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Experimental and analytical investigation of reinforced high strength concrete continuous beams strengthened with fiber reinforced polymer

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ABSTRACT

Carbon and glass fiber reinforced polymer (CFRP and GFRP) are two materials suitable for strengthening the reinforced concrete (RC) beams. Although many in situ RC beams are of continuous constructions, there has been very limited research on the behavior of such beams with externally applied FRP laminate. In addition, most design guidelines were developed for simply supported beams with external FRP laminates. This paper presents an experimental program conducted to study the flexural behavior and redistribution in moment of reinforced high strength concrete (RHSC) continuous beams strengthened with CFRP and GFRP sheets. Test results showed that with increasing the number of CFRP sheet layers, the ultimate strength increases, while the ductility, moment redistribution, and ultimate strain of CFRP sheet decrease. Also, by using the GFRP sheet in strengthening the continuous beam reduced loss in ductility and moment redistribution but it did not significantly increase ultimate strength of beam. The moment enhancement ratio of the strengthened continuous beams was significantly higher than the ultimate load enhancement ratio in the same beam. An analytical model for moment–curvature and load capacity are developed and used for the tested continuous beams in current and other similar studies. The stress–strain curves of concrete, steel and FRP were considered as integrity model. Stress–strain model of concrete is extended from Oztekin et al.'s model by modifying the ultimate strain. Also, new parameters of equivalent stress block are obtained for flexural calculation of RHSC beams. Good agreement between experiment and prediction values is achieved.

1. Introduction

Externally bonding fiber reinforced polymer (FRP) sheets with an epoxy resin is an effective technique for strengthening and repairing the reinforced concrete (RC) beams under flexural loads. Consequently, a great amount of research, both experimental and theoretical, has been conducted on the behavior of FRP strengthened RC structures including beams, slabs and columns [1–4]. In particular, their practical implementation in flexural strengthening has been numerous [5–13] and resulted in tremendous improvement in their application. The most widely used and studied composites for flexural strengthening the RC simply beams are CFRPs. Researches concluded that externally bonded FRP could increase the capacity of RC elements efficiently. A large loss in beam ductility, however, occurs when CFRP are used for flexural strengthening of RC beams, because these materials have dissimilar behavior to that of steel, that is, they exhibit a linear stress–strain behavior up to failure [7,10,11]. Also, behavior of strengthened RC beam by GFRP has been studied, As a result, the ductility and stiffness of CFRP strengthened beams are noticeably lower and higher than those of GFRP strengthened beams, and all the beams reported are simply supported having an average concrete compressive strength of 30 MPa [5,6,8,11,13].

The review of the literature on experimental studies on the response of RC simply supported strengthened beams with externally bonded FRP reveals that several different failure modes were observed. The possible failure mechanisms that observed in experimental tests are summarized by Teng et al. [2]. Premature failures such as delaminating FRP and laminate separation can significantly limit the capacity enhancement and prevent the full ultimate flexural capacity of the retrofitted beams from being attained. Several studies were conducted to identify ways of preventing premature failures with a view to improve the load capacity and ductility of strengthened concrete beams. A number of authors have recommended the use of steel anchor bolts, steel clamps at the strip ends and mechanical fasteners for preventing premature failure of RC beams strengthened with FRP Plates [14–17]. Other researchers studied the use of end anchorage techniques such as U-strap, L-shape jackets and steel clamp for preventing premature failure of RC beams strengthened with FRP sheets [18–20].

