Pre and post-fire mechanical properties of structural steel and concrete in steel-concrete composite cellular beams

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Abstract. This paper presents an experimental investigation into possible variations of mechanical properties of structural steel and concrete in composite cellular beams exposed to ISO 834 fire and cooled down phases. Four full-scale fire tests were performed on protected and unprotected beams under assumed service loads. Tensile stress-strain behavior of steel coupons taken from the beams and compressive strengths of concrete cores taken from the reinforced concrete slabs are studied. Material coupon tests for steel are carried out as per TS EN ISO 6892-1. As for the concrete, compression tests were conducted. Coupon test results reveal that, after fire testing, a maximum reduction ratio of 65% in ultimate strain is obtained for the unprotected beam samples. This indicates that the reductions in the mechanical properties of steel in the protected beams are much less when compared to those of the unprotected beams. It is also found that the maximum increase in post-fire strength/pre-fire strength ratios for concrete is 11% for the unprotected beam, while a 20 % decrease is recorded for water based protected cellular beam. For the protected specimens, the RC slabs were exposed to higher temperatures, and the compressive strength of concrete after testing was lower than that of the unprotected beam slabs.

1 Introduction

With the help of computerized cutting and re-assembly by arc welding, steel-concrete composite cellular beams are frequently used in multi-story steel framed structures for increased strength and stiffness, thereby leading to cost-effective solutions. As such, longer spans can be achieved in addition to integration of building services. Given a maximum depth and minimum service opening dimensions, an optimum solution for cellular beam design is possible. These beams are much affected by fire loading mainly from open web configurations and therefore deserve in-depth investigation. This paper discusses potential changes in material mechanical properties of steel-concrete composite cellular I-beams. Both protected (solvent and water based intumescent coating) and unprotected beams are investigated under ISO 834 [1] heating and cooling phases. Within the scope of this study,

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the effects of pre and post-fire conditions of structural steel and concrete have been analysed via near full-scale specimens.

Several studies [2-4] have examined to understand the post-fire mechanical properties of steel. It is seen that the mechanical properties of steel are based on many factors such as pre-fire material properties of steel, heating-cooling conditions, rates and loading conditions. Post-fire mechanical properties in mild-strength structural steel could be recovered by at least 75 % of their mechanical properties for temperatures up to 600°C [2-3]. Mirmomeni claimed that the behavior of mild steel which has been exposed by high strain loading and temperatures is different in design codes in terms of yield stress and ultimate stress changing with temperature [4].

Similar studies have been carried out to investigate the possible changes in the mechanical properties of concrete after fire [5-7]. Results from these studies reveal that, while the compressive strength of concrete decreased in the short term, long term (1~2.5 years) compressive strength of concrete was improved.

In order to determine the effectiveness of level of fire protection, this study emphasizes on possible variations in mechanical properties of steel and concrete materials used in fire testing of steel-concrete composite cellular beams. This study reviews some of the previous work-done by others and provide valuable insights into experimentally obtained pre and post fire material strengths.

2 Experimental Program

2.1 Specimens

Four full-scale tests were performed on protected and unprotected beams. A total of four beams/specimens (namely, Beams 1, 2, 3, and 4) were designed, manufactured, and tested to failure under fire. The specimens are configured with properties as follows: Unprotected composite cellular beam (Beam 1), unprotected, solid webbed welded built-up composite beam (Beam 2), solvent-based protected composite cellular beam (Beam 3), and water-based protected composite cellular beam (Beam 4). The cellular composite beam specimens, spanning a length of $L=4.7$ m, use a cross section of hot-rolled IPE 140 profile made of a steel grade of S275. A large cell diameter ($H/D_0=0.7$) and closely spaced cell configurations with small intermediate web post values ($w_{\min}=50$ mm) are selected for the evaluation of the worst case scenarios in such beams.

