REINFORCED CONCRETE BOX BEAM STRENGTHENED BY CARBON-FIBER-REINFORCED POLYMER SUBJECTED TO COMBINED SHEAR AND TORSION

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by

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LIST OF SYMBOLS

A_{0h}	area enclosed inside the hoops
A_c	gross area of the concrete cross section
A_{cor}	gross area enclosed by the centerline of the shear flow
A_{fs}	area of FRP strip
A_t	area of transverse reinforcement
A_{sl}	area of longitudinal reinforcement
A_{lb}	area of bottom longitudinal reinforcement
A_{lt}	area of top longitudinal reinforcement
a_0	depth of equivalent stress block
a_v	distance between loading point and support of beam
b	width of beam
b_w	minimum width of cross section over the effective depth
b_{cor}	width of shear flow
d	effective depth of beam
d_f	depth of FRP sheets measured from the level of longitudinal reinforcement
E_f	Young’s modulus of the FRP in GPa
E_{yt}	Young’s modulus of the stirrup in MPa
f_{yt}	yield strength of transverse reinforcement
f_{yL}	yield strength of longitudinal reinforcement
f_{lb}	yield strength of bottom longitudinal reinforcement

f_{lt}	yield strength of top longitudinal reinforcement
$f_c^{'}$	compressive strength of concrete
$f_{cd}^{'}$	design compressive strength of concrete
f_{cm}	mean compressive strength of concrete
f_{cu}	Cube compressive strength of concrete
f_t	tensile strength of concrete
f_{fu}	ultimate tensile strength of the FRP
F_s	tensile force of stirrup
F_{fl}	tensile force of longitudinal FRP fiber
F_{fs}	tensile force of transverse FRP fiber
h_{cf}	side bonding height of FRP
h_0	effective depth of beam
h	depth of beam
h_{cor}	depth of the shear flow
k	reduction factor for the FRP effective strain
L_a	length of moment arm
L_e	effective bond length
$L_{\max}$	maximum available bond length
p_c	perimeter of the outer dimensions of the concrete cross section
s_t	spacing of transverse reinforcement
s_f	spacing of the FRP strips
T_u	torsional capacity of RC beams with FRP under combined shear and torsion

T_{u0}	torsional capacity of RC members strengthened with FRP under pure torsion
T_r	torsional moment contributed by RC beams
T_c	contribution of concrete to the torque
T_s	contribution of transverse and longitudinal reinforcement to torque
T_f	torsional moment contributed by FRP
t_f	thickness of FRP strip
t	thickness of web of box beam
u_{cor}	perimeter of the centerline of the shear flow
V_n	shear strength of the concrete, transverse reinforcement, and FRP sheets
V_c	shear strength contribution of concrete
V_s	shear strength contribution of transverse reinforcement
V_f	shear strength contribution of FRP sheets
V_u	shear capacity of RC beams with FRP under combined shear and torsion
V_{u0}	shear capacity of RC members strengthened with FRP under pure shear
W_t	plastic-resistant moment of the cross section of torsional members
w_f	width of FRP strip
w_{fe}	effective width of FRP strip
Z	lever arm length (generally may be set to $d_f/1.15$)
ρ_L	ratio of total longitudinal reinforcement
ρ_t	ratio of total transverse reinforcement
ρ_f	FRP reinforcement ratio
ω_L	non-dimensional longitudinal reinforcement index

ω_t	non-dimensional web reinforcement index
ξ	strength ratio of longitudinal reinforcement to transverse reinforcement
α	angle of inclination of the FRP fiber
β_c	concrete cracking coefficient
β_w	FRP width to spacing ratio coefficient
β_L	coefficient to compensate for insufficient FRP bond length
β_f	angle of orientation of the fiber direction to the longitudinal axis of the beam
θ	angle of the diagonal crack with respect to the longitudinal axis of the beam
φ	coefficient of FRP configuration
ε_{fe}	effective strain in the fibers

LIST OF ABBREVIATION

RC	reinforcement concrete
FRP	fiber-reinforced polymer
CFRP	carbon-fiber-reinforced polymer
GFRP	glass-fiber-reinforced polymer
AFRP	aramid-fiber-reinforced polymer
ACI	American Conrete Institute
CSA	Canadian Standard Association
fib	International Federation for Structure Concrete
ISIS	Intelligent Sensing for Innovative Structures
CECS	China Assciation for Engineering Construction Standardiztion
JSCE	Japan Society of Civil Engineers
LVDT	linear variable differential transducer
FE	finite element

