Construction and Building Materials 158 (2018) 670–682

Contents lists available at ScienceDirect

Construction and Building Materials

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

Theoretical modelling and acoustic emission monitoring of RC beams strengthened with UHPC

Prabhat Ranjan Prem *, A. Ramachandra Murthy, Mohit Verma

Council of Scientific and Industrial Research – Structural Engineering Research Centre, Chennai 600113, India

HIGHLIGHTS

- Non-linear fracture mechanics model to predict moment capacity.
- Strength based model to predict load deflection response of strengthened beams.
- Classification of acoustic emission parameters to study the progress of crack.
- Effect of reinforcement ratio on AE parameters in RC beams strengthened with UHPC.

ARTICLE INFO

Article history:
Received 7 July 2017
Received in revised form 10 October 2017
Accepted 12 October 2017

Keywords:
UHPC
Fracture mechanics
Strength model
Acoustic emission
Strengthening

ABSTRACT

In this study, theoretical modelling and acoustic emission (AE) studies are carried out on damaged reinforced concrete beams strengthened with ultra high performance concrete (UHPC). The contributions from the paper include (i) development of an integrated nonlinear fracture mechanics model to predict the moment carrying capacity of composite beam considering (a) stress intensity factors due to cement paste, steel, UHPC and applied load (b) vectorial contributions of crack displacement from external moment, steel and UHPC force (ii) prediction of load deflection response of strengthened beams by strength based model which applies concepts of force equilibrium and strain compatibility method (iii) analysis of the effect of reinforcement ratio on AE parameters from parametric analysis. The presented results can be effectively utilized for designing UHPC thickness and health monitoring of structures strengthened with UHPC.

1. Introduction

The growing demand to meet stringent requirements of sustainability, serviceability and durability characteristics, research lead towards development ultra high performance concrete (UHPC). From literature, it is found that UHPC have a very dense cementitious matrix with inclusion of micro steel fibers leading to, compressive strength generally greater than 150 MPa, ductility, deflection hardening and deflection softening properties, toughness, energy absorption capacity and blast resistant characteristics [1,2]. The excellent material properties of UHPC can be utilized to reduce section enlargement while doing strengthening using jacketing methods or external plate ponding. UHPC as a retrofitting material have been found to overcome the drawbacks found in fiber reinforced polymer such as delamination and brittle failure. The studies presented by Tayeh et al. [3], have shown promising results in rehabilitation of crash barrier wall, bridge piers, beam-column joints, enhancing shear and flexural resistance of the composite members by UHPC. Recent, published research showed highlighted superior performance of strengthened beams in terms of flexural capacity and torsional performance with UHPC jacketing [4,5]. From literature review, it is observed that the critical parameters considered for strengthening flexural damaged structures include (i) existing reinforcement ratio in the reinforced concrete (RC) beams (ii) damage state of substrate member (iii) strengthening thickness of UHPC for jacketing or overlaying (iv) health monitoring of strengthened members with UHPC. The present paper forms the continuation of earlier work carried out by the authors on development of mix design [6,7], methodology of curing [8], determination of fracture [9], impact properties [10,11] and repairing flexural members [12–14]. In the present paper, theoretical model is presented for predicting the moment capacity of strengthened beams by using non linear fracture mechanics approach and strength based theory. The second part of the paper examines the effect on AE parameters during strengthening when the reinforcement ratio of beams are different (0.57% – A, 0.89% – B and 1.30% – C) and strengthened with an overlay of 15 mm UHPC thickness.

* Corresponding author.
E-mail address: prabhat@serc.res.in (P.R. Prem).

https://doi.org/10.1016/j.conbuildmat.2017.10.063
0950-0618/

Table 1
Mix design of UHPC.

Cement kg/m^3	Silica fume kg/m^3	Quartz powder kg/m^3	Fine aggregates kg/m^3	Water l/m^3	Superplasticizer l/m^3
787	196	314	867	173	14.63

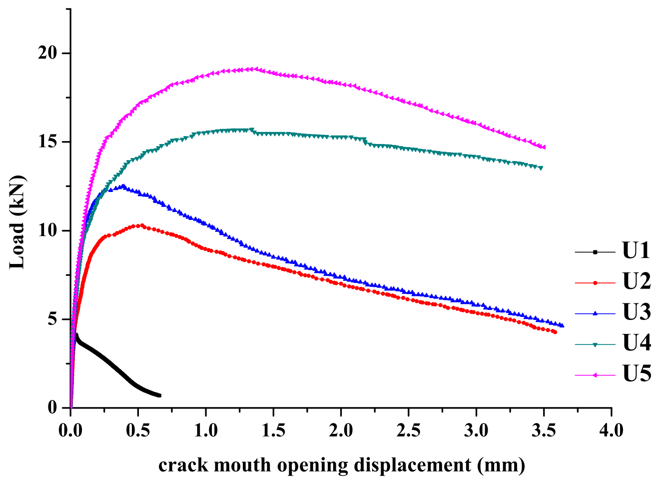

Fig. 1. Load versus crack mouth opening displacement.

