Composite Structures 161 (2017) 119–131

Contents lists available at ScienceDirect

Composite Structures

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

Controlled failure warning and mitigation of prematurely failing beam through adhesive

Mohammad Arsalan Khan [a,*], Vadim V. Silberschmidt [b], Jamal El-Rimawi [a]

[a] School of Civil and Building Engineering, Loughborough University, Leicestershire, Loughborough LE11 3TU, United Kingdom
[b] School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, Loughborough LE11 3TU, United Kingdom

ARTICLE INFO

Article history:
Received 14 May 2016
Revised 11 November 2016
Accepted 11 November 2016
Available online 16 November 2016

Keywords:
Premature failure
Cohesive zone model
Retrofitting
Debonding
Brittleness of failure

ABSTRACT

In plated beam, an adhesive is used primarily to adhere the external plate to the concrete beam to achieve a composite action. Even though some work has been found to indicate that the choice of softer adhesive increased the capacity of beam (MacDonald & Calder, 1982), relatively stiffer adhesives have been largely assumed to provide better strengthening. Largely, due to the fact that adhesive has been widely considered as an insignificant structural component towards the capacity of a composite beam; material capabilities (if not structural) of adhesive have also been ignored for further research towards studying its effects on premature failures (particularly debonding). Under mixed-mode loading, the adoption through discretisation of Cohesive Zone Model as a bulk material (indicative of adhesive component) and to simulate interfacial cracks is shown here to achieve the objectives. The outcomes of the research indicate the critical material properties of adhesive in all directions, such as stiffness, strength and crack energy, play crucial role in controlling the behaviour of modes of failure. Further, based on this study, recommendations have been proposed on the choice of adhesive type at different locations of plated beam so as to capture a failure warning and avoid catastrophic failure.

1. Introduction: practical significance of failure modes

An adhesively plated RC beam is susceptible to premature failures before it can attain its desired capacity, especially debonding and peeling due to their uncertain and brittle nature. Peeling is different than debonding in a way that former is caused as a consequence of formation and propagation of flexural crack at plate end, while latter is due to the formation of interfacial cracks at a composite interface (largely adhesive-concrete interface for plated RC beams). Focusing on debonding, the initial objectives of this paper is to associate possible modes of failure with debonding in terms of location of formation and/or propagation.

1.1. Major debonding types

1.1.1. Mid-span debonding

Sebastian [1] pointed out that debonding at mid-span debonding is a self-propagating process. In the flexural region of the beam, intermediate cracks shall appear in the concrete substrate and the debonding would initiate at the toes of these cracks propagating outwards from high bending region to lower. It is observed that the crack will travel through the plane very close to concrete-plate interface involving no concrete aggregate in the fracture plane.

The formation of flexural crack in concrete causes differential transverse deformations of the two materials at common interface; resulting into transverse stresses leading to failure due to interfacial crack (see Fig. 1). Alfano et al. [2] held accountable the propagation of such flexural cracks to cause localised yielding of reinforcement(s).

1.1.2. Plate end interfacial debonding

If the plate ends are discontinuous at supports, with increased mid-span deflection, plate will undergo slip at interface due to difference in material properties as well as deformation in normal direction due to relative stiffness.

To model the development of peak stresses at plate end, the FE model of Teng et al. [3] was in disagreement with the theoretical model of Smith and Teng [4]. The 3D FE model by Ascione and Feo [5], mainly adopted for predicting the shear and normal stresses in the adhesive layer of the plated RC beam, largely agreed with

* Corresponding author at: Department of Civil Engineering, Z. H. College of Engineering and Technology, Aligarh Muslim University, Aligarh 202002, Uttar Pradesh, India.

E-mail addresses: mohd.arsalan.khan@hotmail.co.uk (M.A. Khan), v.silberschmidt@lboro.ac.uk (V.V. Silberschmidt), j.a.el-rimawi@lboro.ac.uk (J. El-Rimawi).

