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Repair of shear-deficient normal weight concrete beams damaged by thermal shock using advanced composite materials

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A B S T R A C T

The use of advanced composite materials such as Fiber Reinforced Polymers (FRPs) in repairing and strengthening reinforced concrete structural elements has been increased in the last two decades. Repairing and strengthening damage structures is a relatively new technique. The aims of this study was to investigate the efficiency and effectiveness of using Carbon Fiber Reinforced Polymer (CFRP) to regain shear capacity of shear-deficient normal weight high strength RC beams after being damaged by thermal shock. Sixteen high strength normal weight RC beams ($100 \times 150 \times 1400$ mm) were cast, heated at 500 °C for 2 h and then cooled rapidly by immersion in water, repaired, and then tested under four-point loading until failure. The composite materials used are carbon fiber reinforced polymer plates and sheets. The experimental results indicated that upon heating then cooling rapidly, the reinforced concrete (RC) beams exhibited extensive map cracking without spalling. Load carrying capacity and stiffness of RC beams decreased about 68% and 64%, respectively, as compared with reference beams. Repairing the thermal damaged RC beams allowed recovering the original load carrying without achieving the original stiffness. Repaired beams with CFRP plates with 90° and 45° regained from 90% to 99% of the original load capacity with a corresponding stiffness from 79% to 95%, whereas those repaired with CFRP sheet on the web sides and a combination of CFRP plates and sheet regained from 102% to 107% of the original load capacity with a corresponding stiffness from 81% to 93%, respectively. Finally, finite element analysis model is developed and validated with the experimental results. The finite element analysis showed good agreement as compared with the experimental results in terms of load–deflection and load–CFRP strain curves.

1. Introduction

Reinforcing concrete structures are often subjected to cycles of heating–cooling such as in chimneys, concrete foundations for launching rockets carrying spaceships, concrete near to furnace, clinker silos and nuclear power plants, or those subjected to fire then extinguished using water. Temperature cycles are critical to the stability of concrete structures and require considerations upon design [1,2]. As well stipulated, the mechanical properties of concrete are preserved for exposure temperatures below 300 °C, yet are decreased considerably as temperature exceeds 500 °C. Additional damage results from rabid cooling such as in the case of distinguishing of fire with cool water due to the creation of temperature gradient between concrete core and its surface. This results in tensile stresses on the concrete surface that are high enough to crack concrete. Another source of damage results from incompatible expansion and contraction of aggregate and surrounding cement paste. The magnitude of damage is influenced by many factors such as the size of concrete members, the type of cement and aggregate, the concrete moisture content and the predominant environmental factors. Those are represented in heating exposure time and rate, type of cooling, and maximum temperature attained [3].

The shear deficient reinforced concrete (RC) beams may be externally strengthened with bonded Fiber Reinforced Polymer (FRP) composites through bonding on their sides only, U jacketing, or complete wrapping. Debonding and FRP rupture are the main shear failure modes of strengthened beams with FRP [4–11]. Different types of materials and techniques were used in strengthening and retrofitting of existing concrete structures such as steel plates bolting, reinforced concrete jackets, pre-stressed external tendons, and most recently FRP composite which has been used on a large scale in different countries. FRP composites have many advantages over conventional methods represented in the ease of application, high strength-to-weight ratio, excellent mechanical

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strength, and good resistance to corrosion, especially that most structures are damaged due to dynamic loads, corrosion of steel, and freeze–thaw cycles [12,13].

2. Research significance

Flexural and shear are the main failure modes of RC beams. Shear failure of RC beams is classified as brittle and occurs unexpectedly without any warning while the flexural failure is ductile. Therefore, it is a necessity to make sure that the shear design of RC beams must be safe in order to develop their full flexural capacity. Unfortunately, many of existing RC beams suffering shear deficiencies due to construction faults, poor construction practices, mistakes in design calculations, changing in structure function, improper detailing of shear reinforcement and steel corrosion. Exposure of such beams to thermal shock due to any of the reasons described earlier would aggravate the weakness of the high shear zone that unless otherwise strengthened would cause imminent shear failure. External strengthening with FRP composites has established itself as an efficient method for the repairing of deficient beams in flexure yet its efficiency in regaining shear strength, especially when concrete is thermally damaged, has not been well established.