Concrete class selected for the slab/topping is C25/30, showing cylinder and cube strengths, respectively. The slab has dimensions of 4700 mm (length) x 1000 mm (width) x 78 mm (thickness) and was concreted on a trapezoidal steel sheeting deck in a permanent form and as the principal reinforcement for the slab. A widely used S235 steel grade metal deck type with a depth of 38 mm, cell spacing of 151 mm, and thickness of $t=0.7$ mm was selected. A welded wire mesh (Q188/188) with a diameter of 6.0 mm and a 150 mm x 150 mm nominal wire pitch was used as a secondary (non-structural) reinforcement to control (rather than prevent) cracks in the concrete slab. To provide the composite action between the beam and slab, typical welded headed shear studs of 19 mm in diameter and 75 mm in height were used.

Fig.1. Front view and a typical section from the cellular specimens.

2.2 Pre-Fire Mechanical Properties of Structural Steel and Concrete

Standard material coupon tests were carried out following the principles given in TS EN ISO 6892-1 [8]. To determine the material properties precisely, 12 coupons were taken from the specimens having a steel grade of S275 JR and made with IPE 140 for the four beams used in the fire tests. As a result of the tensile tests, the average yield stress obtained from the Beam 1 samples was $R_e = 314$ MPa, whereas the tensile (ultimate) and rupture/fracture stresses were $R_m = 450$ and $R_f = 210$ MPa, respectively. Total elongation of the samples was determined to be 31.1%.

In Beam 2, the average yield stress of the samples was found to be $R_e = 313$ MPa, whereas the tensile and rupture stresses were $R_m = 448$ and $R_f = 300$ MPa. Total elongation amount at fracture was 32.7%. For Beam 3 samples, the average yield stress was $R_e = 309.5$ MPa. Tensile and rupture stresses were obtained to be $R_m = 446$ and $R_f = 130.5$ MPa, respectively. Total elongation was recorded to be 31.6%. Finally, in Beam 4, the yield, tensile, and rupture stresses were determined to be $R_e = 311.6$, $R_m = 438.3$, and $R_f = 269$ MPa, respectively. The average total elongation of the samples was measured to be 38.1%.

Fig. 2. (a) Tensile (coupon) test results, (b) Photo from the tensile test at fracture.

Seven and 28-day compression tests were conducted for concrete samples. During the testing period, the average compressive strength of the concrete samples obtained was 30 MPa. Because this strength is larger than the design value (C25, $f_{ck} = 25$ MPa), composite beam design steps were repeated and revised based on this experimental value. For the structural fire tests, regarding reinforced concrete (RC) elements according to the TS EN 1363-1[9] standard, the duration of concrete drying is specified as at least 3 months (90 days) before the day of the tests. Therefore, the specimens were left to dry until the test day.

2.3 Test Setup and procedure

Experiments were carried out in an accredited fire testing laboratory according to EN 1363-1 [9]. In the experimental scenario, it is assumed that the beams of the building represent a library building in Turkey. As stated in TS 498 [10] standard, for the floor beams of a library, a total load of 30 kN (uniformly distributed) was considered for each tested beam. Beams 3 and 4 were protected using thin film coatings to provide a fire resistance for 60 minutes. After the mechanical load representing the total gravity load was stabilized, in order to obtain the ISO 834 values of the temperature curve in the furnace, 8 burners were activated. During the tests, the gas temperature in the furnace was monitored by 8 plate type thermocouples and a total of 56 thermocouples was used in each beam.

Fig.3. Images from the tests (a) Photo before the test of Beam 4 inside the furnace, (b) Web temperatures of beams in fire tests.

The web temperatures in Figure 3 indicate that Beam 2 reached highest web temperature (820.2 °C) the fastest (at 40 min) at the moment of failure. Although Beam 1 reached 721.2 °C at the failure limit (24.5 min), it was found that the temperature increase was faster than the unprotected solid webbed Beam 2. The solvent-based Beam 3 specimen provided the specified (60 min) fire resistance as designed; the web temperature was determined to be 620.3 °C. Water-based protected Beam 4 was unable to provide the 60 min fire resistance, and the web temperature reached 644 °C at 41 min.

