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Flexural behavior of ECC-concrete composite beams reinforced with steel bars

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HIGHLIGHTS

- Calculate formula for deflections, cracking, yield and ultimate moments are proposed.
- Experimental testing of steel reinforced ECC-concrete composite beams is carried out.
- Various failure modes of ECC-concrete composite beams are identified.
- Validation of the proposed equations is achieved against experimental results.
- Parametric analysis on the flexural behavior of composite beams is conducted.

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ABSTRACT

This paper presents analytical technique and simplified formulas for the calculations of cracking, yield and ultimate moments of different cases as well as deflections of ECC-concrete composite beams reinforced with steel bars. The technique is based on the simplified constitutive models of materials, strain compatibility, perforce bond of materials and equilibrium of internal forces and moment. Experimental testing of eleven ECC-concrete composite beams reinforced with steel bars is also presented. All beams tested had the same geometrical dimensions but different steel reinforcement strength and ECC thickness. The proposed formulas showed good agreement with the experimental results of various moment values and deflections. A parametric analysis shows that yield and ultimate moments increase with the increase of concrete strength in case of compression failure but, essentially, remain unchanged in case of tensile failure. With increasing the tensile resistance, for example by increasing ECC height replacement ratio, reinforcement ratio, strength of steel reinforcement and ECC, ultimate curvature and energy dissipation increase in case of tensile failure and decrease in case of compressive failure. On the other hand, ductility and energy dissipation ratio decrease with the increase of reinforcement ratio and strength, but, essentially, remain unchanged with increasing the height replacement ratio and strength of ECC.

1. Introduction

Under the combined effects of mechanical loads and environmental exposure, many reinforced concrete structures deteriorate due to steel corrosion and cannot meet the requirement of ultimate limit state and durability. Therefore, repair and rehabilitation of such structures have become a large part of construction activity.

During the last decade, concrete technology has been undergoing rapid development, resulting in the production of a new concept of engineered cementitious composite (ECC) to overcome the brittle behavior of cement-based materials. ECC exhibits multiple micro cracks, leading to a significant increase in strain capacity and ductile behavior. It has also excellent toughness and energy absorption capacity [1], self-healing ability [2,3], fire performance [4], remains durable under erosion environment (sulfate-chloride environment [2], freezing-thawing and sulfate coupling environment [5]).

Few investigations were devoted to improve the performance of ECC, such as hybridization with non-round polypropylene fiber and low modulus polyvinyl alcohol fiber [6], incorporating $CaCO_3$ whisker to improve compressive strength and tensile strain-hardening [7], increasing slag content improved the ductility, hardened air content, water absorption, porosity and sorptivity [5], using recycled concrete fines as microsilica sand substitute in the production of ECC [8], incorporating high volumes of fly ash and micro PVA

