Engineering Structures 155 (2018) 222–234

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Comparative fire behavior of geopolymer and epoxy resin bonded fiber sheet strengthened RC beams

Hai Yan Zhang[a,b], Hao Ran Lv[a], Venkatesh Kodur[c,*], Shu Liang Qi[a]

[a] State Key Laboratory of Subtropical Architecture Science, South China University of Technology, Guangzhou, PR China
[b] Shanghai Key Laboratory of Engineering Structure Safety, SRIBS, Shanghai 200032, PR China
[c] Department of Civil and Environmental Engieering, Michigan State University, East Lansing, MI, USA

ARTICLE INFO

Keywords:
Fire test
FRP strengthening
Concrete beams
Fiber sheet
Geopolymer
Epoxy resin

ABSTRACT

This study presents results from fire resistance experiments on one RC control beam and seven fiber sheet strengthened RC beams, using geopolymer and epoxy resin as adhesive agents. Thermal response and deflection evolution of these beams with fire exposure time were monitored. The effectiveness of carbon fiber reinforced geopolymer (CFRG) strengthening system and carbon fiber reinforced polymer (CFRP) strengthening system at high temperatures is compared. Post-fire test observations and measured response parameters clearly show that the CFRG strengthening system remains fully effective at high temperatures, and thus CFRG strengthened beams experience lower deflections for longer duration (about 2 h) of fire exposure than corresponding CFRP strengthened beam with similar load levels. However, CFRG strengthened beams do not exhibit higher fire resistance than CFRP strengthened beam as anticipated. To explain this unexpected trend in results, detailed analysis, as well as numerous material level exploratory tests were conducted. The different failure mechanisms and additional contribution from cable action so as to enhance fire behavior of CFRP and CFRG strengthened beams were analyzed. Further test results and analysis clearly show that the early falling-off of fire insulation and fracturing of longitudinal CFRG system is the main cause for lower fire resistance in CFRG strengthened beams. When a layer of primer is applied between geopolymers and the insulation, the early falling-off of fire insulation can be prevented, and thus the fire resistance of CFRG strengthened beams can be enhanced (above 3 h).

1. Introduction

In the last two decades, the construction industry has shown great interest in the use of external bonded fiber reinforced polymer (FRP) for strengthening concrete structures, due to its superior strength properties, light weight and good corrosion resistance. However, its poor high temperature tolerance hinders its widespread applications in buildings and infrastructure, where fire safety is a primary design consideration [1–3]. The poor high temperature tolerance of FRP material is mainly due to the presence of organic polymer matrix as bonding agent. Organic polymer matrix exhibits significant deterioration in bond at temperatures close to its glass transition temperature (T_g – typically less than 100 °C) [4], which in turn leads to FRP strengthening system losing its effectiveness after attaining T_g. To enhance high temperature resistance of FRP strengthening system, inorganic matrix/fiber systems are being developed [5,6]. The feasibility of using cement-based or non-cement based adhesive agents for bonding fiber sheets or textile was explored by researchers [7,8]. Among these inorganic matrixes, geopolymer is regarded as a promising viable alternative to organic polymers, due to its excellent mechanical behavior and environmentally friendly characteristics [9–12].

Experimental data on the mechanical properties of fiber sheet strengthened concrete members bonded with geopolymers at ambient temperature (15–30 °C) have already been reported in literature [11,13]. Results show that fiber sheet-geopolymer system is as effective in increasing strength and stiffness of reinforced concrete (RC) beams, as fiber sheet-organic polymer system at ambient temperature. Under high temperature conditions, the microstructural evolution, thermal and mechanical properties of geopolymer material were extensively studied [14–17]. However, these tests on geopolymers were mainly conducted at material level. Up to now, only a very limited experimental data on the mechanical behavior of reinforced concrete (RC) members strengthened by fiber sheet-geopolymer system at structural level under fire conditions is reported. Zheng et al. [18] conducted fire tests on four beams strengthened by fiber sheet-geopolymer system with fire insulation. The test results showed that the effectiveness of the

