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Steel Frame - Concrete Slab Composite Floor Fire Resistance Experiment†

Serdar SELAMET[1]
Taygun Fırat YOLAÇAN[2]

ABSTRACT

In this study, the first research based structural fire resistance test of a steel-concrete composite floor in Turkey is conducted and the ultimate goal is to fill the knowledge gaps in the current Turkish building code for the structural fire engineering and provide valuable insight for the development of new theoretical, computational and experimental research. The tested composite floor is specifically designed for a high-rise steel building. The floor is equipped with a patent pending mechanism to provide symmetric boundary conditions on two edges. The floor is subjected to ISO-834 standard fire curve from the bottom surface for 105 minutes followed by 90 minutes cooling. Displacement and temperature measurements show that at elevated temperatures, the concrete slab carries the load by the tensile membrane action without a contribution of the secondary beam. This study suggests that secondary steel beams do not need to be fire protected as the concrete slab is adequate to carry the gravity loading during fire.

Keywords: *Fire resistance test, symmetric connection mechanism, structural fire engineering, composite floor, steel connection.*

1. INTRODUCTION

The strength of composite floors, which consist of primary beams, secondary beams, concrete floor and steel connections, will be measured with experimental methods in this study under fire induced high temperatures. In addition to the fire resistance experiment, patent pending new connection mechanism, which is vertically free and capable to transfer moments, is designed. This innovative mechanism enables to conduct fire testing on a larger size floor by reducing its size to one symmetric quarter.

Only the quarter of a real composite floor (8.6 m x 7.6 m) will be exposed to ISO834 standard fire by using the connection mechanism mentioned above and will be air cooled by subsequent 90 minutes. During the experiment, the deflection and temperature values of the composite floor will be recorded and the fire performance of the floor will be examined.

Fire experiments conducted in recent years showed that reinforced concrete slab systems are more resistant to collapse then initially estimated [3, 4]. The reason for this phenomenon is the membrane action which occurs with the edge support given by surrounding beams and

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1 Boğaziçi University, İstanbul, Turkey - serdar.selamet@boun.edu.tr
2 Boğaziçi University, İstanbul, Turkey - firat.yolacan@boun.edu.tr

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columns to the concrete slab. An approximate analytical solution is available for this action [5, 6, 7]. In addition, observations made during the experiment gave information about the collapse mechanism of composite floor systems [8, 9]. Although it is known that concrete slabs are resistant to fire with membrane action against tensile forces, it is a matter of debate whether the steel shear connections could sustain large rotations and tensile forces in such a system [10, 11, 12]. Steel connections have an important function to satisfy structural stability, especially to prevent column buckling by providing horizontal restraint [1, 13, 14]. Therefore, fire induced forces may lead to collapse of steel structure in case of an inadequate connection stress distribution or insufficient ductility. Fire induced large deflections in a composite floor can only be achieved by increasing rotational capacity of the steel connections and sufficient ductile design [15, 16, 17]. In addition, the fire resistance of the bolts differs from other steel materials and this makes it more difficult to determine the fire performance of steel connections [18].

In the light of the literature given above, the contribution of this project to the literature will be as follows:

In previous fire experiments in the literature, only the performance of concrete slabs against fire has been investigated. The fire resistance experiment of the composite system consisting of steel beams and connections will bring a new approach to this research field. In addition, a new connection mechanism that satisfy symmetrical boundary conditions is validated to work efficiently in both room and high temperatures.

2. FIRE RESISTANCE TEST

Figure - 1 shows the symmetrical quarter of 8.6 m x 7.6 m floor system from a high rise building. The symmetrical quarter of the floor system is 4.3 m x 3.8 m in dimensions and consists of primary beams, secondary beams, concrete slab and steel connections. The concrete slab was cured for 4 months and it was prepared for the testing purposes with 2.6% moisture content in accordance with Eurocode Standards. The experiment was conducted in Efectis Era Avrasya Fire Laboratories. According to Turkish Fire Code, all structural members including the slab system must satisfy 120 min fire resistance under the standard fire curve (ISO 834) for buildings that are higher than 30.5 m height [19]. However, for the article mentioned above the steel beams are assumed to be protected against fire. Because the secondary beam was not protected in the experiment, bottom of the floor system was heated for 105 minutes with ISO834 standard fire curve and then it was cooled for 90 minutes in a controlled manner.