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Nomenclature

ε_s	tensile strain in steel bar
σ_s	tensile stress in steel bar
f_{sy}	yield strength of steel bar
ε_{sy}	yield strain of steel bar
E_s	elastic modulus of steel bar
ε_{su}	ultimate tensile strain of steel bar
ε_c	compressive strain in concrete
σ_c	compressive stress in concrete
f_c	concrete compressive strength
ε_{co}	compressive strain corresponding to concrete stress of f_c
ε_{cu}	ultimate compressive strain of concrete
$f_{cu,k}$	concrete cube compressive strength
n	a coefficient related to the compressive stress-strain relationship of concrete
ε_{ct}	tensile strain in concrete
σ_{ct}	tensile stress in concrete
ε_{ctu}	ultimate uniaxial tensile strain of concrete
f_{ctu}	ultimate uniaxial tensile stress of concrete
ε_{ec}	compressive strain in ECC
σ_{ec}	compressive tress in ECC
f_{ecp}	compressive strength of ECC (peak point of ECC compressive stress-strain curve)
ε_{ecp}	compressive strain corresponding to peak stress of ECC f_{ecp}
f_{ecu}	ultimate compressive stress of ECC (after peak point)
ε_{ecu}	ultimate compressive strain corresponding to ultimate stress of ECC f_{ecu}
ε_{et}	tensile strain in ECC
σ_{et}	tensile stress in ECC
f_{etc}	tensile stress of ECC at first cracking
ε_{etc}	tensile strain of ECC at first cracking
f_{etu}	ultimate tensile strength of ECC
ε_{etu}	ultimate tensile strain of ECC
b	width of cross-section
h	height of cross-section
h_s	distance of the center of steel bars to the cross-section tensile edge
h_e	thickness of ECC
h_t	height of cross-section part in tension (neutral axis depth)
x	vertical distance of any point to the tensile edge of cross-section
h_p	vertical distance of concrete where its strain reaches ε_{co} to the tensile edge of cross-section
ρ	curvature radius of deformed composite beam
$d\theta$	rotating angle increment of cross-section
φ	curvature of deformed composite beam
f	maximum deflection of specimen at mid-span
S	a coefficient related to loading and supporting condition
M	moment acting on the cross-section
l_0	length of composite beam
E	elastic modulus of sectional material
I	inertia moment of cross-section
M_{cr}	cracking moment of cross-section
φ_{cr}	cross-section curvature corresponding to cracking moment
M_y	yield moment of cross-section
φ_y	cross-section curvature corresponding to yield moment
M_u	ultimate moment of cross-section
φ_u	cross-section curvature corresponding to ultimate moment
u_φ	curvature ductility of cross-section
E_y	energy dissipation capacity of elastic stage
E_p	energy dissipation capacity of whole stage (up to ultimate curvature φ_u)
r_E	energy dissipation ratio
l	length of composite beam
l_m	length of the pure flexural span
l_{mv}	length of the flexural-shear span
l_f	length of the free overhang span
r_h	ECC height replacement ratio
h_0	effective height of cross-section
f_{su}	ultimate tensile strength of steel bar
$M_{cr,t}$	experimental cracking moment
$M_{y,t}$	experimental yield moment
$M_{u,t}$	experimental ultimate moment
$M_{cr,c}$	predicted cracking moment
$M_{y,c}$	predicted yield moment
$M_{u,c1}$	predicted ultimate moment by using yield strength of steel reinforcement
$M_{u,c2}$	predicted ultimate moment by using ultimate strength of steel reinforcement
ρ_s	reinforcement ratio.

fibers to improve the cyclic freeze-thaw resistance and microstructure of ECC [3,9], adding waterproofing admixture to improve wetting property and reduce the sorptivity, and shrinkage-reducing admixture together with calcium sulfoaluminate cement to control the drying shrinkage [10].

Experimental study showed that the use of ECC in the tensile zone around longitudinal steel reinforcement has slightly improved both the flexural capacity [11–13] and deformation ability [12,13], but significantly reduced the crack width before yielding of steel reinforcement [12]. Therefore, durability of composite ECC/reinforced concrete elements can be greatly improved due to the enhancement of waterproof and corrosion resistance [14–16]. A theoretical analysis of bending resistance of ECC-RC composite beams was developed and it is compared well with the experimental results [17,18]. On the other hand, when the ECC thickness increased beyond a certain critical value, both the flexural strength and ductility of ECC-concrete composite beams significantly enhanced [19,20].

Because of its excellent tensile performance, ECC can be used in strengthening unreinforced masonry walls [16,21–23], reducing the extensive amount of transverse reinforcements in beam-column joints of rigid-framed bridges, enhancing the joint seismic resistance and reducing reinforcement congestion and construction complexity [24–27]. ECC can also be used in hydraulic structures for its good durability [2,16,28], highway engineering for its ability of withstanding large deformations from heavy loading and temperature variations [29], in hot arid coastal climatic condition structures [30], in lightweight building facade and pavement [31], in pavement overlay to extend the service life [32] and in impact and blast resistant protective panels [16]. The wide range of applications of ECC demonstrates that incorporating ECC can significantly improve the performance of structures and reduce the associated life cycle cost.

Theoretical analysis covering the whole loading process of composite beams is still limited. Based on simplified constitutive models of materials and equilibrium of internal forces and moments,