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Experimental study and numerical analysis of flexural behaviour of post-fire reinforced concrete beam

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Abstract. A cycle of heating and cooling can cause gradual chemical changes in reinforced concrete after a fire and these can affect the strength of the concrete. The study aims to analyse the deflection and damage of post-fire concrete beams. The method of study used numerical and experimental analysis on reinforced concrete beam models 1250 mm in length, with a cross-section width of 100 mm and height of 200 mm. The combustion of the specimen was carried out in a brick furnace for a duration of 30 and 60 minutes with an average combustion temperature of 930 and 926 °C. The flexural strength test of the post-burn beam was carried out using a load cell and measured using LVDT at room temperature. The results showed that the deflection that occurred on reinforced concrete beams burned for 30 minutes (BN30) resulted in increased beam deflection by 7% compared to the unburned concrete beam model (BN). Similarly, the concrete beam model which was burned for 60 minutes (BN60) resulted in a 22% increase in beam deflection compared to the unburned concrete beam model. Also, there is a sloping pattern in the relationship curve between load and deflection with increasing duration of the combustion time. This condition is due to a 62% decrease in the load received by the beam when the beam burned for 30 minutes (BN30). Likewise, when the beam burned for 60 minutes (BN60), this caused a 72% decrease in load compared to the unburned concrete beam model. Thus, the duration of fire combustion in concrete beams significantly affects the strength of the reinforced concrete beam.

1. Introduction

Rapid development has led to the use of reinforced concrete materials as the primary choice for building structure planners. The selection of concrete as the main material component in various constructions is due to the easy construction method, and the efficiency and quality of the reinforced concrete. A reinforced concrete beam is a mixture of steel and concrete with the width and number of reinforcements determined based on reinforced concrete standards [1]. The combination of concrete and steel reinforcement is required to withstand the tensile force on the concrete. The material of concrete has several advantages: it is easily formed, easy to obtain, with high stiffness, and high fire resistance [2]. Thus, concrete is more suitable for use as the primary material in fire-resistant building structures compared to steel profile material. Although concrete has high-temperature resistance, it cannot avoid the effects of fire, both physically and mechanically [3]. The study aims to analyse the behaviour of bending on reinforced concrete beams after a fire disaster. The fire conditions are simulated by placing the specimens in a brick kiln for a predetermined period. So, the research is expected to assist structural building planners in knowing what happens to a building structure after exposure to fire.

The concrete has constituents such as coarse aggregates, fine aggregates, hydraulic cement, water, and other additive materials. Steel reinforcement in the concrete serves to increase its strength. Thus, reinforced concrete has a combination of forces in withstanding the compressive force assumed by the concrete and the tensile force borne by the reinforcing steel. Moreover, concrete and reinforcing steel can be combined in several ways. The interaction of the concrete and the steel reinforcement will prevent slip of the steel against the concrete. Therefore, the tension between the steel and concrete is negligible under changes in air temperature [4].

The relationship between the load and deflection of reinforced concrete consists of three stages before collapse: first, the preparatory stage, which is the structural stage before cracking; second, the post-layering stage, is the structural stage which has a controlled crack, where the distribution and crack width are within reasonable limits; and finally the post-serviceability stage is the phase when the stress on the tensile reinforcement has reached its melting stress [5].

The concrete may be exposed to high temperatures due to fire. Therefore, some researchers have studied post-burn reinforced concrete, such as [3, 4, 6, 7] and [8]. The studies explained that the strength of concrete decreases when the fire temperature reaches 400 °C. Meanwhile, there is a decrease in the steel reinforcement capacity by 75% at temperatures reaching 675 °C [9]. The decrease of strength in reinforced concrete reduces its ability to withstand the load given. The decrease in the flexural strength of a reinforced concrete beam after a fire causes the beam deflection value to increase. This is due to the stiffness of the beam, which continues to decline during the fire. The decrease in the stiffness of the beam causes the cross-section of the beam to become arched due to loading and the gravity shift at each point on the reinforced concrete beam also increases.

2. Research methodology

The methodology of the research started with determining the size of the reinforced concrete to get the size on a laboratory scale. The next stage was testing the characteristics of the concrete mix base material to produce mix design reinforced concrete beams. After the mix design work was finished, the concrete mixture was poured into a formwork mould and cured for 28 days to ensure the strength of concrete according to the design of the plan. Curing was performed by covering the concrete surface with a wet jute sack. When treatment (curing) was completed, the reinforced concrete beams were burned in brick kilns with temperature measurements using an infrared digital thermometer. Testing of the flexural strength of the beam model was conducted by burdening two perpendicular loading points on the specimen using a loading frame.