RASUK KEKOTAK KONKRIT BERTETULANG DIPERKUKUHKAN DENGAN POLIMER BERTETULANG FIBER-KARBON TERTAKLUK KEPADA TINDAKAN GABUNGAN RICIH-KILAS

ABSTRAK

Rasuk kekotak, dengan kekuatan kilasan tinggi, ringan dan rintangan struktur yang besar, amat popular digunakan dalam struktur jambatan. Walau bagaimanapun, rasuk kotak mungkin gagal dengan tiba-tiba disebabkan oleh jumlah dan beban trafik meningkat dan kapasiti berkurang akibat dan pada kemerosotan. Teknik pengukuhan polimer bertetulang gentian (FRP) telah dikaji dan digunakan dalam struktur untuk meningkatkan keupayaan lenturan dan ricih rasuk. Namun, sangat sedikit perhatian ditumpukan kepada rasuk kotak konkrit bertetulang (RC) dari segi ricih, kilasan, mahupun gabungan ricih-kilasan. Oleh itu dalam kajian ini, tiga set ujikaji ke atas rasuk kotak RC diperkukuhkan dengan polimer karbon-bertetulang gentian (CFRP) dalam ricih, kilasan tulen, dan gabungan ricih-kilasan telah dijalankan. Berdasarkan eksperimen, matlamat utama adalah untuk: (a) meramal sumbangan ricih CFRP; (b) menilai keberkesanan pengukuhan dan meramalkan sumbangan CFRP kepada kilasan; (c) menyiasat kelakuan rasuk kotak dengan pengukuhan tertakluk kepada gabungan ricih-kilasan dan membangun persamaan matematik untuk meramal kekuatan. Model *fib* Bulletin 14 dengan koefisien pengurangan yang dicadangkan dalam keberkesanan urat fiber dapat meramalkan sumbangan CFRP dalam ricihan pada rasuk kekotak RC diperkukuhkan. Di samping itu, didapati bahawa konfigurasi CFRP U-jacketing dengan jalur membujur mempunyai prestasi yang lebih baik dalam pengukuhan kilasan RC kotak rasuk. Satu model penggabungkan telah didedahkan sebagai model yang boleh dipercayai dan konservatif dalam menghitung kekuatan kilasan rasuk RC dipasang. Seterusnya, keberkesanan pengukuhkan CFRP dalam gabungan ricih-kilasan RC rasuk kotak adalah berkadar songsang dengan nisbah kilasan-ricih. Persamaan yang diperoleh dengan model ubahsuai ketegangan berkesan dalam serat dapat memberi keputusan wajar ke atas kekuatan kilasan kepada rasuk kotak RC dengan pengukuhan atau tanpa pengukuhan tertakluk kepada tindakan gabungan.

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ABSTRACT

Box beams, with high torsional stiffness, light weight, and great structural resistance, are popularly used in the bridge structures. However, these box beams may fail suddenly due to increased traffic volumes and loads and diminished capacity from deterioration. Fiber-reinforced polymer (FRP) strengthening technique has been studied and used in structures to improve the flexural and shear capacity of beams. However, very few strengthening studies have paid much attention to reinforced concrete (RC) box beams subjected to shear, torsion, and combined shear and torsion. Therefore, in this research, three sets of experiments on RC box beams strengthened with the carbon-fiber-reinforced polymer (CFRP) in shear, pure torsion, and combined shear and torsion were conducted. Based on experiments, the main aims are to: (a) predict the shear contribution of CFRP; (b) evaluate the strengthening effectiveness and predict the CFRP contribution to torsion; (c) investigate the behavior of strengthened box beams subjected combined shear and torsion and develop mathematical equations to predict strength. The *fib* Bulletin 14 model with the reduction coefficient proposed in effective strain of fiber could reliably predict the shear CFRP contribution to shear in strengthened RC box beam. In addition, it was found that the configuration of CFRP U-jacketing with longitudinal strips had a better performance in the torsional strengthening of RC box beam. One combined model had been revealed to be reliable and conservative in calculating the torsional strength of retrofitted RC beams. Further on, strengthening effectiveness of CFRP in combined shear and torsion to RC box beams was inversely proportional to torque-to-shear ratio. The derived equations with modified model of effective strain in fiber could give the desirable results of torsional strength to the strengthened or unstrengthened RC box beams subjected combined action.

