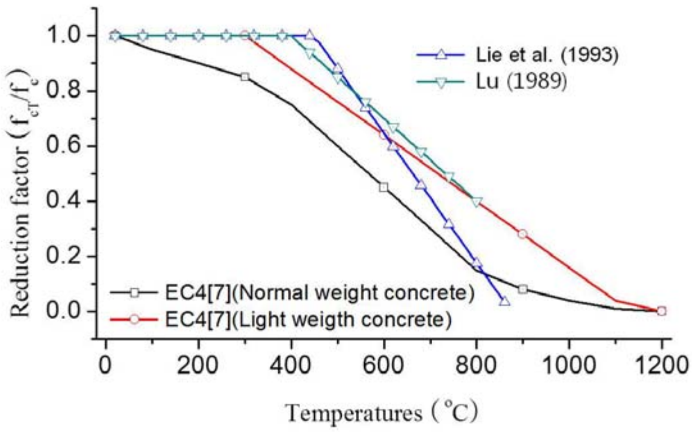


Fig. 10 Concrete property models at elevated temperatures

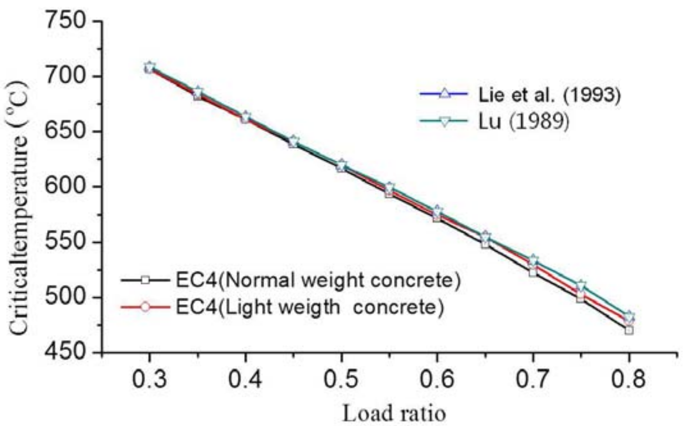


Fig. 11 Influence of concrete property models on the critical temperatures of composite beam

5.8 Discuss and comparison

Through the parametric study above, it can be seen that the fire duration and depth of slab have great influence on the fire resistance of composite steel and concrete beams. This may be due to that the fire duration and depth of slab has great relation with the temperature of concrete. At a definite fire duration, the temperature is higher when the depth of slab is thinner, and with definite depth of slab, the temperature is higher when the fire duration is longer. Some finite element analysis has also been conducted by Zhou *et al.* (2005) to investigate the factors affecting the fire resistance of composite beams. The results of the analysis proved that at a definite load ratio, the depth of concrete slab, number of connectors and shape of steel beams have significant influence on the fire resistance of the composite beams, and the strength of concrete, width of concrete slab and Grade of steel has little influence on the fire resistance of composite beams. Furthermore, load ratio and thickness of fire protection are two key parameters affecting the fire resistance of composite beams. By comparing the finding in this paper and that by Zhou *et al.* (2005), most of them are agree with each other, except that the influence of shape of steel beam on the fire resistance of composite beams is discrepant. This may be due to the degree of influence defined has some difference.

6. Simplified approach for fire resistance design of composite beams

6.1 Critical temperature

From the parametric studies, it is shown that, only slab depth and required fire duration have big influence on the critical temperatures of composite beams. Therefore, based on the method presented in section 4, the critical temperature of composite beams can be obtained according to various depths of slabs and fire durations at various load levels as listed in Table 4 and 5 for simply and rigidly supported composite beams respectively.

