Journal of Constructional Steel Research 129 (2017) 276–285

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Fire behavior and resistance of partially encased and slim-floor composite beams

Jae-Kwon Ahn, Cheol-Ho Lee *

Dept. of Architecture & Architectural Engineering, Seoul National University, Seoul 08826, Republic of Korea

ARTICLE INFO

Article history:
Received 6 July 2016
Received in revised form 15 November 2016
Accepted 16 November 2016
Available online xxxx

Keywords:
Fire resistance
Partially encased beam
Slim-floor beam
Coupled thermal-stress analysis

ABSTRACT

In this study, fire behavior and resistance of unprotected H-section, partially encased (PE), and slim-floor (SF) composite beams were experimentally and numerically investigated under standard fire condition. Experimental results of this study showed that unreinforced or reinforced PE beams and reinforced SF beams can achieve the standard fire resistance of 2 hours or more up to the load ratio of about 0.30. The use of fire reinforcements in SF composite beams was shown to be very effective in increasing the fire resistance time. It was again confirmed that the maximum and average temperature criteria can significantly underestimate or overestimate the realistic fire resistance of PE and SF composite beams. The test-validated coupled thermal-stress analysis indicated that the fire resistance predicted by the bending moment capacity criterion alone can be unconservative for the types of composite beams of this study. It is emphasized that the deflection-related criteria should be considered for the rational fire resistance rating of PE and SF composite beams.

1. Introduction

Conventionally, composite beams have been constructed of H-section steel beams connected to concrete floor slab via shear studs as shown in Fig. 1 (a). The presence of a composite floor slab increases local and lateral stability of H-section beams and the flexural resistance under sagging (or positive) moment. However, since H-section composite beams generally have large section factor (H_p/A, the ratio of the fire exposed perimeter to the cross sectional area of the steel), costly fire protection is often mandatory to maintain their flexural capacity of 30 min or more under standard fire condition. As alternatives, the use of partially encased (PE) or slim-floor (SF) beams, which lead to not only reduced story height but also low section factor in fire, has been suggested [1–6]. As can be seen in Fig. 1 (b) and (c), concrete filling in these beams functions as fire protection and can considerably increase the flexural capacity in fire.

For the last two decades, several researchers have studied the fire behavior of composite beams including PE or SF sections. Kodaira et al. [1] studied the effect of the reinforcement through the fire tests of 8 PE beam specimens with different cross sections and load ratios. (As is well known, the 'load ratio' is a non-dimensional measure of the load resisted by a member at fire limit state. The load ratio is generally defined as the ratio of load or moment at the fire limit state to member resistance at ambient temperature.) They investigated the fire resistance of PE beams based on the deflection criterion or the rate of deflection criterion. The key factors affecting the fire resistance time were reported as the size of the cross section, the connection to the reinforced concrete floor, and the applied load ratio. Piloto et al. [2] experimentally studied the bending limit states of PE beams under both fire and ambient temperature. They investigated the influence of load level on the fire resistance and compared the behavior of PE beams with different stirrup attachments to the web (welded and non-welded stirrups). Newman [3] carried out the fire tests on unprotected SF beams with precast concrete floor. The specimens with different cross-section geometries were subjected to the load ratio ranging from 0.17 to 0.55. All specimens achieved the fire resistance time of more than 60 min without any fire protection.

On the other hand, numerical studies have also contributed to the understanding of the fire behavior of composite beams. In the numerical study by Bailey [4], asymmetric (symmetric about only vertical axis as shown in Fig. 1(c)) composite beams were represented as one-dimensional two-noded finite elements with 7 degrees of freedom. The numerical model used for analyzing simply supported asymmetric SF beams under standard fire was shown to be very accurate. Ma and Makelainen [5] conducted numerical analysis of SF beams by using the commercial finite element analysis code, ABAQUS. The SF beams were modeled by combining shell (concrete slab) and beam (asymmetric steel beam) elements. In their modeling, concrete was assumed to be an elasto–plastic material after reaching compressive and tensile strength. Ellobody [6] investigated the fire behavior of unprotected SF beams by developing a nonlinear 3-dimensional FE (finite element) model. After validating the mechanical and thermal material nonlinearities of concrete and steel components against existing fire tests, the

* Corresponding author.
E-mail address: ceholee@snu.ac.kr (C.-H. Lee).

http://dx.doi.org/10.1016/j.jcsr.2016.11.018
0143-974X/

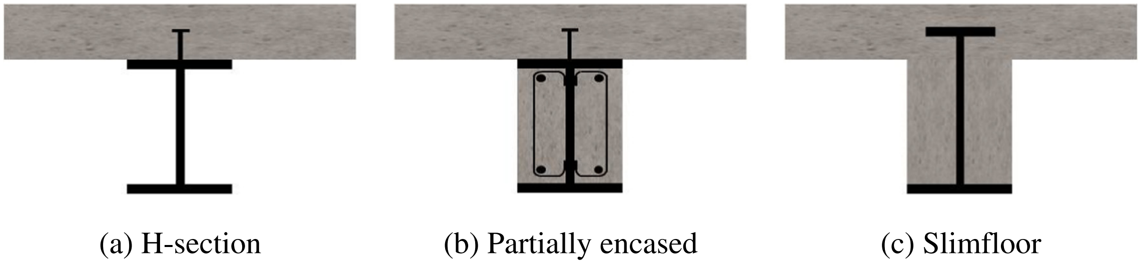

Fig. 1. Typical section details of H-section, partially encased, and slimfloor composite beams.