The materials used in the mix design of the reinforced concrete beams with a compressive strength of concrete 20 MPa are coarse aggregate, fine aggregate, PCC (Portland composite cement), and reinforcing steel of 6 and 10 mm diameters by Indonesian Code Standard (SNI 03-2834-2000) [10]. Planning of the concrete with mixed composition for 1 m^3 can be seen in table 1.

Table 1. Mix design of reinforced concrete for 20 MPa in 1 m^3.

Coarse Aggregate (kg)	Fine Aggregate (kg)	PCC (kg)	Water (kg)
1151.50	895.76	325	174.63

The strength of reinforced concrete beams, f'c is 20 MPa were made into three models, with BN notation for reinforced concrete beams without burning, BB30 for reinforced concrete beams burned for 30 minutes, and BB60 for reinforced concrete beams burned for 60 minutes. The size of the cross-section of the reinforced concrete beam is 100 mm x 200 cm, and the length of the beam is 1250 mm. The spacing of the stirrups is 53 mm and the concrete cover is 17 mm. The details and dimensions of the reinforced concrete beam used can be seen in figure 1.

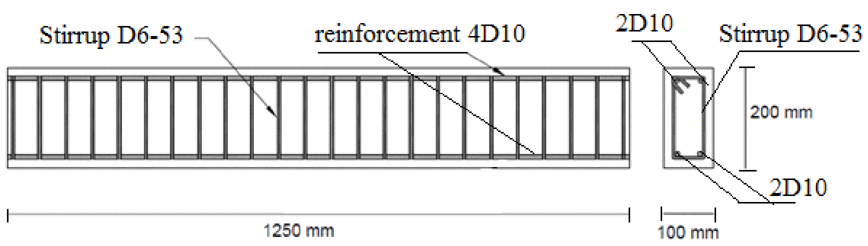

Figure 1. Detail of reinforced concrete beam.

Combustion of the reinforced concrete beams for the BB30 and BB60 models is carried out in a brick furnace. The fuel of the furnace is logs that are entirely burned. The condition of the fire is controlled by remain on and does not change significantly. Therefore, the addition of fuel during combustion causes the temperature of the fire to be stable. The combustion of the specimen was carried out in a brick furnace for a duration of 30 and 60 minutes with an average combustion temperature of 930 and 926 °C and initial temperature was 930°C. The temperature is recorded at all times to get the real temperature of the furnace. The temperature measurement uses an infrared digital thermometer every 5 minutes with a measurement distance of 20 cm from the furnace, as shown in figure 2. The average temperature of the furnace is recorded, as shown in table 2.

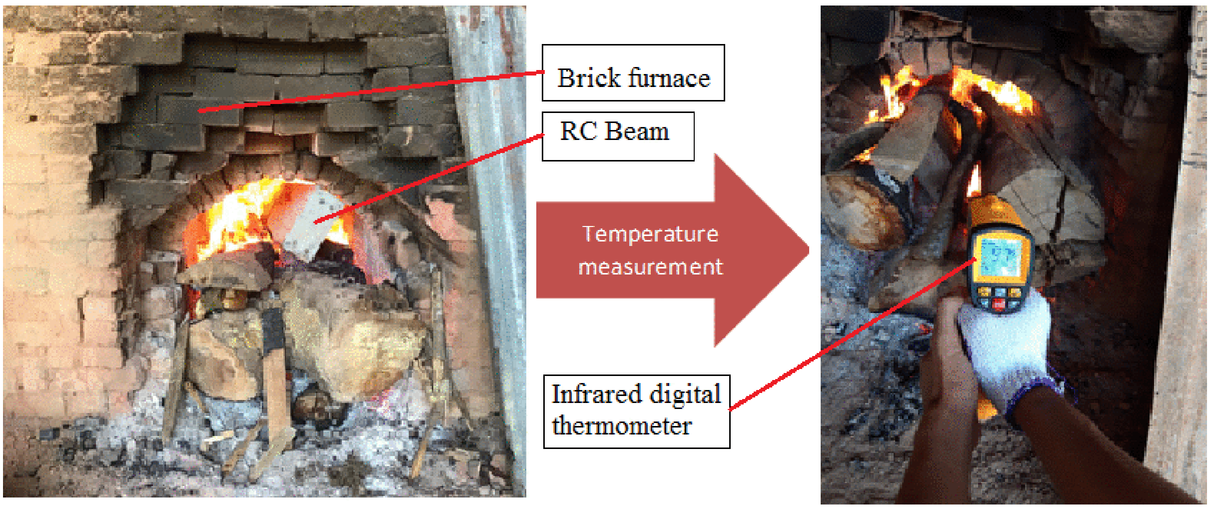

Figure 2. The burning process and temperature measurement of the reinforced concrete beam.