Table 4 Critical temperatures of simply-supported composite beams

Load level	Critical temperatures (℃)								
	Fire duration 60(min)			Fire duration 90(min)			Fire duration 120(min)		
	Slab depth 50(mm)	Slab depth 70(mm)	Slab depth 100(mm)	Slab depth 50(mm)	Slab depth 70(mm)	Slab depth 100(mm)	Slab depth 50(mm)	Slab depth 70(mm)	Slab depth 100(mm)
0.3	690	696	702	628	688	700	606	641	698
0.35	654	672	679	597	656	677	576	606	672
0.4	620	649	656	566	620	654	539	573	649
0.45	591	628	636	535	585	631	497	539	626
0.5	559	606	615	501	553	609	441	505	603
0.55	528	582	591	455	520	588	339	463	579
0.6	497	559	569	393	485	566	—	413	556
0.65	463	531	549	—	441	542	—	—	528
0.7	422	497	524	—	393	516	—	—	501
0.75	367	459	501	—	—	489	—	—	472
0.8	—	417	472	—	—	459	—	—	427

Table 5 Critical temperatures of rigidly-supported composite beams

Load level	Critical temperatures (℃)											
	Fire duration30(min)			Fire duration 60(min)			Fire duration 90(min)			Fire duration 120(min)		
	Slab depth 50(mm)	Slab depth 70(mm)	Slab depth 100(mm)	Slab depth 50(mm)	Slab depth 70(mm)	Slab depth 100(mm)	Slab depth 50(mm)	Slab depth 70(mm)	Slab depth 100(mm)	Slab depth 50(mm)	Slab depth 70(mm)	Slab depth 100(mm)
0.3	649	652	657	629	644	657	612	626	652	604	610	647
0.35	626	629	634	604	621	634	586	598	629	577	583	623
0.4	604	607	612	580	595	610	557	570	604	547	557	598
0.45	580	583	589	551	570	586	530	544	580	511	526	567
0.5	554	557	567	522	540	561	496	511	554	468	492	537
0.55	526	533	540	492	511	537	452	476	526	412	452	508
0.6	496	504	515	456	476	508	394	439	496	—	394	468
0.65	460	476	484	417	439	476	—	389	460	—	—	430
0.7	421	439	452	355	389	443	—	—	417	—	—	370
0.75	365	389	412	—	—	398	—	—	350	—	—	—
0.8	—	—	355	—	—	314	—	—		—	—	—

6.2 Determination of thickness of fire protection

The temperature of steel components with fire protection can be approximately calculated by CECS200:2006 (2006)

$$Ts = \left(\sqrt{0.044 + 5\times10^{-5}B} - 0.2\right)t + 20 \tag{7}$$

where B is the comprehensive coefficient of heat conductivity; $B = \frac{\lambda_i}{d_i}\cdot\frac{F}{V}$; F is the area per length of steel members exposed to fire(m); V is the volume per length of steel members(m^2); λ_i is the heat conductivity for fire protection ,W/(mºC); d_i is the thickness of fire protection (m) and t is the duration in fire (s);

The thickness of fire protection can be deduced from Eq.(7). So

$$d_i = \frac{5\times10^{-5}\lambda_i}{\left(\frac{T_{cr}-20}{t}+0.2\right)^2 - 0.044}\cdot\frac{F}{V} \tag{8}$$

7. Example and comparison

An example for fire protection design of a simply-supported composite beam is presented to demonstrate the application of the fire desistance design procedure, and comparison is made between the CECS200:2006, EC4, BS5950 and the simplified approach. As for the rigidly supported composite beams, the procedure is very similar to the simply-supported.

7.1 Basic details of the composite beam

The depth and effective width of concrete slab is 120mm and 1500mm. The steel deck is GH-344 and the rib height is 76mm. The grade of concrete is C30, with the strength is 14.3MPa. The shape of steel beam is H350×150×8×12, with the steel grade is Q235. The span of the composite beam is 4m. The design load is 90kN/m and fire duration is 90min. the heat conductivity of the fire protection is 0.1 W/ (m ºC).

7.2 Result of CECS200:2006

Firstly, the moment at the mid span can be calculated as $M = ql^2/8 = 90\times 4^2/8 = 180\text{kN}\cdot\text{m}$;

Then, it is assumed that the depth of fire protection is 18mm to calculate the steel temperature. The temperature of upper flange of the steel beam with the fire protection is 364 ºC and that of lower flange and web is 688ºC. Thus the ultimate moment resistance capacity is obtained to be 182kN·m, which is larger than *M*. So the critical temperature of the composite beam is 688 ºC.

