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Concrete cover separation failure of overlay-strengthened reinforced concrete beams

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ABSTRACT

This paper presents an analytical approach based on the concrete tooth model for overlay-strengthened beams failed with concrete cover separation at the cut-off point of overlay end. The length of concrete cover separation required for the peak load of overlay-strengthened beam to be reached is derived from the proposed analytical procedure which is based on experimental observations. The reliability and accuracy of the proposed analytical procedure has been verified by comparing the analytical and experimental crack spacing as well as peak load of the overlay-strengthened beams. Finally, the concept of maximum efficient capacity of overlay strengthening method is presented.

1. Introduction

Overlaying is considered as a major retrofitting method for flexural and fatigue strengthening or retrofitting of concrete flexural members. As shown in Fig. 1, in this method, the reinforcements such as steel bars or Fiber-Reinforced Plastic (FRP) grid are arranged underneath the lower surface of the concrete members and the Polymer Cement Mortar (PCM) or High Performance Fiber Reinforced Cementitious Composites (HPFRCC) is sprayed onto them. In light of the weak bond strength of overlaying with normal cement based materials, the PCM and HPFRCC offer a good compromise of bond strength and durability. Comparing with steel bars as overlay reinforcement, the FRP grid is of low weight and high corrosion resistance and gaining more and more interest recently.

Existing experimental observations [1,2] have shown that the application of externally bonded PCM or HPFRCC overlay to strengthen RC structures can lead to brittle failures involving debonding of the overlay before the design load is reached with classical failure modes. The flexure failure with concrete crushing (Fig. 2a) is quite similar as that of conventional RC structures. The shear failure can be observed with shear cracks either at the overlay end (Fig. 2b) or near to the overlay end (Fig. 2c). In an overlay-strengthened beam, the debonding failure can initiate either near mid-span owing to flexural or shear cracks (Fig. 2d), or at the edge of overlay as a result of stress concentration at the cut-off point (Fig. 2e and f). These premature debonding modes can also be observed in the beam strengthened with other soffit plate like steel plate and FRP sheet [2–5]. The design procedure for the PCM or HPFRCC overlay to strengthen a RC element should avoid these premature debonding failures.

Among the premature debonding failure modes, concrete cover separation, as shown in Fig. 2e, is often observed in the experiments. Current models to explain the concrete cover separation of a strengthened beam fall into three broad basis [2]: (1) the derivation of elastic stress concentrations at the overlay end (2) the shear capacity of strengthened beams and (3) the concrete tooth model. However, it has been reported that none of the current models can predict the peak load satisfactorily when concrete cover is separated [2]. Besides, despite the fact that numerous studies have been carried out to investigate the concrete cover separation problem of RC members strengthened with steel or FRP plate [6–13], there are very limited studies concerning PCM, HPFRCC or other cementitious materials overlay debonding [1,14,15].

The authors are conducting a series of studies with the aim at development of an analytical approach for flexural strengthening of an existing structure with external overlay with predicting debonding failure. The objective of this paper is to establish a simple and accurate design methodology to predict the load carrying capacity of PCM or HPFRCC overlay strengthened RC beam failed by concrete cover separation from the cut-off point of overlay end. The concrete tooth model is induced as an analytical tool and the length

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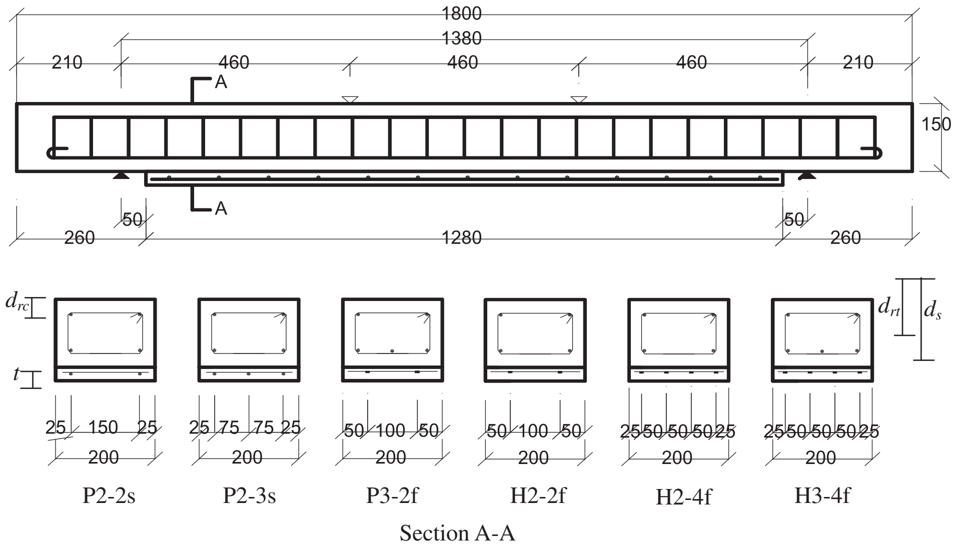

Fig. 1. Overlay strengthened RC beam (unit: mm).

of concrete cover separation corresponding to the peak load is derived analytically based on experimental observations. The reliability and accuracy of the proposed analytical procedure are then verified by comparing the analytical and experimental peak load of the overlay-strengthened beams provided in this paper.