CHAPTER ONE

INTRODUCTION

1.1 Background of study

A box beam is formed when two web plates are joined by a common flange at both the top and the bottom, which is widely used in bridge structures (Sennah and Kennedy, 2001; Badie et al., 1999). The bridge type is related to providing maximum efficiency of use of material and construction technique, for the particular span, and applications. Compared with rectangular and T-shape cross-section beams, the primary advantage of box girders is the large torsional stiffness that makes the beams ideal for use in curved interchanges for which the bridge geometry can lead to large torques. The torsional stiffness of a box section is generally in the range of 100 to more than 1000 times larger than that of a comparable T-shaped section (Helwig et al., 2007). Besides, box beams produce an aesthetically pleasing closed superstructure soffit and maintain a high span-to-depth ratio (Badie et al., 1999). Besides, Reinforcement concrete (RC) or prestressed concrete box beam has good torsional stiffness, lightweight, and high structural resistance. However, box girders are rarely used in buildings, whose structures are usually made of rectangular and T-section beams with slabs. The above-mentioned characteristics of box cross section beams have made the concrete box beam bridges the most widespread bridge type today (Schlaich and Scheef, 1982), such as railway, highway, urban curved, and pedestrian bridges, with different length spans. As a structural member, the beam is usually subjected to bending, shear, and torsional moments, particularly all of these three combined. As regards the mechanism of practical bridges, previous studies have focused on the resistance capacity of the structural elements in shear and bending moments for straight bridges. In particular conditions, the eccentric loading can generate torsional moment, which is sometimes disregarded by engineers. However, for curved bridges, apart from shear and bending moments, the torsional moment should be taken as well in view of its importance in design.

Many concrete box beam bridges worldwide are suffering from increased traffic volumes and loads, diminished capacity from chloride-induced deterioration and other stringent updates to design code regulations. In beams, flaws occur in the form of crack extensions, decreased rigidity, increased deflection, and significantly reduced loading capacity.

In extreme situations, bridges require higher strength to resist earthquake, design error, or construction inaccuracies. As such, building a new bridge to replace the old one is a possible option, but this approach may be uneconomical because of the manpower and material resources. A cost-effective alternative to building new structures is strengthening and rehabilitating existing structures. This approach has received extraordinary investigation attention and has been applied in practical structures.

In the past two decades, by immersing continuous fibers in resin matrix bonding fibers, fiber-reinforced polymer (FRP) composites have gradually replaced steel plates for use in retrofitting reinforced concrete (RC) members. Methods for strengthening beams with FRP materials have been broadly accepted and employed worldwide.

According to the fiber composites applied in practice, typical FRP composites are categorized into three types, namely, carbon-fiber-reinforced polymer (CFRP); glass-fiber-reinforced polymer (GFRP); and aramid-fiber-reinforced polymer (AFRP). FRP materials provide an ideal combination of mechanical and physical characteristics, such as high tensile strength, lightweight, high fatigue strength, non-corrosion, easy formability, and remarkable long-term durability. Furthermore, easy installation of FRP system benefits from the properties of formability and being lightweight. As an outstanding choice for external reinforcement, FRP materials can provide corrosion immunity and are commonly resistant to chemicals. Compared with the conventional retrofitting methods, the properties and versatility of FRP systems are more significantly cost-effective (Mertz, 2003; Moy,2013) and less time-consuming (Raghu et al., 2000).

The strengthening technique with FRP systems has been utilized in the retrofitting of the practical box beam bridges (Täljsten, 2005; Chiaw, 2006) to enhance the flexural and shear capacity of beams as shown in Figures 1.1 and 1.2. FRP strengthening of box beams has also been conducted experimentally to investigate the flexural mechanics of strengthened box members (Askar and Abd-Alkhalek, 2012). The present study concentrates on the behavior of RC box beams strengthened with CFRP under the action of shear, torsion, and combined shear and torsion to further evaluate and understand the research experimentally and theoretically.