2. Research significance

In the present paper, theoretical studies are conduct towards development of non linear fracture mechanics model and strength model. The fracture model accounts for bi-linear tension softening parameters to predict the moment capacity of strengthened beams while strength model evaluates the flexural behaviour by considering force equilibrium and strain compatibility. In other studies, parametric analysis is done to study the effect of reinforcement ratio in substrate beams after strengthening with UHPC. The values of acoustic emission parameters are classified in five different damages zones to study failure mechanisms of composite beams. From overall studies an analytical and parametric study is presented to study the behaviour of strengthened reinforced beams with UHPC.

3. Material properties

3.1. Ultra high performance concrete

The mix design of UHPC is presented in Table 1 [8]. The ductility of UHPC is improved with straight micro steel fibers having aspect ratio of 81 and 38. The fibers are of 6 (F1) and 13 mm (F2) length (l), each with diameter (d) of 0.16 mm. Five batches of UHPC are cast, of which details are - U1 with 0% fiber, U2 with 2% F1, U3 with 2.5% F1, U4 with 2% F2 and U5 with 2.5% volume fraction (V_f) F2. The split tensile strength of U1–U5 mix is found to 11.8, 18, 20.2, 22.6 and 23.8 MPa. In order to study the fracture response of UHPC, notched prisms (100 × 100 × 350 mm) is measured under three-point loading as per RILEM recommendations [15]. The fracture response of UHPC prisms is shown in Fig. 1. From the obtained results Mix U4 is chosen to cast UHPC overlay.

3.2. Reinforced concrete beams

A set of virgin RC beams (A, B and C) of size (100 × 200 × 1500 mm) are tested under four point bending to determine average flexural capacity. The average ultimate load (P_u) of control beams is determined from Fig. 4a. The properties of beam, instrumentation and test set up is given in Fig. 2 and Fig. 3, respectively. After testing of control beams, virgin RC beams of each type are cast again and preloaded till 90% of ultimate load to induce damage. The damaged beams of each category are now strengthened with precast UHPC overlays of 10 mm (A1, B1 & C1), 15 mm (A2, B2 & C2) and 20 mm (A3, B3 & C3) thickness in tension region by epoxy and tested till failure. The flexural behaviour of strengthened beams under bending is given in Fig. 4b–d.

4. Analytical modelling

4.1. Inverse analysis of UHPC mixes

The load versus crack mouth opening displacement of UHPC prisms given in Fig. 1 are used to evaluate stress and crack displacement ($\sigma - w$) relationship from inverse analysis through crack hinge model. The obtained parameters are used for modelling UHPC as a strengthening member for damaged RC beams. The $\sigma - w$ relationship for UHPC is derived from the model developed by [16,17]) for fiber reinforced concretes. In the model the tensile stress before crack initiation is modelled elastically while the cracked state is done by crack hinge model given by Eq. (1) and (2) and further simplifications.

$$\sigma = \begin{cases} E\varepsilon & \text{Pre-CrackedState} \\ g(w)f_t & \text{Cracked} \end{cases} \quad (1)$$

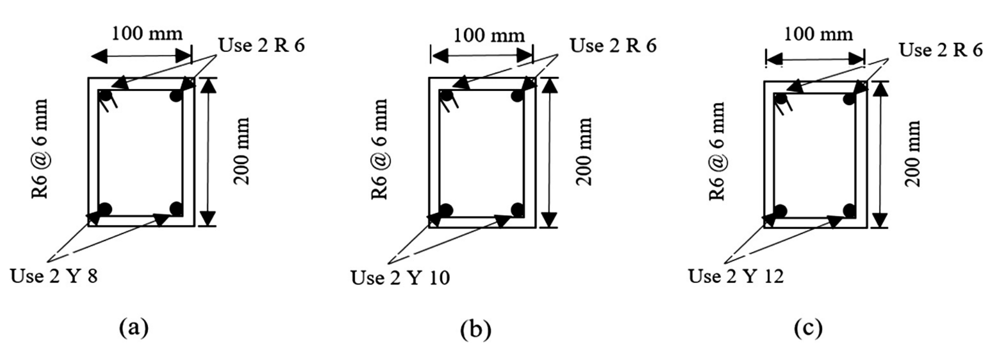

Fig. 2. Cross section of control beams: (a) A (b) B (c) C.