* Corresponding author.
E-mail address: Kodur@egr.msu.edu (V. Kodur).

https://doi.org/10.1016/j.engstruct.2017.11.027
Received 4 March 2017; Received in revised form 26 October 2017; Accepted 11 November 2017

strengthening system was maintained during fire exposure, but the fire exposure time in these tests was only 90 min. Often longer fire resistance rating (such as 2 or 3 h) are required for structural members. Currently there is a need for reliable test data on fire performance of RC beams strengthened with fiber sheet-geopolymer strengthening under 2–3 h of fire exposure. To develop such data, fire tests were conducted on one RC control beam and seven flexural strengthened RC beams with fiber sheets, using geopolymers and epoxy resins as adhesive agent. Data generated in these tests are utilized to compare fire behavior of RC beams strengthened through fiber sheet-geopolymer system and fiber sheet-epoxy resin system under fire conditions.

In authors' previous studies, a new type of metakaolin-fly ash based geopolymer was developed [9,19]. Test results showed that its bond strength at ambient temperature is close to that of epoxy resin, and no significant strength degradation occurs at temperatures lower than 300 °C [9,20]. Therefore, fiber sheet strengthened beams using this kind of geopolymer as adhesive agent are expected to have better high temperature performance than those using epoxy resin. However, from the fire tests on beams, it was shown that the beams strengthened by fiber sheet-geopolymer system did not exhibit higher fire resistance time than those strengthened by fiber sheet-epoxy resin system. To explain this unexpected trend in results, detailed analysis on failure mechanisms of strengthened beams and material level exploratory tests were conducted. The effect of pre-cracking, fiber sheet type, number of layers of fiber sheet, and insulation primer on fire behavior of strengthened beams was also studied.

2. Experimental program

The experimental program consisted of fire resistance experiments on one unstrengthened control beam and seven flexural strengthened RC beams through fiber sheets. The test variables included fiber sheet type (carbon fiber or basalt fiber), number of layers of fiber sheet (1 or 2 layers), adhesive agent type (geopolymer or epoxy resin), and insulation bonding primer (with or without).

2.1. Fabrication of test specimens

Reinforced concrete beams and strengthening system selected for this experimental study had similar geometric and material configuration as those utilized in the test programs by Liu et al. [21] and Wu et al. [22]. Eight similar rectangular RC beams were fabricated for undertaking fire resistance tests. These beams were 250 mm wide, 400 mm deep and 5300 mm long. The beams were cast with ready-mixed concrete, produced in a concrete plant. The average cubic compressive strength at an age representative of fire resistance test was 40.4 MPa. The internal longitudinal steel reinforcement, placed at a cover of 25 mm, comprised two Φ22 deformed rebars (Type HRB335), with a yield strength of 363.5 MPa, as flexural reinforcement, and two Φ12 deformed rebars (Type HRB335), with a yield strength of 420.6 MPa, as compression reinforcement. The stirrups used as shear reinforcement were φ8 plain rebars (Type HPB235) and placed at a spacing of 160 mm in the middle pure bending section and two cantilever sections, and at a spacing of 80 mm in the shear bending sections. Since the current study is mainly aimed of comparing the effectiveness of fiber sheet-epoxy resin and fiber sheet-geopolymer flexural strengthening system under fire conditions, the shear reinforcement in beams was intentionally overdesigned to prevent shear failure. For flexurally strengthened beams, it is common to overdesign RC beams for shear capacity [6,8,20]. The reinforcement details in a typical RC beam are shown in Fig. 1.