The BB30 reinforced concrete (RC) beam is slowly removed from the furnace after 30 minutes, while the BB60 RC beam model remains inside until 60 minutes. Then the beam is slowly lifted from the furnace for the cooling process. The cooling process is done naturally without using water, and therefore, it takes several hours until the temperature of the RC beam reaches room temperature. The process aims to show the effect of rapid cooling when a fire occurs. After the cooling process is complete, the experimental works are done for the RC beams to obtain the flexural strength based on SNI 4431 [11].

Table 2. Temperature of the brick furnace during burning.

Duration (minute)	Temperature (°C)
Start	930
5	920
10	901
15	931
20	944
25	948
30	934
Mean in 30 minutes	**930.00**
35	952
40	930
45	912
50	902
55	922
60	912
Mean in 60 minutes	**926.00**

Flexural strength testing of the RC beam was carried out using the loading frame. The design of the point loading on the reinforced concrete beams can be seen in figure 3. The measurement tool is a load-cell and deflection measurements, which are carried out using a Linear Variable Displacement Transducer (LVDT).

3. Result and discussion

Damage to the beam due to load in the form of flexural cracks occurs in the middle span of the beam. Flexural testing on the BN beam can be seen in figure 3.

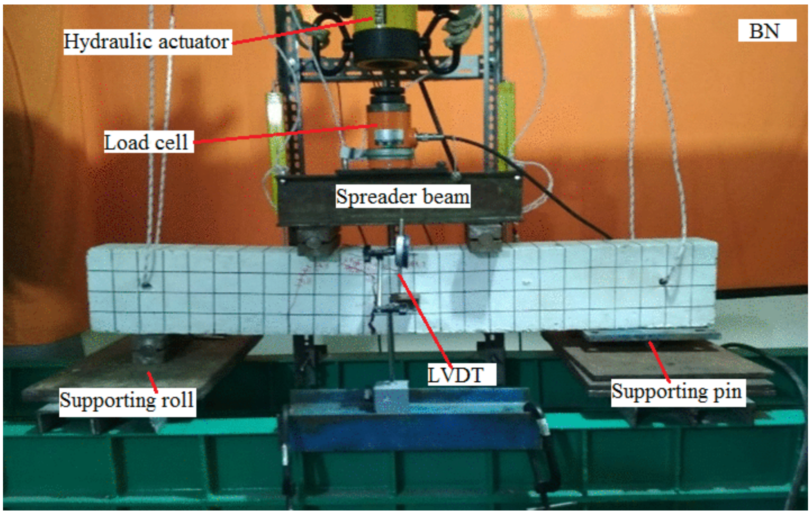

Figure 3. Flexural testing on RC beam BN model.

The recording of the temperature of the fire in the brick furnace shows an increase and decrease in temperature. This is caused by the firewood, which starts burning naturally in the brick furnace.

Therefore, the temperature is kept stable during the combustion process. Flexural testing on the reinforced concrete beams is carried out to determine the ultimate capacity of the beam. The test results on the BN beam indicate that the first crack occurred at the load of 20.5 kN, and the ultimate load was 61.2 kN.

Flexural testing of BB30 beams shows that the first crack occurred at 13.1 kN loading and the ultimate load occurred at 25.4 kN. Damage to the RC beam model due to the load in the form of cracks occurs in the entire beam span. The cracks occur on the whole surface of the post-fire beam. Flexural testing on the BB30 beams can be seen in figure 4.

Figure 4. Flexural testing on RC beam BB30 model.

The flexural testing of the BB60 beams shows the first cracks due to load occurred at 9.8 kN and the ultimate load at 20.4 kN. The first crack is defined as a crack that first appears on the surface of the specimen when it is loaded. Meanwhile, the ultimate load is defined as the maximum load can be received before the specimen collapses. Damage to the beams due to the load occurred as cracks in the entire beam. More cracks occurred on the BB60 beams than on the BB30 beams. Flexural testing on the BB60 beams can be seen in figure 5.

Figure 5. Flexural testing on RC beam BB60 model.

The bending test results on the beam are compared with numerical analysis using LUSAS V17 to obtain validation values. The input data for numerical analysis includes the thermal conductivity and specific heat value of concrete and steel material. The thermal conductivity of concrete is 0.8333 (W/m.K), whereas steel is 27.3 (W/m.K) during temperature, 800°C ≤ T ≤ 1200°C Meanwhile the specific heat of concrete is 1288.889 (J/kg.K) and steel is 650 (J/kg.K). Figure 6 shows the results of the flexural load when the first crack and the ultimate load occurs.