Table 1
Test specimens.

Specimen	Steel section (mm)	Span (mm)	Fire exposure	Rebar	M_{max} (kNm)	M_p (kNm)	Load ratio (M_{max}/M_p)
HSB-L25	H-294 × 200 × 8 × 12	7700	3 sides	–	126.3	503.8	0.25
PEB-L25	H-294 × 200 × 8 × 12	7700	1 side	–	126.3	503.8	0.25
PEB-R-L33	H-294 × 200 × 8 × 12	7700	1 side	4-D25	228.9	695.9	0.33
PEB-R-L49	H-294 × 200 × 8 × 12	7700	1 side	4-D25	343.3	695.9	0.49
FEB-L50	H-294 × 200 × 8 × 12	7700	–	–	252.6	503.8	0.50
SFB-L34	AH-350 × 230 × 350 × 12 × 19	7700	1 side	–	296.5	881.0	0.34
SFB-R-L34	AH-350 × 230 × 350 × 12 × 19	7700	1 side	4-D25	363.8	1080.5	0.34
SFB-R-L51	AH-350 × 230 × 350 × 12 × 19	7700	1 side	4-D25	545.7	1080.5	0.51

Note: Following abbreviations were used for specimen designation.
HSB = H-Section Composite Beam; PEB = Partially Encased Beam; FEB = Fully Encased Beam; SFB = Slim-Floor Beam; AH = Asymmetric H-section; R = Reinforcement; LXX = Load Ratio in XX (%).

behavior and fire resistance of unprotected SF beams were investigated with considering load ratio, sectional geometries, beam length, and fire scenario as the key variables.

All existing experimental and numerical studies mentioned above have indicated that PE or SF composite beams can be a promising alternative to H-section composite beams. However, despite previous research efforts, understanding of the effects of fire reinforcement and load ratio on the fire behavior of PE and SF composite beams is still insufficient. Although the design recommendations for composite beams under fire are given in EN 1994-1-2 [7] based on the concepts of the critical temperature and the bending moment capacity, behavior predictions per these recommendations are often inaccurate and inconsistent as will be shown in this paper. Further experimental and numerical studies are needed to establish a reliable and simple-to-use design procedure for PE and SF composite beams under fire.

In this paper, fire behavior and resistance of various composite beams including H-section, PE, and SF beams were experimentally investigated through standard fire tests. Cross-sectional shapes, the number of the encased surfaces, the presence of fire reinforcement, and the load ratio of the composite beams were chosen as the key test parameters. Test-validated coupled thermal-stress analyses were also conducted in order to supplement test results.

2. Experimental study under standard fire

2.1. Design of test specimens

In this study, 8 composite beam specimens in total were prepared for experimental investigation as summarized in Table 1. See Figs. 2 and 3 for the specimen details. All H-section and PE beams included H-294 × 200 × 8 × 12 (H-shape section with height × width × web thickness × flange thickness in mm) steel section, and SF beams adopted asymmetric steel section (AH-350 × 230 × 350 × 12 × 19, height × top flange width × bottom flange width × web thickness × flange thickness in mm) made by trimming the tip of the upper flange of H-350 × 350 × 12 × 19. Refer to the note in the bottom of Table 1 for specimen designation. It is noted that three sides of the steel section are exposed to fire in HSB specimen while FEB specimen has no fire exposure. All the remaining specimens have only one-side fire exposure, or the bottom flange is the only side exposed to fire. Three PEB specimens were nominally identical except the load ratio and the presence or absence of fire reinforcements. The same was true of three SFB specimens. Four D-25 fire reinforcements were provided with a concrete cover thickness of 50 mm and 90 mm for PEB and SFB specimens, respectively. Fig. 3 also shows the location of thermocouples in each specimen. Measured mechanical properties of steel,

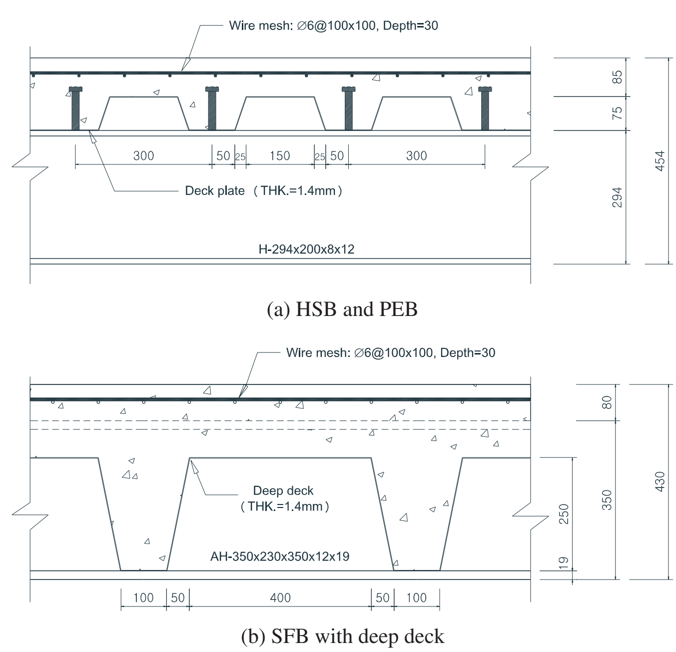

Fig. 2. Longitudinal section details of HSB, PEB, and SFB specimens.