1-Primary Beams **2**-Fire Furnace **3**-Secondary Beams **4**-Concrete Slab

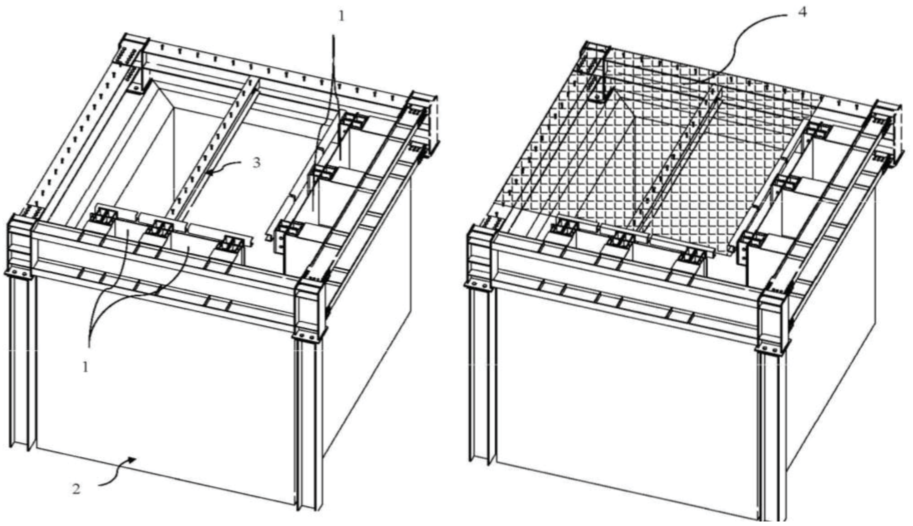


Figure 1. CAD drawings of 4.3 m x 3.8 m sized steel – concrete composite floor system on the fire furnace (a) without concrete slab, (b) with concrete slab

2.1 Test Setup

The structural members that belong to the composite floor system which consists of primary beams, secondary beam, concrete slab and steel connections are labeled in Figure – 1 and Figure – 2. HEA 400 European steel section is used for primary beams that are on the composite floor edges and these beams are connected to each other with a fixed connection. The other two edges of the floor system are symmetrical axes and they are connected to primary beams at the corners with the connection mechanism which satisfy symmetrical boundary conditions as shown in Figure – 3 and Figure – 4. Four primary beams rest on fire furnace walls and connected to the furnace steel frame with shear studs. The concrete slab tested in the experiment is C30 concrete. The concrete thickness varies between 70 to 120 mm which depends on the corrugated steel sheet. S500 A252 types steel reinforcement mesh is placed in the concrete slab with 50 mm concrete cover from the bottom surface. IPE330 European steel section is used as the secondary beam and is placed at the center of the floor. IPE330 is connected with HEA400 via a shear connection shown in Figure – 3. The steel frame of the floor system weighed nearly 11 ton and with the concrete slab, the floor weighed 14 tons.

Composite floor system is placed horizontally over the fire furnace. During the assembly of the composite floor, the primary beams seated on the fire furnace walls were fastened with steel bolts and welding. The entire area of the slab, IPE330 and steel shear connections remained inside the fire furnace and directly exposed to fire. HEA 400 beams and the edge beams that satisfy the symmetrical boundary conditions (total of four members) remain outside of the fire furnace and are indirectly exposed to the fire. All parts of the composite floor except the symmetrical connection mechanism and the shear connection remained unprotected from fire. Two pieces of 25 mm ceramic wool insulation are used to protect the symmetric boundary condition mechanism and the connection region against fire induced high temperatures.

1-Primary Beams **5-**Lineer Bearing System **6-**C Profile **7-**Moving Beam **8-**Bearing **9-**Pim **10-**Primary Pim Side Support Plate **11-**Secondary Pim Side Support Plate **12-**Vertical Support Plate **13-**Horizantal Support Plate **14-**Shear Stud

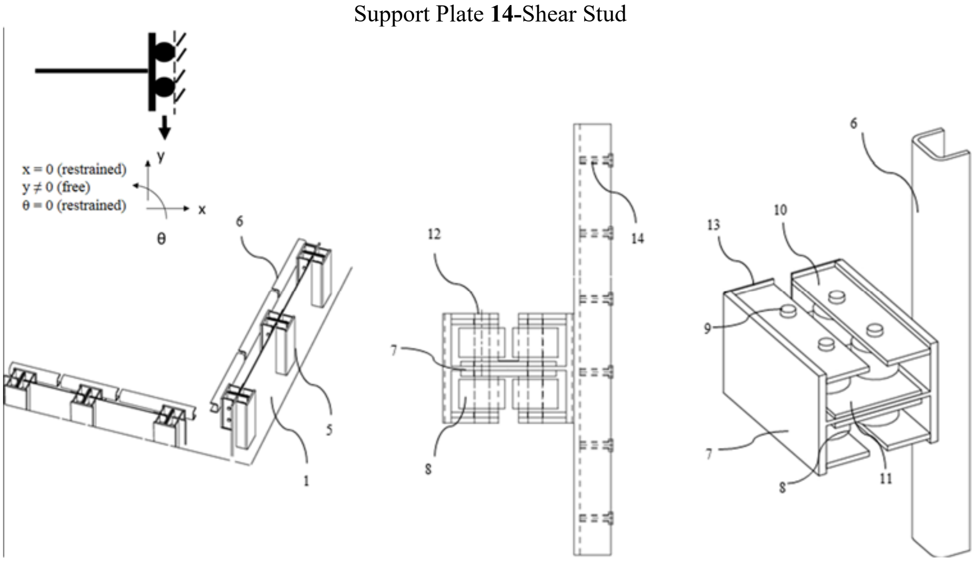


Figure 2. Connection mechanism that satisfy symmetrical boundary conditions: CAD drawing of a linear bearing system which is horizontally fixed, vertically free and capable of transferring moments.