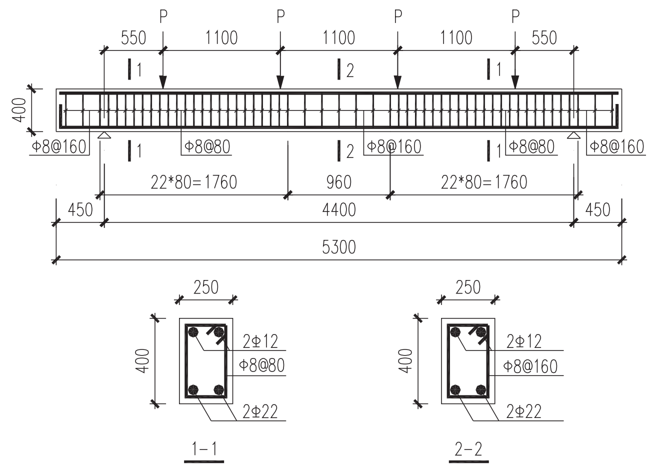

Fig. 1. Geometric dimensions and reinforcement details of a typical RC beam.

2.2. FRP strengthening

Seven of the RC beams (designated as B2 to B8) were flexurally strengthened, and one beam was left unstrengthened as the control beam (designated as B1). The strengthening system consisted of one or two layers of longitudinal fiber sheets and six U-shaped fabrics strips. The longitudinal fiber sheet was bonded on the beam soffit along the longitudinal direction, to enhance the flexural capacity of beams. The U-shaped fabrics strips, placed near the loading and bearing (support) locations and wrapped on the two sides and soffit of the beam, was to provide an anchorage for the longitudinal fiber sheets. This kind of strengthening system, namely "longitudinal fiber sheets + U-shaped fabrics strips", is widely used in Chinese engineering practice for strengthening RC beams, with insufficient moment capacity. Design details of these beams followed the specifications in Chinese code CECS 146:2003 [23].

Two types of commercially available fiber sheets, including carbon fiber (CF) sheet and basalt fiber (BF) sheet, with unidirectional plain weave, were used as the strengthening material. The carbon fiber sheet, with thickness of 0.167 mm, has an ultimate tensile strain of 1.73%. The basalt fiber sheet, with thickness of 0.16 mm, has an ultimate tensile strain of 1.7%. The cost of fiber sheet, in Chinese market (2016 rates), was \$6.5/m^2 for carbon fiber (CF) sheet, and \$2.6/m^2 for basalt fiber (BF) sheet.

The longitudinal fiber sheets and U-shaped fabrics strips were bonded on the beams through organic epoxy resin or of inorganic geopolymer. The organic matrix was provided by a commercial China supplier. The inorganic geopolymers were self-prepared by blending metakaolin and fly ash mixture with potassium silicate solution. The optimum mix proportions and detailed preparation procedures of geopolymers are given by Zhang et al. [19]. The unit cost of self-made geopolymer is \$1.9 per kilogram and is about 30% of the unit price of commercial organic matrix (\$5.1 per kilogram), but the total cost (unit cost multiplied by usage amount) of geopolymer is about 10% higher than that of commercial organic matrix, due to higher usage amount (in mass). The cost of mass-produced geopolymers is to be lowered greatly, due to decrease in shared transportation fee of raw materials.

The tensile strength of CFRP (carbon fiber reinforced polymer) composite using organic matrix is 3455 MPa and that of CFRG (carbon fiber reinforced geopolymer) composite is 3149 MPa. The tensile strength of BFRP (basalt fiber reinforced polymer) composite is 1202 MPa.

Prior to applying fiber sheets, the beams were inverted (upside down), and then the soffit of each beam was sanded-off with a grinder until coarse aggregates were exposed. Uniformly abraded bottom surfaces were washed with clean water and then dried before applying fiber sheet system. The fiber sheets, cut 4400 mm in length and 250 mm in width, were bonded on the beam soffit either through epoxy resin or geopolymer, as the longitudinal strengthening system. The FRP strengthening of beams using epoxy resin was in accordance with the specifications in Chinese code of CECS 146:2003 [23], which is similar