2. Experiment review

The main objective of the experimental program was to provide a better understanding on the failure mechanism of concrete cover separation of overlay-strengthened beams. Experimental works on strengthened beams including three PCM overlay and three HPFRCC overlay with steel bar or FRP grid as reinforcement were carried out.

2.1. Experiment program

Fig. 1 shows the geometrical details of the strengthened beam using PCM or HPFRCC overlay method. The bottom surface of RC beams was treated by Water Jet (*WJ*) method and special attention was paid to provide adequate moisture on the substrate concrete surface. The substrate concrete surface was kept saturated and free water was removed before the casting of PCM or HPFRCC.

The acronym designation adopted for beams shown in Fig. 1 was as follows: first letter is the word character *P* or *H* designating PCM or HPFRCC overlay group beams; the first number appearing after *P* or *H* represents number of tension reinforcing bars in RC part; the following number indicates number of longitudinal steel reinforcing bars or longitudinal FRP bars in FRP grid as overlay reinforcement; the last letter *s* or *f* designating the usage of steel bar or FRP grid as overlay reinforcement. Table 1a shows the mechanical properties of concrete beams, where d_{rc}, d_r, v_s, f_c', f_{ct} and E_{con} denote distance from beam compression face to centroid of steel compression reinforcement, distance from beam compression face to centroid of steel tension reinforcement, spacing of stirrup, concrete cylinder compressive strength, concrete tensile strength and modulus of elasticity of concrete respectively. Table 1b and c give the mechanical properties of reinforcement in the RC beam and the geometric and material properties of PCM or HPFRCC overlay, where $E_{rc(r,v,s)}$, $f_{yrc(r,v,s)}$, $f_{urc(r,v,s)}$, $D_{rc(r,v,s)}$, denote the modulus of elasticity, yielding strength, ultimate strength and unit diameter of compression reinforcement, tension reinforcement, shear reinforcement and strengthening reinforcement, respectively. $n_{rc(r,s)}$ denotes the number of compression, tension reinforcement and strengthening reinforcement, respectively. f_o', f_{ot}, E_o, and t denote the cylinder compressive strength, tensile strength, modulus of elasticity and thickness of the overlay material, d_s denotes distance from beam compression face to centroid of overlay strengthening reinforcement, A_s denotes cross-sectional area of strengthening reinforcement. The other beam parameters can be found in Fig. 1.

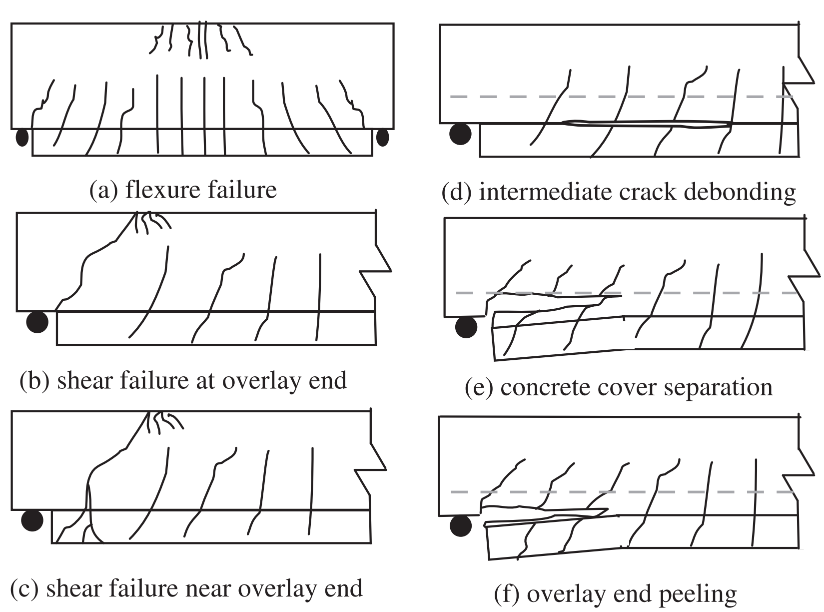

Fig. 2. Failure modes of PCM overlay strengthened beam.