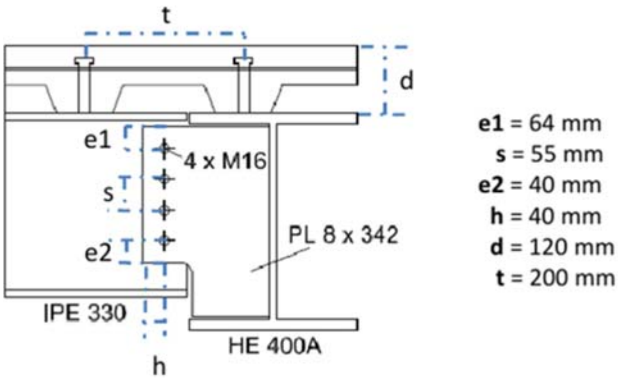


Figure 3. IPE330 Secondary beam - HEA400 primary beam shear connection detail.

2.2. Symmetrical Connection Mechanism

Fire performance experiments are generally conducted with fire furnaces. However, fire experiments of large size structural systems, e.g. composite floor systems, cannot be performed in fire furnaces due to size limitations. Large span floor systems can only be tested if they are scaled. However, the temperature distribution along the scaled model is generally quite different from the temperature distribution of the actual system and this situation results in different fire performance in the scaled model.

There is not a national or international fire laboratory with a fire furnace that can be used for fire experiments of large span structural systems of more than eight meters. Therefore, large span composite floor systems cannot be tested in fire laboratories.

In the scope of this study, a fire resistance test mechanism, which is horizontally fixed, vertically free and capable to transfer moments, that resist tension and compression forces, is innovated. The CAD drawing and final manufactured product of the mechanism are shown in Figure – 2 and Figure – 4, respectively. This invention has a pending patent application from Turkish Patent Office [20].

Figure 4. Linear bearing system which is horizontally fixed, vertically free and capable to transfer moments of the connection mechanism that satisfy symmetrical boundary condition.

2.3. Measurement Methods

The specimen is equipped with measuring instruments before the application of the static loading and the fire test. Temperatures are measured with thermo-couples, and linear variable differential transformers (LVDT) are used to measure deflection.

2.3.1. Temperature Measurement Devices

K-type thermocouples are used which are covered with iron-chromium alloy Inconel material and can operate up to 1200°C. Figure – 5 shows the distribution of thermocouples which are located at the mid-span and connection region of IPE330, at the mid-span of HEA400 and on the steel reinforcement mesh. The thermocouples, which are placed inside the fire furnace (T4 – T11), are used to verify whether or not the fire furnace was heated in compliance with the ISO834 fire curve uniformly by the burners. Four thermocouples are placed near the connection region between IPE330 and HEA400, three thermocouples are placed at the mid-span of IPE330 and another three thermocouples are placed around symmetrical connection mechanism (TC15-TC24). All of the thermocouples are placed on steel surface and the thermocouples near the shear connection remain under ceramic wool insulation. Twelve thermocouples (TC3 – TC14) are placed on the A252 steel reinforcement in concrete slab.

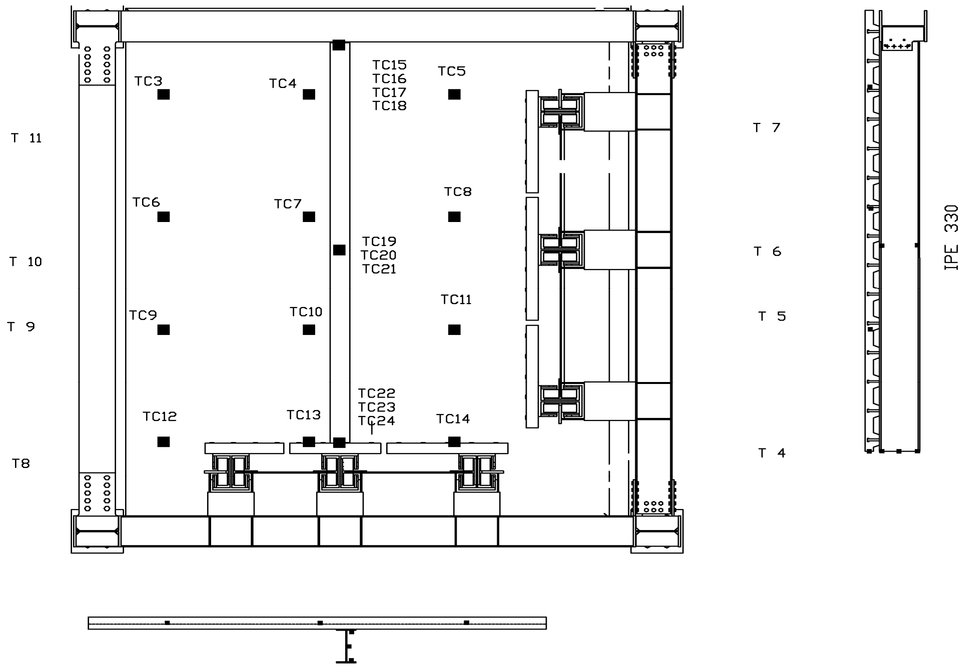


Figure 5. Location map of the thermo-couples (TC) located inside the furnace and composite floor system.