3. Experimental program

3.1. Specimens details

Sixteen high strength RC beams (100 × 150 × 1400 mm), were designed according to the ACI code [14] without shear reinforcement in the shear region. Stirrups were placed only within the constant moment region to allow easier positioning of flexural reinforcement and to provide improved confinement of concrete within the constant moment region, as shown in Fig. 1. The specimens were cast using special wooden molds of 20 mm thickness. The steel reinforcement was prepared in the form of a cage that was positioned inside the molds with proper spacers prior to concrete casting. The inside surfaces of the molds were coated using a thin layer of oil before the steel cage was placed in the molds.

3.2. Materials properties

3.2.1. Concrete mix ingredients

The concrete mix ingredients include ordinary Portland cement (Type I), crushed coarse limestone aggregates, crushed fine aggregates, silica fume, and water. The fine particles consisted from a mixture of fine silica sand and limestone at proportions of 40% and 60%, respectively. American Standards for Testing Materials ASTM-C136 was used to determine the fineness modulus of the fine particles [15], and found to be 2.75. The absorption and bulk specific gravity for fine and coarse aggregates obtained according to ASTM-C128 and C127 [15] were found to be (5.5% and 2.6) and (4.9% and 2.5), respectively. The unit weight for coarse aggregate was obtained according to ASTM-C29 [15], and found to be 1568 kg/m^3. Commercially available super-plasticizer (Flocrete SP33) was used to improve workability.

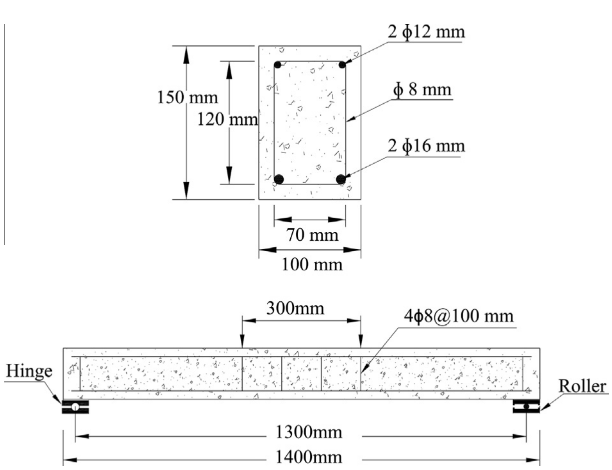

Fig. 1. Geometry and reinforcement details of the test specimens.

3.2.2. Steel reinforcement

Grade 60 deformed steel bars of 16 mm diameter were used in the tension zone of the reinforced concrete (RC) beams, a steel bars of 12 mm diameter used as top steel reinforcement, and 8 mm diameter bars were used for stirrups.

3.3. Concrete mix design

A w/c ratio of 0.3 according to ACI-211 [14] design procedure was used in concrete mix to achieve 28-days average compressive cylinder strength of 50 MPa and a slump of about 100 mm. The contents of cement, silica fume, gross water, coarse and fine limestone, and silica sand were 600, 67, 263, 980, 263.4 and 175.6 kg/m^3, respectively. The super-plasticizer was used at 2% by binder weight. A standard concrete cylinder (100 × 200 mm) was used to determine the compressive and splitting tensile strengths obtained according to ASTM-C39 and C496 [15], respectively, for concrete before and after damaged by thermal shock.

3.4. Repair materials

Two types of repair materials were used namely carbon FRP (CFRP) plates and sheets as follows:

Carbon Fiber Reinforced Polymers (CFRP) plates and sheets: Unidirectional plates and sheets at a thickness of 1.4 and 0.17 mm and a width of 50 and 500 mm, respectively, were used in the repairing of thermally damage RC beams. The physical properties and geometric of the CFRP plates and sheets are listed in Table 1. Epoxy based impregnating adhesive (concresive 2200 and MBrace Saturant) was used to glue the plates and sheets on the web sides of the beams. The quantity of the adhesive coat recommended for bonding the CFRP plates and sheets with concrete surface is 2.72 and 0.7–1.6 kg/m^2, respectively.

3.5. Thermal shock process

A special electrical furnace was used to expose beam and cylinder specimens to heat. The furnace is equipped with an electronic panel automatically controls the temperature and time of exposure. Fourteen RC beam specimens were subjected to heat at 500 °C for about two hours using the electrical furnace before immersion inside the water. Fig. 2 shows the time–temperature schedule for the furnace.

Table 1
Properties of carbon fiber reinforced polymer.

CFRP type	Plate	Sheet
Tensile strength	3900 MPa	2700 MPa
Tensile E-modulus	230,000 MPa	165,000 MPa
Strain at break	1.5%	1.4%