3 Post-fire properties of structural steel and concrete

3.1 Steel

At the end of the fire tests, tensile tests were conducted on the coupon samples taken from the web of steel profiles to determine the potential changes in the mechanical properties of the samples exposed to high temperatures (max. steel temperatures in furnace are given in Table 1) and cooling phase in the furnace with air. For coupon tests, seven pieces were taken from each of the specimens in areas with less deformation. Tensile specimen dimensions were determined and produced according to TS EN ISO 6892-1 [8]. Coupon tests were carried out in an accredited Engineering Building Materials Laboratory close to the fire testing laboratory. Results of the experiments conducted on the coupon samples are shown in Table 1.

Table 1. Mechanical properties of the samples (taken from webs) after testing.

	Max. Steel Temperature at Web (°C)	Yield Stress (R_e) (MPa)	Tensile Stress (R_m) (MPa)	Strain at Failure (%)
Beam 1	721.2	307.0	416	11.4
Beam 2	820.2	332.0	479.0	28.1
Beam 3	620.3	328.5	479.0	26.1
Beam 4	644	312.5	463.0	25.6

According to results from the pre (Fig.2) and post-experiment (Table 1.) mechanical properties of the coupon samples, the greatest reduction in strain at failure was obtained in Beam 1 (cellular beam with no fire protection) with a 65 % reduction. This indicates that the reductions in the mechanical properties of steel material in the protected beams are much less when compared to those of the unprotected beam. Mechanical properties of Beam 2 sample before and after tests were compared, and it was shown that the strain failure decreased by 10%. In Beam 3, a 17% decrease in strain was obtained at failure. Beam 4 showed a 32 % decrease in strain at failure.

3.2 Concrete

Possible changes in the characteristic compressive strength (f_{ck}) of concrete after the fire tests are of significance and were determined by taking core samples from the reinforced concrete slabs according to TS EN 12504-1 [11] standard. Seven samples were taken from Beams 1, 3, and 4. Note that no core samples were taken from Beam 2 since the concrete was severely damaged.

Comparing the average pre (30 MPa) and real post-cooling (post-fire) compressive strength results as given in Table 2, it was found that the post strength/pre-strength variations (increase and decrease) are obtained to be 11 % (max.) and 20 % (min.) for Beam 1 and Beam 4, respectively. These variations are expected results in a concrete element after a fire due to deterioration of the concrete body of the specimens, although the strength may slowly recover (max. 11%) depending on the storage conditions of the specimens.

Table 2. Post-fire compressive strengths of concrete core specimens.

No of Cores	Specimen	Ultimate load (kN)	Compressive strength (MPa)	Post/ Pre- Ratio
1	Beam 1	143.8	33.4	1.11
2	Beam 1	80.7	18.8*	0.63
1	Beam 3	136.7	31.8	1.06
2	Beam 3	135.6	31.5	1.05
1	Beam 4	102.8	23.9	0.80
2	Beam 4	107	24.9	0.83
3	Beam 4	119.7	27.8	0.93

Note that Beam 1 with a star sign (*) gave an unreliable value possibly from inappropriate core sampling.

For all specimens, two main types of crack patterns were determined after examining the composite slabs with trapezoidal steel decking, a welded reinforcing mesh, and cast-in-situ concrete. Both longitudinal (along the beam axis) and transversal cracks were formed on the top surface of each specimen. Owing to the stiffness of the regions near the support

points, the shear force reaches the highest value, and the web buckling and secondary bending effects in the nearest web cells cause concrete slab cracking in the transverse direction, as also observed in a similar study conducted by Cho [12].

4 Conclusions

Potential variations in mechanical properties of structural components of steel-concrete composite beams were examined before and after fire tests. It was determined that the maximum change (reduction) in steel strain at failure was in Beam 1 with 65 % (i.e. unprotected composite cellular beam). On the other hand, change in yield and tensile strengths is negligible and is lower than 10 %.

Compressive strength of the concrete slab before and after the fire tests is also evaluated. Highest decrease is in Beam 1 sample with 11 % [13].

Two types (longitudinal and transverse) cracks were identified in all slabs. It is understood that the cracks perpendicular to the axis of the beam are due to development of local buckling deformations in the web with significant amount of Vierendeel effect due to high shear force in the regions close to the beam support [13].

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