http://dx.doi.org/10.1016/j.compstruct.2016.11.049
0263-8223/

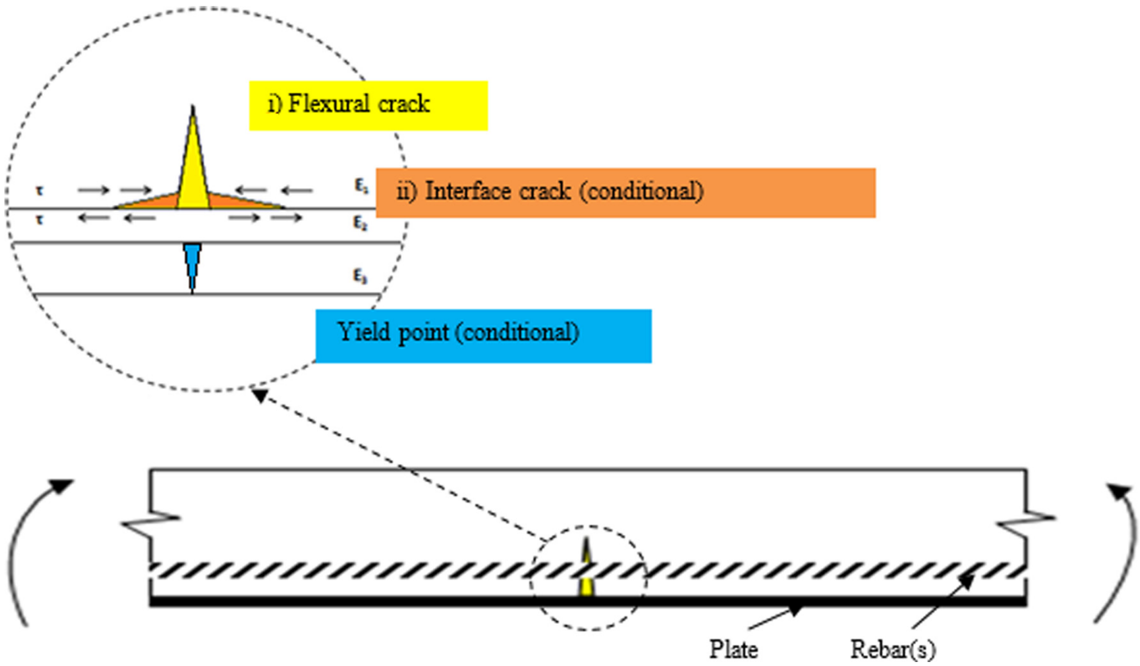

Fig. 1. Propagation of flexural crack along plate length.

the experimental test observations of Jones et al. [6]. When compared to real scenario, it is seen that, such behaviour of stress variation (particularly, at plate ends) does not emerge in analytical simplifications of Roberts [7], Roberts and Haji-Kazemi [8] and Oehlers [9]. Due to complexities in theoretical procedures, researchers such as De Lorenzis and Zavarise [10], could not quantify for non-linear material properties of the composite system for investigating plate end debonding.

1.2. Parameters and their role on the behaviour of plated beam

The use of epoxy adhesive, composed of a resin and a hardener, is a common practice in externally retrofitting concrete beams with FRP or steel [11,12]. Although, not as a significant structural strengthening component; however, as a component for structural integrity, the material properties of adhesive are likely to affect the premature capacity of the beam mainly in debonding. Therefore, in the present study, the theoretical and numerical framework at interface is devised to make viable the investigation on large number of adhesive parameters on modes of failure.

To tackle debonding due to adhesive, the selective material parameters include the elastic modulus of adhesive E_g, shear modulus of adhesive G_g, shear strength of interface t_s°, normal strength of interface t_n°, fracture energy of adhesive G_{fg}.

1.2.1. Initial stiffness of adhesive

In their FE model, Teng et al. [3] reported an increase in interfacial stresses with the increase in adhesive elastic modulus with modulus varying within the range of 2000–6000 MPa. Macdonald and Calder [13], altering adhesive stiffness in an unspecified range, found that it has virtually no significant effect on the load-deflection behaviour of the beam; although, it was seen that the use of a stiffer adhesive generated more flexural cracks at a closer spacing than either the as-cast beams or plated beams using a flexible adhesive could show. The reason behind this behaviour was not identified or explained. Macdonald [14] qualitatively reported that soft adhesive has an advantage over stiff adhesive in that it is capable of withstanding movement while it is being cured.

1.2.2. Shear strength of interface

From literature, it is seen that the pull-off capacity for the plated beams using stiff adhesives is closer to the tensile strength of concrete. Reeve [15] found that the pull-off capacity for adhesives having elastic moduli of 4482 MPa and 2227 MPa were respectively 2.85 MPa and 2.65 MPa, where the 28 day compressive strength of concrete was 23.3 MPa. Oh et al. [16] found that the shear strength of interface tested through double lap pull-out test varied with changing plate and adhesive thickness. For adhesive with modulus of elasticity of 2300 MPa, the average shear strength was observed within a range of 1.1 MPa–2.5 MPa, where the 28 day compressive strength of concrete was 46.3 MPa, modulus of elasticity of 32,000 MPa, and the split tensile strength of 2.93 MPa. Jones et al. [6] achieved maximum interface bond strength of 5.01 MPa (that is, for a mixed mode failure) for a concrete having an average compressive strength of 53.6 MPa and the average splitting tensile strength of 3.55 MPa. Whereas, the observations made by Heathcote [17] have suggested an average value of 2 MPa for the shear strength of interface.

2. Method and numerical model

2.1. Method

2.1.1. Discretisation of material behaviour of a common interface

One of the original theoretical concepts of fracture of concrete is extended in the context of current problem to illustrate the behaviour of common interface between two materials. Due to the formation of micro cracks in quasi-brittle materials or deformation-softening materials, such as concrete, it is favourable to adopt crack energy equivalent to cracking strain for analysis.

Fig. 2 shows a typical stress-displacement relationship of a non-linear material or composite interface generally subjected to tension or shear or both (mixed mode). Initially, as the force is increased, the equivalent behaviour at interface is demonstrated by average stiffness.

After certain loading, this is followed by a crack that initiates within a matrix of a weakest material. Unlike conventional