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Nomenclature

A	coefficient
A'	constant
A_{con}	area under stress–strain curve of concrete (mm^2)
A_f	cross-section area of FRP reinforcement (mm^2)
A_s	total cross-section area of tensile steel (mm^2)
A'_s	total cross-section area of compressive steel (mm^2)
B	coefficient
B'	constant
b	width of beam section (mm)
b_f	width of FRP (mm)
C	coefficient
C'	constant
c	depth of neutral axis (mm)
D'	constant
d_c	distance from extreme compressive fiber to line of action of concrete compressive force (mm)
d_f	distance from extreme compressive fiber to centroid of FRP (mm)
d_s	effective depth of beam section (mm)
d'_s	distance from extreme compressive fiber to centroid of compressive steel (mm)
E_c	modulus of elasticity of concrete (MPa)
E_f	modulus of elasticity of FRP (MPa)
E_s	modulus of elasticity of steel (MPa)
f_c	stress in concrete (MPa)
f'_c	concrete cylinder compressive strength (MPa)
f_{cu}	concrete cube compressive strength (MPa)
f_{fu}	ultimate tensile strength of FRP (MPa)
f_0	constant
f_r	tensile strength of concrete in flexure (MPa)
f_s	stress in tension steel (MPa)
f_{sf}	steel failure stress (MPa)
f_{su}	steel ultimate stress (MPa)
f_y	steel yielding stress (MPa)
h	depth of beam section (mm)
k	constant
k_m	FRP strain reduction factor
l	clear beam span (mm)
M	predicted resistance moment (kN m)
M_e	elastic moment at ultimate load (kN m)
M_{uh}	ultimate moment at central support (hogging region) (kN m)
M_{us}	ultimate moment at mid-span (sagging region) (kN m)
M_{exp}	experimental moment at ultimate load (kN m)
n	number of plies of FRP
P_y	yielding total load of tensile steel at central support (kN)
P_u	ultimate applied total load (kN)
p	applied predicted load at mid-span (kN)
t_f	thickness of each ply of FRP (mm)
x	constant
α	mean stress factor for resultant concrete compressive force
β	moment redistribution ratio
γ	centroid factor indicating position of compressive force in concrete
ε_c	strain of concrete at compressive extreme fiber (mm/mm)
$\bar{\varepsilon}_c$	strain at area centroid of concrete stress–strain curve (mm/mm)
ε_{co}	concrete strain at the peak stress (mm/mm)
ε_{ct}	strain of concrete at tensile extreme fiber (mm/mm)
ε_{cu}	ultimate strain of concrete (mm/mm)
ε_{db}	debonding strain in FRP (mm/mm)
ε_f	FRP strain (mm/mm)
ε_{ff}	failure strain of FRP (mm/mm)
ε_{fu}	ultimate tensile strain of FRP (mm/mm)
ε_s	strain in tensile steel (mm/mm)
ε'_s	strain in compressive steel (mm/mm)
ε_{sf}	failure strain of steel (mm/mm)
ε_{sh}	hardening strain of steel (mm/mm)
ε_{su}	ultimate strain of steel (mm/mm)
ε_y	yielding strain of steel (mm/mm)
Δ_u	mid-span deflection at ultimate load (mm)
Δ_y	mid-span deflection at yielding load (mm)
φ	curvature of section (mm^{-1})
λ	ratio of the ultimate load of strengthened beams to that of the control beam
μ_Δ	deflection ductility index
ξ	ratio of the yielding load of strengthened beams to that of control beam
χ	ratio of the ultimate moment of strengthened beams at failure time to that of control beam

Although many in situ RC beams are continuous construction, there has been very limited research into the behavior of such beams with external reinforcement [21–24]. In addition, most design guidelines were developed for simply supported beams with external FRP laminates [25–27]. Ductility is even more important for statically indeterminate structures, such as continuous beams, as it allows for moment redistribution through the rotations of plastic hinges. Moment redistribution permits the utilization of the full capacity of more segments of the beam.

Ashour et al. and El-Refaie et al. found out that increasing the CFRP sheet length to cover the entire hogging or sagging zones did not prevent the premature failure; further research into the performance of end anchorage techniques is necessary to minimize the risk of this mode of failure. Also, they suggested that, strengthening both the top surface at central support and beam soffit is the most effective arrangement of the CFRP laminates to enhance the beam load capacity [21,22]. Grace et al. investigated the effectiveness of new triaxially braided ductile fabric in providing ductile behaviors in RC continuous beams strengthened in flexure. They concluded that, the beams strengthened with the new fabric showed greater ductility than those strengthened with the carbon fiber sheet [23]. However, the concrete used by [21–24] was normal concrete with an average cube compressive strength of about 35 MPa. In other words, no research report was observed on strengthening the reinforced continuous beams consist of HSC and RC continuous beams strengthened with GFRP laminate.

The new developments in concrete technology have led to increased applications of HSC all around the globe. HSC offers many advantages over conventional concrete. When the strength of concrete gets higher, some of its characteristics and engineering properties become different from those of normal-strength concrete (NSC) [28,29]. These differences in material properties may have important consequences in terms of the structural behavior and design of HSC members [30]. Oztekin et al. obtained new stress–strain parameters of HSC from experimental stress–strain diagrams. Also, they obtained new equivalent stress block parameters at only ultimate strain not for any given concrete strain [30].These concretes, with very high compressive strength, can result in less ductile responses of structural members. The displacement ductility increases as concrete compressive strength increases for the