2.3.2. Displacement Measurement Devices

The LVDTs are used to monitor the tensile membrane action of the concrete slab, and to determine the time of the membrane action initiation. The LVDTs were placed under the concrete slab and distribution of LVDTs are given in Figure – 6. The LVDTs are made of heat – resisting and inextensible material. These measurements were also used to verify whether or not the symmetrical connection mechanism allows vertical freedom of the floor system.

2.4. Vertical Static Loading

Equation – 1 represents the load combination that should be applied for structural fire design of office type buildings according to Eurocode (EC1). In Equation 1; *w*, *Q* and *G* are total design load, live loads and dead loads, respectively [21]. The live load *Q* is applied uniformly to the concrete slab surface with a magnitude that equals 2.5 kN/m^2 as deemed appropriate Eurocode Standard (EC1). The uniform load distribution is achieved with 10 pieces of 200 kg weight, 5 pieces of 375 kg weight and 13 pieces of 20 kg weight as shown in Figure – 7.

The dead load of the structure *G* is considered as the density of concrete which is nearly 2.4 kN/m^2. According to the above explanation and Equation 1, the fire design load for the test is 3.75 kN/m^2.

$$w = 1{,}0G + 0{,}5Q \quad (1)$$

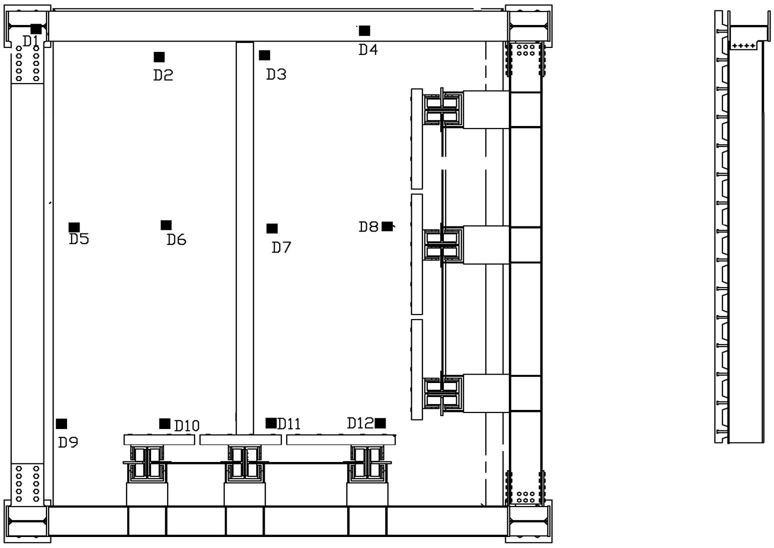


Figure 6. The location map of LVDTs (D1-D12) on the composite floor system.

Figure 7. The loading condition on the composite floor system before the experiment.

3. OBSERVATIONS AND ASSESMENTS

Smoke around the symmetrical axes of the composite floor was detected 5 minutes after ISO834 fire exposure. At 20th minute into fire, visible lateral displacements were observed and on the 25th minute, cracks were formed on the concrete surface. In addition, after the 30th minute of the experiment water vapor exhaust and bubble formation were seen on the concrete slab surface. During the controlled cooling, the concrete slab moved slightly in the upward direction. The reason behind the upward movement was the recovery in strength and stiffness of the secondary beam (IPE330) as a result of cooling.

3.1. Furnace Temperatures

Fire furnace temperatures are measured with the thermocouples placed at the middle of the furnace volume. The distribution of thermocouples (T4 – T11) in the furnace is given in Figure – 5. The fire furnace was equipped with a digital mechanism that automatically arrange the gas pressure and burners to follow the ISO834 temperature curve. After 105 minutes heating, the burners were shut down and the controlled cooling process lasted for 90 minutes.