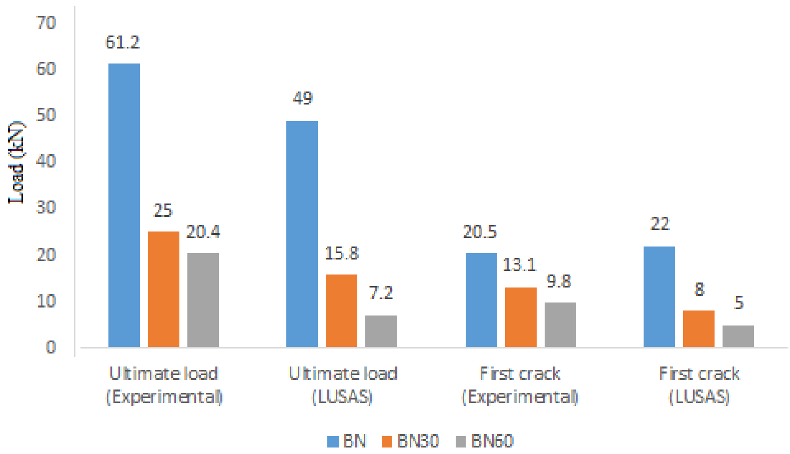

Figure 6. First crack of RC beam in burned and unburned conditions.

The experimental work resulted in the beam's flexural capacity load at the first crack, and the ultimate condition on the RC beam BB30 was found to decrease by around 36.1% and 58.5% compared to the capacity load of the BN RC beam. Meanwhile, the RC beam BB60, based on experimental results, showed a decrease in the first crack and ultimate load capacity of 52.2% and 66.7% compared to the RC beam BN. The LUSAS analysis shows that the load capacity of the first crack and ultimate load of RC beam BB30 decreased by around 63.6% and 67.8% compared to the capacity of the BN RC beam, whereas the BB60 beam in the LUSAS analysis showed a decrease in the first crack and ultimate load capacity by 77.3% and 85.3%. The decreased load capacity in the post-fire reinforced concrete was caused by a decrease in the concrete quality i.e. damage due to heating and cooling. This was caused by reduced adhesion between the concrete and steel reinforcement due to the fire, which thereby reduced the bending load capacity of the reinforced concrete beams.

The result of the bending strength test showed that the deflection occurring on the reinforced concrete beam that burned for 30 minutes (BB30) increased by 7% compared to the unburned concrete beam model (BN). Likewise, the 60-minute burned concrete beam model (BB60) showed a 22% increase in the beam deflection compared to the unburned concrete beam model. Moreover, the slope of the relationship curve between load and deflection (stiffness) increases after exposure to fire to 30 minutes, however, only a slight reduction in stiffness is observed for prolonged exposure (60 minutes). The pronounced difference in stiffness between the unburned beam and beams exposed to fire is related to the loss of stiffness of concrete due to heating and cooling.

The experimental works demonstrated that there is a difference in the amount of deflection between the unburned RC beam (BN model) and the post-fire RC beam conditions. Figure 7 shows that the both stiffness and load capacity decrease with increasing duration of the fire. In the BN beam, the amount of deflection in the ultimate condition is 11.16 mm at the load of 61.2 kN. The reinforced concrete beam BB30 shows a deflection at the ultimate condition of 7.96 mm at 25.4 kN loading, whereas the BB60 beam shows a deflection in the ultimate condition of 7.12 mm at the load of 20.4 kN. The relationship between load and deflection indicates that the load energy needed to achieve a certain deflection amount decreases with increasing fire duration.

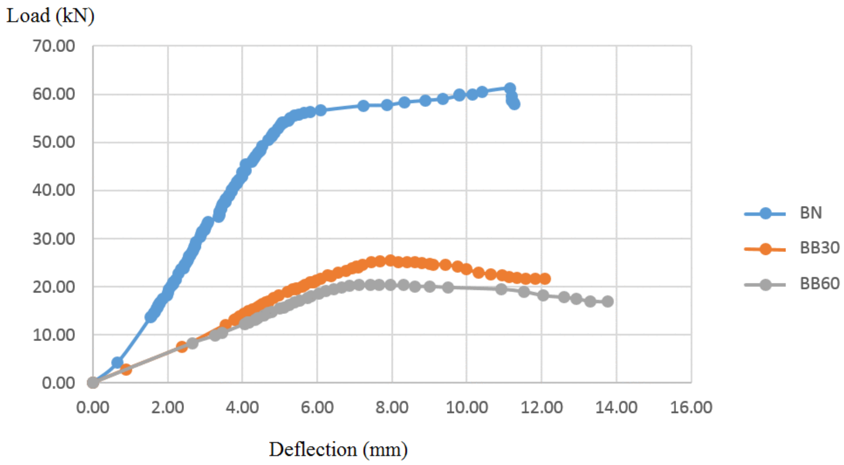

Figure 7. Relationship curves of deflection and loads.