7.3 Result of EC4

In EC4, the critical temperature of composite beams may be determined from the load level applied to the composite section and from the strength of steel at elevated temperatures according to the relationship

$$1.0\eta_{fi,t} = f_{a\max,\theta_{cr}} / f_{ay} \quad (9)$$

where, $\eta_{fi,t}$ is the load level applied to the composite section; $f_{a\max,\theta_{cr}}$ is the steel strength at the critical temperature and f_{ay} is the yield strength of steel at normal temperature.

According to Eq.(9), the critical temperature of the example composite beam is 642ºC.

7.4 Result of BS5950

In BS5950 (1990), the moment capacity for a composite beam at elevated temperature can be determined from

$$M_{cf} = \frac{M_c K_r}{0.7 + 0.2\left(N/N_f\right)} \quad (10)$$

where, M_{cf} is the moment capacity at the ultimate limit state (using partial material factors given in BS 5950-3.1 for the ultimate limit state); K_r is the strength retention factor for 2 % strain based on the steel temperature of the bottom flange and N/N_f is the degree of shear connection in the cold design.

According to Eq.(10), the critical temperature of the example composite beam is 652ºC.

7.5 Result of the simplified approach

Firstly, the moment at the mid span can be calculated as $M = ql^2/8 = 90\times 4^2/8 = 180\text{kN}\cdot\text{m}$;

Secondly, According to GB 50017-2003 (2003), the ultimate moment bearing capacity of composite beam at normal temperature, which is often already a known quantity at the stage of fire resistance design of composite beams, is 491kNm, and then the load level may be determined by Eq (6), and which is 0.37.

Thirdly, According to Table 4, the critical temperature of the composite beams can be determined to be 672ºC.

7.6 Comparison of critical temperatures

The critical temperatures of the example composite beam obtained respectively by CECS200:2006 (2006), ENV 1994-1-2 (1994), BS5950 (1990) and simplified approach are listed in Table 6. As can be seen from the table, the results of them agree with quite well and the validation of the simple approach is verified.

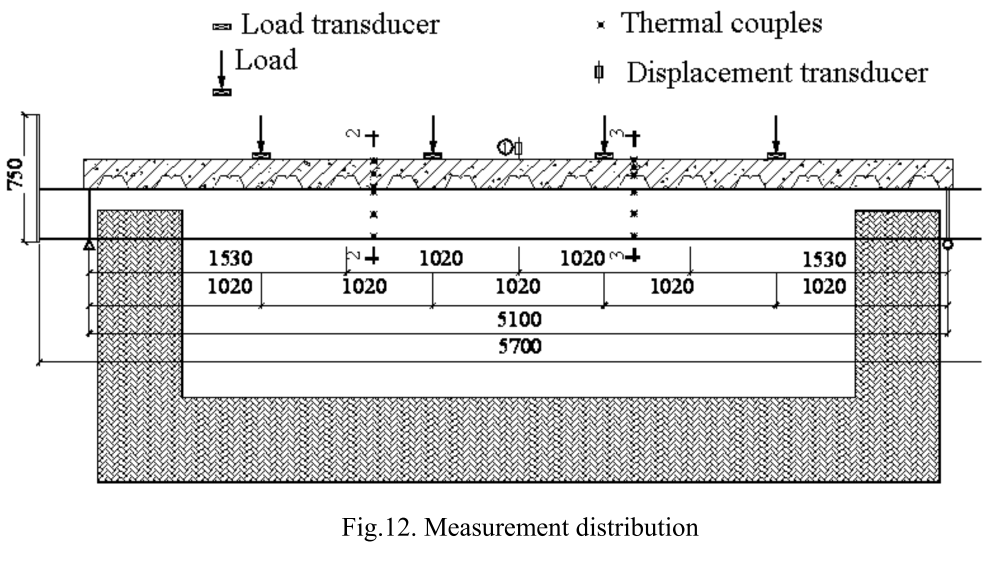
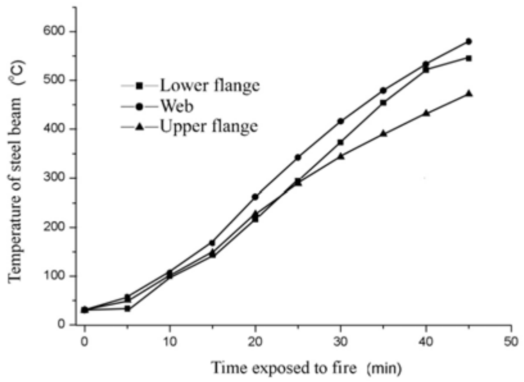
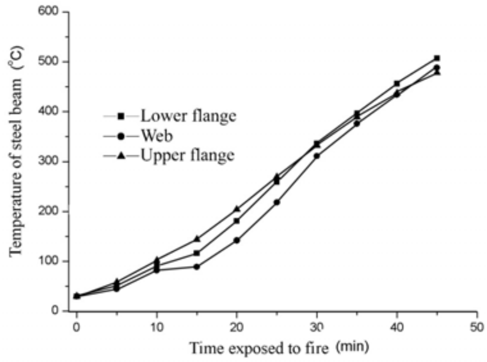