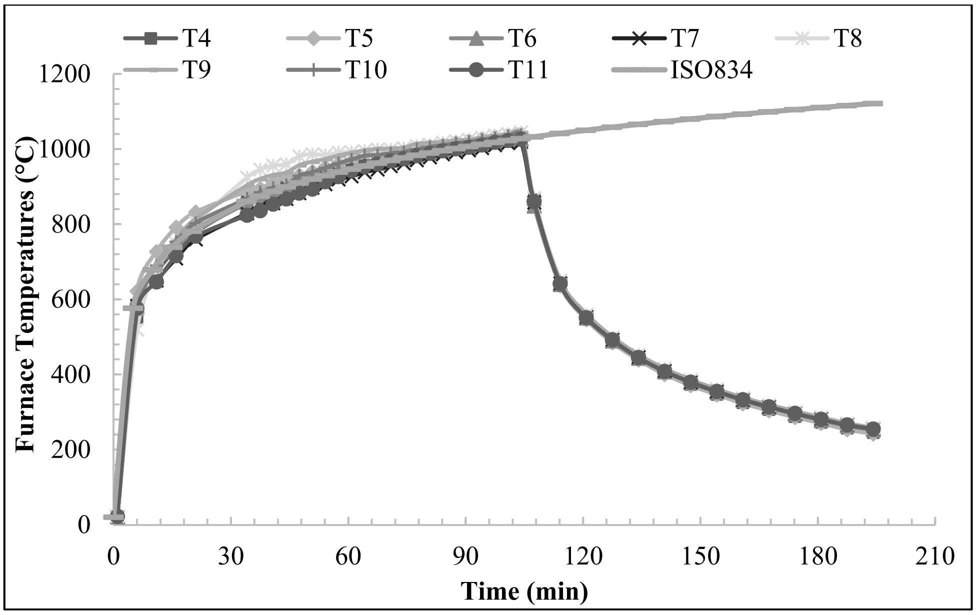


Figure 8. Temperature curves obtained from the different regions of the furnace (see. Figure 5).

3.2. Temperatures of Steel Beam and Concrete Slab Reinforcement Mesh

The temperatures of the composite floor components are measured with thermocouples placed at various locations (see Figure 9). Thermocouple TC10 malfunctioned during the experiment and was disabled at the 5th minute. According to the measurements taken, thermocouples TC21, TC20, TC19 placed at the mid-span of IPE330 and respectively aligned from the bottom flange to the top flange showed a behavior close to ISO834 fire curve as expected. The thermocouple at the mid-span and bottom flange (TC21) was 100°C hotter than TC19. Because the secondary beam was left unprotected, the thermal gradient between bottom and top flange was small. The connection between IPE330 and HEA400 was protected with ceramic wool. The thermocouples TC17, TC16 and TC15 respectively aligned from the bottom to the top of the IPE330 beam near the connection region were exposed to relatively low heating as expected. There was nearly 100°C temperature difference between bottom and top surfaces of IPE330 near the connection region. Thermocouples TC15 and TC18 located on the connection are placed onto the first and third bolts, and TC16 and TC17 are placed onto the single plate. The higher temperature measurement for TC18 with respect to TC15 and TC17 showed that the ceramic wool insulation at the bottom surface of the connection was applied improperly.

Thermocouples TC24, TC23 and TC22 are placed nearby the symmetric connection mechanism from the bottom to the top of IPE330 beam, respectively. The mechanism is protected with ceramic wool but the thermocouples TC23 and TC24 remained unprotected (due to improper setup) and showed different temperature as compared to TC22, which remained under protection as seen from Figure – 9.

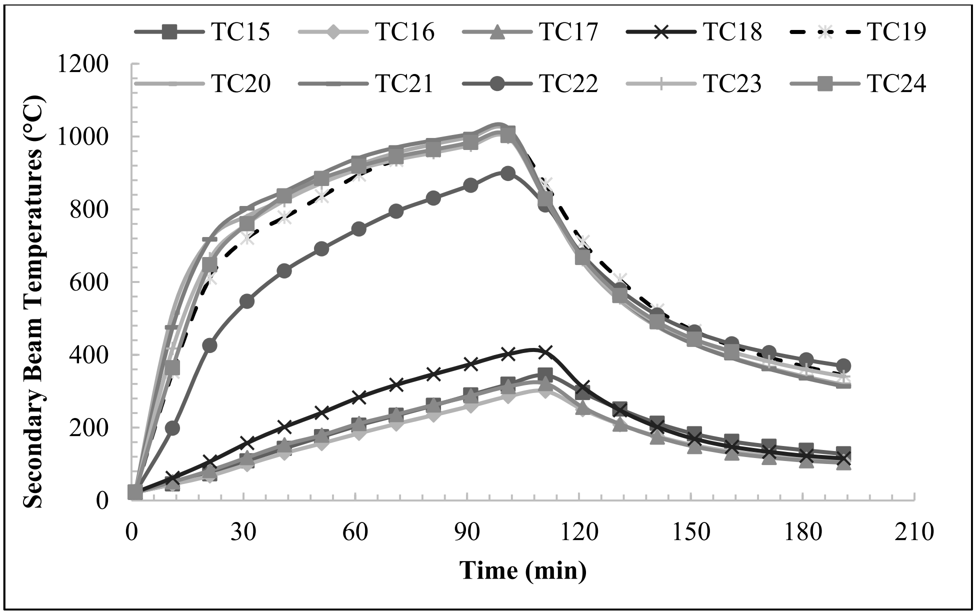


Figure 9. Thermo-couple temperatures on the secondary steel beam IPE330 (see. Fig.5).