Visual examination of the post-fire RC beams BB30 and BB60 shows damage in the form of cracks, peeling and discolouration. The damage that occurs in RC beams can be seen from the colour of the beam surface. The colour of the BB60 RC beam surface is lighter grey than the BB30 RC beam. Greyish white indicates that the concrete surface has been exposed to mean temperatures of more than 900 °C. This was caused by the carbonisation process in concrete, with the formation of calcium carbonate ($CaCO_3$). The formation of $CaCO_3$ causes the surface colour of the concrete to be brighter, as shown in Figure 8. The crack width of the BB30 RC beams ranges from 0.5–1 mm, while the crack width in the BB60 RC beams ranges from 0.5–3 mm. The colour changes that occurred in the BB30 and BB60 RC beams indicate that the concrete surface has been exposed to high temperatures.

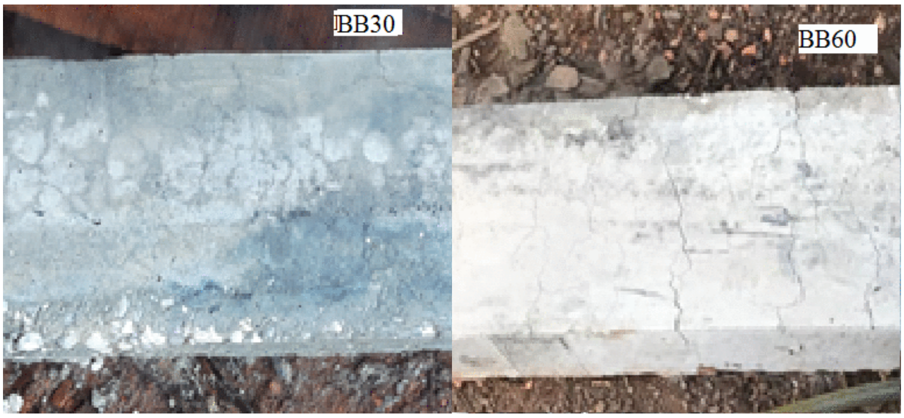

Figure 8. Discolouration of the post-fire RC beams after 30 and 60 minutes.

Randomly distributed cracking was observed over the complete specimen surface. There are several prominent cracks in the position of the stirrups. This condition describes the cracking correspond to the position of the stirrups due to different thermal and mechanical properties of steel and concrete.

4. Conclusion

Based on the result of the analysis of deflection in reinforced concrete beams, it can be concluded that:

a. The deflection that occurs in reinforced concrete beams will increase with increase of the fire duration and temperature.

b. The increase in deflection that occurred in the concrete beam model burned for 30 minutes (BB30 RC beam model) and the concrete beam model burned for 60 minutes (BB60 RC beam model) indicated a decrease in stiffness in the reinforced concrete beams. The result shows the increasing slope of the load-and-deflection curves in the conditions after the fire.
c. The flexural strength test results show that the ultimate load capacity on the BN beam is 61.2 kN. The ultimate capacity on the BB30 RC beam is 25.4 kN, while the ultimate capacity on the BB60 RC beams is 20.4 kN. So the experimental results show a decrease in the ultimate load capacity as the duration of the fire increases. The ultimate load capacity in BB30 RC beams decreases by 58.5% against the BN RC beams, whereas in the BB60 RC beams there is a decrease in ultimate load capacity of 67.8% compared with the BN beam.
d. The results of the flexural strength test on the beams indicate that the deflection in the ultimate condition on the BN beam is 11.16 mm, on the BB30 beam is 7.96 mm, and on the BB60 beam is 7.12 mm.
e. Visual inspection of post-fire concrete with the aim of reviewing the shape and damage that occurs to the burned concrete after 30 and 60 minutes shows damage in the form of cracks, peeling and discolouration. The crack width of the BB30 beams ranges from 0.5–1 mm, while the crack width in the BB60 beams ranges from 0.5–3 mm. The exfoliation that occurs in the BB30 and BB60 beams is destructive peeling. Colour changes that occur in the BB30 and BB60 beams indicate that the concrete surface has been exposed to temperatures above 900 °C.

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