Fig.12. Measurement distribution



(a) Section 2-2



(b) Section 3-3

Fig.13 Temperature results of composite beam by Zhou

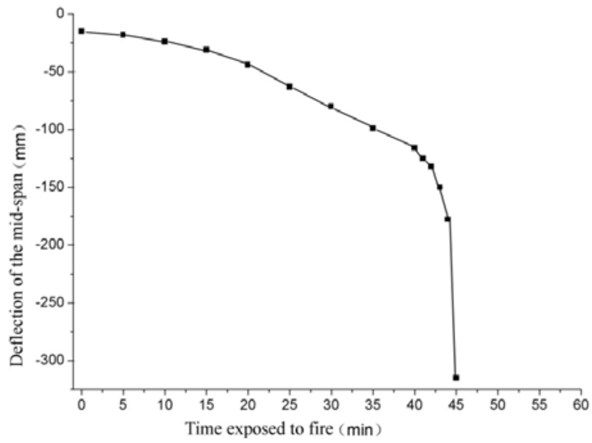


Fig.14 Experiment result of deflection in mid-span

Fig.15. Failure of the Specimen

8. Experimental validation

The simplified approach is validated by an experiment conducted by Zhou (2004) on a full-scale simply-supported composite beam. The width and depth of concrete slab of the specimen is 1350mm and 100mm respectively. The concrete grade is C30. The shape of steel is H300×150×8×8, with the steel grade is Q235B. The load level is 0.7.

Fig 12 shows the measurement distribution of the experiment. The experimental results of temperature of steel beam in section 2-2 and 3-3 are plotted in Fig.13. The deflection of the composite beam in mid-span is shown in Fig.14. The failure mode of the specimen is shown in Fig 15. Form the experimental results, it is observed that the deflection in mid-span increases rapidly after the specimen exposed to fire for 40 minutes. So the critical temperature of the specimen is about 500ºC, obtained from the average of the lower flange and web at the time of 40 minutes of fire exposure (see Fig 13(a)).

From the Table 4, based on the time exposed to fire and load level, the critical temperature for the specimen is obtained to be 472 ºC. The predicted critical temperature obtained with the simplified approach is about 30ºC less than the experimental results. This may be due to the neglect of the contributions of steel deck and reinforced bars to the fire-resistance of composite beams in the simplified approach.

9. Conclusions

In this paper, a simplified approach to obtain the critical temperature and required fire protection is presented. Based on the result of this study, the following concluding remarks can be drawn:

(1) At a definite load level, section shape of steel beams, effective width of concrete slabs, material properties and concrete mechanical model have little influence on the critical temperature of composite beams.

(2) The fire duration and depth of slabs have significant influence on the critical temperature of composite beams.

(3) The simplified approach presented in this study can be simply used to predict the critical temperature of composite beams with an acceptable accuracy.

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