The distribution of the thermocouples on the concrete slab reinforcement mesh are given in Figure – 5, and Figure – 10 shows the measured temperatures in the reinforcement. TC13 was damaged during the assembling of the concrete slab, thus it could not be used for the measurements. In addition, thermocouple TC12 was damaged at 135th minute of the experiment, thus it was not used to collect data after that instant. According to the temperature measurements, it was observed that the temperature difference between the thermo-couples placed on the different regions of the reinforcement mesh reached up to 300°C. One of the reason for the temperature difference is the existence of the ribbed section. Thermocouples in 120 mm thick concrete showed lower temperatures then the ones in 70mm thick concrete slab. The other reason is the lower temperature distribution nearby the furnace walls. While the thermocouples (TC7, TC8, TC 9 and TC11) at the center of the fire furnace heated up to 500-600 °C, the thermocouples located nearby the furnace walls were heated up to only 300 °C.

According to Eurocode Standards, the critical temperature of the secondary beam (IPE330) is 635 °C with respect to the loss of load carrying capacity [22]. As shown in Figure – 9, the temperature of the beam exceeded 635°C at the 25th minute of the experiment and the beam stayed in place as a dead load on the concrete floor system, and the vertical (gravity) loading was carried by the concrete slab. Because of the fire insulation applied around the steel shear connection, the temperature around the connection remained under 400°C; therefore the connection did not lose its load transfer capacity according to Eurocode Standards [22].

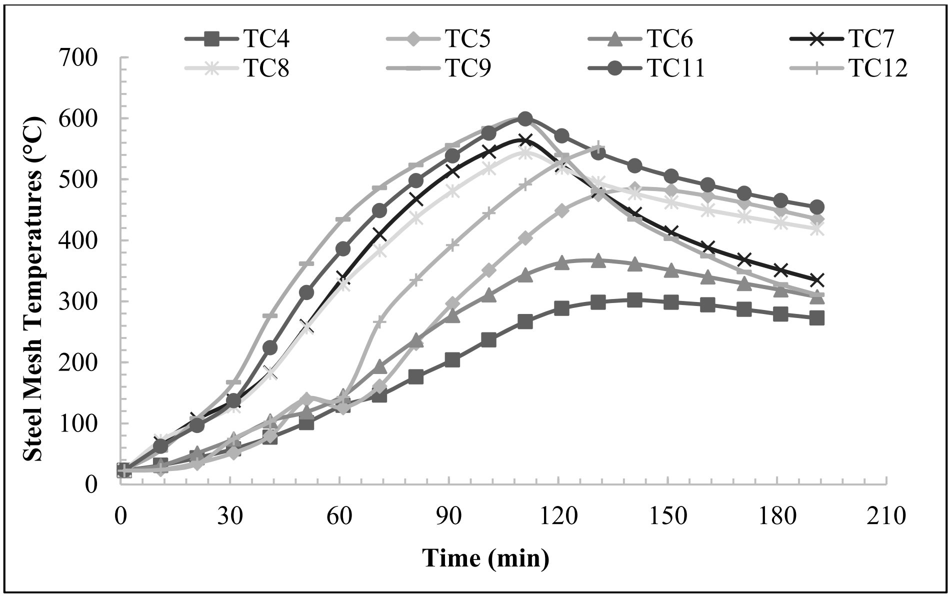


Figure 10. Thermocouple temperatures on the concrete slab steel reinforcement mesh (see. Fig 5).

3.3. Slab Deflections

Once the gravity loading shown in Figure – 7 was applied to the floor system, 45 mm displacement was recorded at the symmetrical perimeter corner. The deflections are shown in Figure – 11. The negative (-) values on Figure – 11 represent vertically downward displacement after setting the deflection due to gravity loading to zero (e.g. base correction). It can be seen from Figure – 11 that while the displacement around the perimeter beams remained low as expected, the region nearby symmetrical boundaries, especially the corner region (D12), displaced downward up to 50 mm during fire. The total displacement of the symmetrical corner (D12) is 95 mm with gravity loading. Because LVDTs D1 to D5 were located nearby the perimeter beam, they deflected lower than the other LVDTs. Because LVDT D3 was on the secondary beam it deflected nearly 20 mm. The reason behind the rapid increase in the deflections for all of the LVDTs was load carrying capacity loss of the secondary beam (IPE330) due to 800 °C average steel temperature along the beam.

The maximum deflection of D11 on the secondary beam was 40 mm and this was higher than the serviceability limit state (L/250) for the composite beams according to Eurocode Standards [21].

The concrete slab deflected less than expected during fire. One of the reason behind this might be the data reading failure and the other reason might be the friction forces that occurred between the components of the symmetrical connection mechanism as a result of axial forces in the slab due to thermal expansion. The friction force validates the proper performance of the connection mechanism. For future experimental studies, it is planned to design a hydraulic system that will gradually increase static loading on the slab to decrease the effect of the friction forces during the fire.

