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An analytical model for predicting the response of RC beams strengthened with strain localized steel plate

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HIGHLIGHTS

- A strain localization mechanism is introduced.
- The behavior of RC beam strengthened by strain localized steel plate is analyzed.
- A parametric study is conducted for this new plating system.

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ABSTRACT

A new plating system based on strain localization mechanism has been recently proposed for strengthening RC structures to overcome the debonding problem. With this new technique, weaker zones are placed on a steel plate to accommodate large local strains, hence delaying or preventing interfacial debonding. This paper develops an analytical method to predict the performance of RC beams strengthened with this new technique. The results agree well with those from finite element analyses. A parametric study is also conducted to investigate effect of the geometric dimension and material properties of the weaker zone on performance of such strengthened RC beam.

1. Introduction

External bonding of fiber reinforced polymer (FRP) or steel plates/sheets has become one of the most popular methods for strengthening or repairing of concrete structures. A key issue affecting safe application of this technique is the concrete-to-plate interface debonding, which can lead to premature failure of structures and hence considerably reduce the effectiveness of the method. Anchorage systems for externally-bonded plates are, therefore, an important mechanism to overcome the interfacial debonding problem. Various anchorage systems have been proposed, such as end anchorage, fiber anchor, U jacketing, and mechanical fastening [1–6], to delay the debonding. More recently, a hybrid-bonded system has been developed to overcome the interfacial debonding problem [7–9]. Although these bond systems can more or less improve the interfacial bond characteristics, they cannot change the suddenness of failure of externally-bonded system, be it a debonding failure or FRP rupture, both of which are catastrophic and highly dangerous.

As a most recent attempt to overcome the problems of externally-bonded strengthening systems, a new system has been proposed and is being investigated in an ongoing research project at City University of Hong Kong [10,11]. With this newest technology, nanostructured steel plates, which is highly strong yet ductile, are used to replace FRP plates for structural strengthening, so that brittle material failure can be avoided. Also, a strain localization mechanism is developed to prevent debonding of the plate. A brief introduction of this new bond system is given below.

Surface Mechanical Attrition Treatment (SMAT) was a recently developed nano-technology to form nanocrystallized surface layer [12,13] for metal materials by actuating a number of spherical projectiles to affect the material surface. The SMAT generates repetitive severe plastic deformation on the surface layer of a material and refines the microstructure of the subsurface layer to nanoscale, so that their yield strength can be largely increased

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Nomenclature

A_s A_w A_{s1}	sectional area for stronger zone, weaker zone and steel bar
b_c	width of RC beam
b_s	width of steel plate
d_{sp}	plastic displacement of stronger zone
d_{wp}	plastic displacement of weaker zone
E_c	elastic modulus of concrete
E_p	plastic modulus of stronger zone
E_s	elastic modulus of stronger zone
E_{s1}	elastic modulus of steel bar
E_w	elastic modulus of weaker zone
F_a, F_b, F_c, F_e	external loads for point a, b, c, e.
f_a, f_b, f_c, f_e	mid-span displacements for point a, b, c, e.
f'_c	concrete compressive strength
f_t	concrete tensile strength
G_f	fracture energy for interface
h_0	height of RC beam
h_c	thickness of concrete cover
L	length of the steel plate
L_e	length of elastic zone of steel plate
L_s	length from support to plate end
L_x	length from plate end to left side of weaker zone
L_p	length of the steel plate plastic zone
l_0	length between two supports
l_d	length of the debonding zone
l_l	effective bond length
l_s	length of the softening zone
l_w	length of weaker zone
M_{sy} M_{wy}	yield section moment for stronger zone and weaker zone
P	tensile force provided by weaker zone
t_s t_w	thickness for stronger zone and weaker zone
u_c u_s	axial displacement for concrete and steel plate
β_w	coefficient of width ratio
β_l	coefficient anchorage length
δ	slip between concrete and plate
$\delta_f \delta'_f$	slip at debonding and its reduced value
δ_0	relative slip at softening
ε_1	steel bar strain in tensile zone
ε'_1	steel bar strain in compressive zone
ε_c	concrete strain
ε_{cu}	crushing/ultimate strain of concrete
ε_o	concrete strain at peak load
ε_{sp}	plastic strain for stronger zone
ε_{sy}	yield strain for stronger zone
ε_{su}	ultimate strain for stronger zone
ε_{wdb}	strain in weaker zone for case of full debonding
ε_{wy}	yield strain for weaker zone
ε_{wu}	ultimate strain for weaker zone
φ	section curvature
σ_{s1}	stress of steel bar in tensile zone
σ'_{s1}	stress of steel bar under compression
$\sigma'_{sp}(x)\sigma_{sp}(x)$	tensile stress for stronger zone after yield and its component due to hardening
σ_{su}	ultimate strength for stronger zone
σ_{sy}	yield strength for stronger zone
σ_{wy}	yield strength for weaker zone
σ_{wu}	ultimate strength for weaker zone
τ_{max}	concrete/steel bond strength
τ'_{max}	reduced value of τ_{max}
τ	concrete/steel shear strength