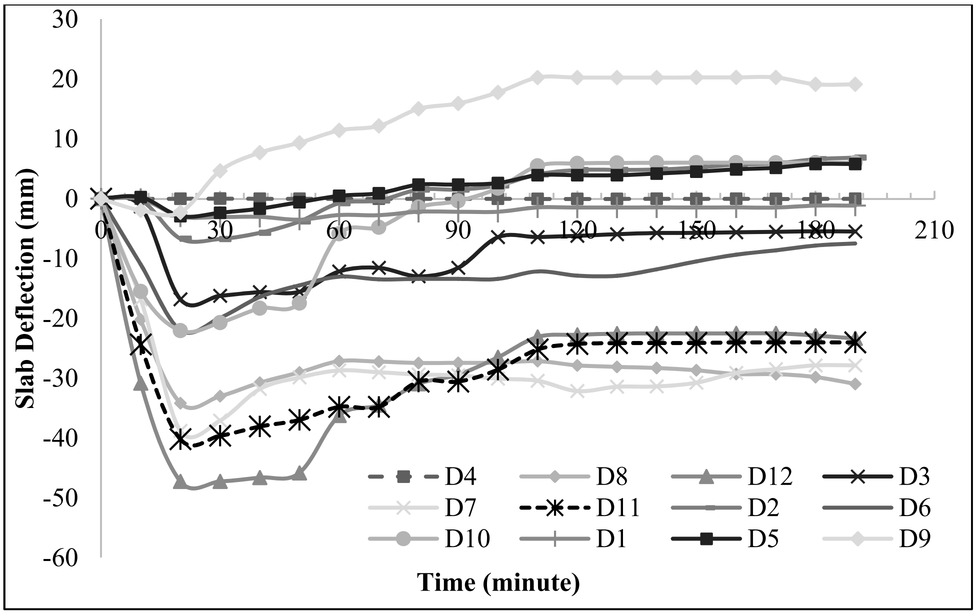


Figure 11. Slab deflections measured at different locations of the concrete slab after the static loading during the fire. (See. Figure 6)

3.4. Observations

Proper performance of the connection mechanism, which satisfies symmetrical boundary conditions for the composite floor system, is validated under elevated temperatures. As it can be seen from Figure – 12 the secondary beam (IPE330) did not lose its stability, but it experienced local buckling of the bottom flange nearby the shear connection region (see Figure 3)

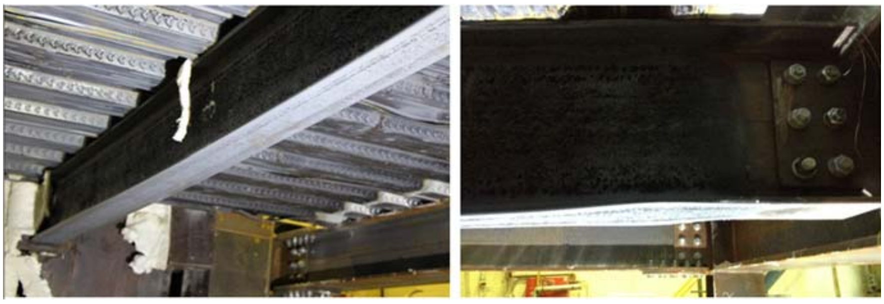
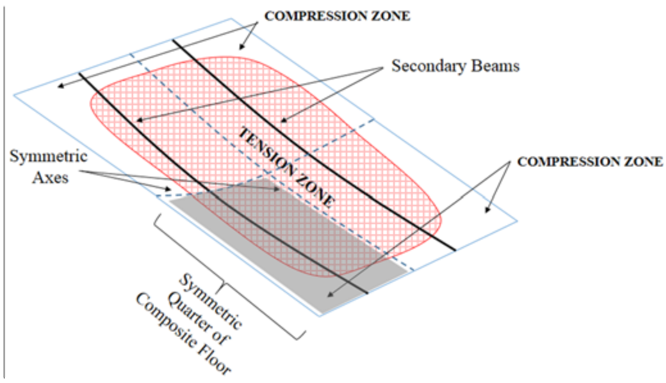


Figure 12. Deformed shape of the unprotected secondary beam (IPE330) and the steel deck after the test, local buckling on IPE330 beam around the shear connection.

The top surface of the concrete slab before and after the fire experiment is shown in Figure 13a-b. Gradually increasing deflection towards the symmetrical perimeters resulted tension zone in the slab and caused cracks on the concrete surface. These cracks are the proof of the membrane action mechanism of the concrete slab.

(a) (b)



(c)

Figure 13. (a) The top surface of the concrete slab system before the experiment, (b) concrete cracks after the experiment (highlighted in red), (c) illustration of the tensile membrane action.

4. RESULTS AND RECOMMENDATINOS

This study reveals findings of the first structural fire resistance test of a composite floor conducted in Turkey and it is aimed to improve the structural fire response guidelines in Turkish fire regulations.

With the fire test, it is validated that a typical composite floor system has at least 105 minutes of fire resistance. According the results, the unprotected secondary beam (IPE330) was heated up to 800°C and lost its load carrying capacity. However, it was observed that the membrane action in the concrete slab provided an alternative load carrying mechanism in the case of secondary beam failure. Therefore, it is suggested that the secondary beams can be left unprotected against fire. For high rise and long-span steel framed buildings if the secondary beams that transfer dead and live loads to perimeter beams remained unprotected against fire, it is possible to reduce 15% - 20% of the fire protection cost. This suggestion will provide a basis for national and international codes and will reduce carbon foot print of the steel construction industry.

In addition, the steel reinforcement temperatures in the concrete slab reached up to 400 °C. It is suggested that the steel reinforcement mesh should be placed far above the concrete slab bottom surface to satisfy fire protection with sufficient concrete cover. Although placing the steel reinforcement nearby the compression zone is not a classical design approach, reinforcement near the concrete top surface is more advantageous in fire design. In order to benefit from the tensile membrane action, the steel reinforcement must have high strength and ductility for the entire duration of the fire.

In this study, a connection mechanism, which satisfy symmetrical boundary conditions for structural fire tests, was used for the first time. This mechanism was designed as vertically free while it is horizontally restrained, resistant to tensile and compression forces and capable to transfer moments. This invention made under the scope of this project has a pending patent application from Turkish Patent Office. The results of the fire test validates that the connection mechanism properly functions.

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References

[1] Gann, RG. Final report on the collapse of World Trade Center Building 7, Federal building and fire safety investigation of the World Trade Center disaster, NCSTAR-1A, NIST, 2008.

[2] The Geneva Association, World Fire Statistics Newsletter, 29, 2014.

[3] Beitel J and Iwankiw N., Analysis of needs and existing capabilities for full-scale fire resistance testing, National Institute of Standards and Technology, NIST GCR, 02-843, 2002.

[4] British Steel plc, Swinden Technology Centre U. The behaviour of multi-storey steel framed buildings in fire, Technical report, British Research Establishment (BRE), UK, 1999.

[5] Bailey CG., The structural behaviour of steel frames with composite floor slabs subject to fire: Part 1: Theory, The Structural Engineer, 78(11), 19-27, 2000.

[6] Bailey CG., Membrane action of slab/beam composite floor systems in fire, Engineering Structures, 26, 1691-1703, 2004.

[7] Bailey CG. and Toh WS., Small-scale concrete slab tests at ambient and elevated temperatures, Engineering Structures, 29, 2775-2791, 2007.

[8] Buchanan Andrew H., Structural Design for Fire Safety, New York, Wiley, 2001.

[9] Wald F, da Silva LS, Moore D, Lennon T, Chladna M, Santiago A, Benes M, and Borges L., Experimental behaviour of a steel structure under natural fire, Fire Safety Journal, 41(7), 509–522, 2006.

[10] Astaneh-Asl A, Liu J, McMullin KM., Behavior and design of single plate shear connections, Journal of Constructional Steel Research, 58(5-8), 1121-41, 2002.

[11] Garlock ME and Selamet S., Modeling and behavior of steel plate connections subject to various fire scenarios, Journal of Structural Engineering, ASCE, USA, 136(7), 897–906, 2010.

[12] Selamet S, Garlock ME., Robust fire design of single plate shear connections. Engineering Structures, 32(8), 2367-2378, 2010.

[13] Chung KF and Ip KH., Finite element investigation on the structural behaviour of cold-formed steel bolted connections, Engineering Structures, 23(9), 1115-25, 2001.

[14] El-Rimawi JA, Burgess IW, Plank RJ., The influence of connection stiffness on the behaviour of steel beams in fire, Journal of Constructional Steel Research, 43(1-3), 1997.

[15] Selamet S, Garlock ME., Predicting the maximum compressive beam axial force during fire considering local buckling, Journal of Constructional Steel Research, 71, 189-201, 2012.

[16] Selamet S, Garlock ME., Plate buckling strength of steel wide-flange sections at elevated temperatures. Journal of Structural Engineering, ASCE 2013; 139(11): 1853-1865.

[17] Selamet S, Bolukbas C., Fire resilience of shear connections in a composite floor: Numerical investigation, Fire Safety Journal, doi:10.1016/j.firesaf.2016.02.003, 2016.

[18] Kirby BR., The behaviour of high-strength Grade 8.8 bolts in fire, Journal of Constructional Steel Research, 33(1-2): 3-38, 1995.

[19] Binaların yangından korunması hakkında yönetmelik, Resmi Gazete, Sayı 27344, 2009.

[20] "Simetrik sınır koşulları sağlayan bir yangın dayanım test mekanizması", Evrak tarihi: 26.11.2015, Evrak No: 2015-GE-436248, Dosya No: 2015/14992

[21] CEN. ENV 1991-1-2:2002 – Eurocode 1, Actions on structures, Part 1.2: General actions – Actions on structures exposed to fire, Brussels, 2002.

[22] CEN. ENV 1993-1-2:2005 – Eurocode 3, Design of steel structures, Part 1.2: General rules – Structural fire design, Brussels, 2005.