while retaining its Young's modulus and ductility. When SMAT technology is used to treat thin stainless steel plates, it is possible to achieve a strength similar to FRP plate with the same thickness. As a result, this nanomaterial is ideal for structural strengthening as it is as easy in handling in construction as FRP and as ductile as steel material. Since SMAT can vary along the plate length, a strain localization mechanism is developed to delay or avoid debonding. The strain localization mechanism is illustrated in Fig. 1 [10,11]. The darker zones of the steel plate indicate SMAT zones which results in higher yield strength and the lighter zones are non-SMAR zones with lower yield strength. During the loading process, the strain increase is localized in the non-SMAT zones after the steel plate yield. Therefore, the SMAT zones remain elastic even at a very large displacement. As debonding is closely related to the strain of the external reinforcement and would not occur if the strain is controlled within a certain limit, the RC beam and the steel plate could keep working together without any other mechanical anchorage measures.

An experimental program was completed to validate the effectiveness of this system [10], and another numerical study was also undertaken to understand its general behavior [11]. The objective of this work is to develop an analytical tool to quantify the performance of the RC beam strengthened with this new technology.

2. General behavior of steel plated beams

2.1. Critical thicknesses of steel plate

When an RC beam is strengthened by the adhesive bonding at its bottom with a steel plate that has uniform properties along the length, there are two possible failure modes of the plating system: debonding and rupture of the plate. If concrete crushing does not occur or is ignored, one of the two failure modes will happen sooner or later when the beam displacement keeps increasing. In other words, whether a plating system fails or not depends on its maximum allowable displacement. Therefore, in this work, when failure of a plating system is mentioned, it refers to a particular displacement value. Whether debonding occurs or not up to a given allowable beam displacement depends on the thickness of the plate. A very thin plate will not cause debonding and a very thick plate will lead to debonding. For a particular structure and a certain allowable displacement, the maximum plate thickness t_0 at which debonding just occur is an important threshold value of

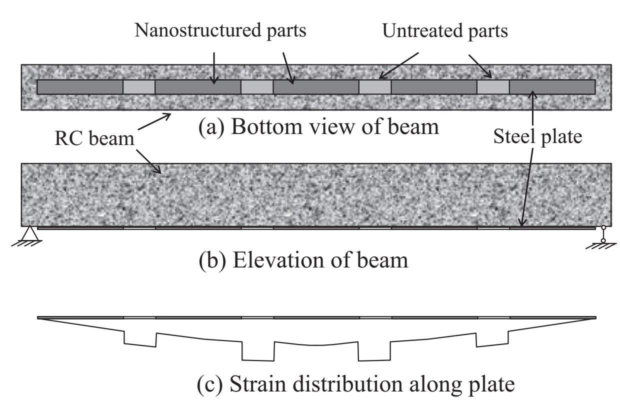

Fig. 1. Nano-structured steel plating system [10,11].