UNIVERSITI PUTRA MALAYSIA

STRUCTURAL BEHAVIOUR OF DISTRESSED AND STRENGTHENED POST-TENSIONED BOX GIRDER BEAMS

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

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DEDICATION

To God Almighty

And my Wonderful Family

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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Faculty : Engineering

Box girder prestressed concrete beams are used widely in bridge construction due to its efficient structural response under flexural as well as torsional loading. Prestressing can be either internally or externally applied to a beam. Every year, many prestressed concrete bridge girders are damaged due to accidental load and /or due to an aggressive environment surrounding the bridge. Corrosion and /or snapping of prestressing cables will cause serious damage in the bridge structure.

Many researchers have covered the strengthening of prestressed concrete girders under flexure or under shear. Very limited research is available on the significance of different strengthening techniques under combined shear–flexural loading. Furthermore, torsional load is another important aspect which needs to be considered when discussing the strengthening techniques effect.

This research covers the effect of snapping of externally prestressed cables on the structural behaviour of box girder bridge beams subjected to a combined flexural – shear – torsional load. Five full scale box-girder beams were cast and tested experimentally. The first beam specimen acted as a control beam while in the remaining four beam specimens, 15% of the prestressing cable area was snapped. After snapping, one specimen was tested till failure and the other three specimens are strengthened using different techniques and tested till failure. To restore the beam capacity, three different strengthening techniques were used under the same load combination. The techniques adopted for this research are externally bonded CFRP laminates, extra longitudinal prestress cables and vertical prestressing applied by using bolts and nuts system.

The results show that snapping of 15% of the prestressing cable will result in a 74% increase in deformation at service load and a 22% decrease in ultimate load. Furthermore, the snapping of the prestress wire will increase the stresses in the cables by 70% as compared to the unsnapped beam. All the strengthening techniques used can effectively restore the beam capacity at service and overcome the effect of cable snapping, however, at ultimate the restorative capacity of one of the strengthening techniques could not be fully established due to a localized failure.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains.

KELAKUAN STRUKTUR DAN TEKNIK PENGUKUHAN RASUK KOTAK PASCA TEGASAN BERMASALAH

Oleh

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Galang rasuk kotak konkrit pra-tegasan digunakan secara meluas di dalam pembinaan jambatan disebabkan oleh respons strukturnya yang efisien di bawah kenaan beban lenturan dan juga beban kilasan. Pra-tegasan dapat dikenakan ke atas sesuatu rasuk sama ada secara dalaman atau luaran. Setiap tahun, terdapat banyak galang jambatan konkrit pra-tegsan yang rosak disebabkan oleh beban tambahan dan/atau suasana persekitaran jambatan yang agresif. Pengakisan dan/atau pemutusan kabel pra-tegasan akan mengakibatkan kerosakan yang serius bagi stuktur sesuatu jambatan.

Ramai penyelidik telah menjalankan penyelidikan yang merangkumi kaedah pengukuhan galang konkrit pra-tegasan di bawah kenaan lenturan atau di bawah kenaan ricih. Walaubagaimanapun, penyelidikan terhadap kepentingan pelbagai teknik pengukuhan di bawah kenaan beban gabungan ricih-lenturan adalah begitu terhad. Tambahan pula, beban kilasan merupakan satu lagi aspek penting yang perlu diberi pertimbangan apabila membincangkan tentang kesan teknik pengukuhan.

Kajian ini merangkumi kesan pemutusan kabel pra-tegasan luaran terhadap tindakan struktur rasuk jambatan kotak galang yang tertakluk kepada beban gabungan lenturan-ricih-kilasan. Lima rasuk kotak galang berskala penuh telah disiapkan mengikut acuan dan diuji di makmal. Spesimen rasuk yang pertama bertindak sebagai rasuk kawalan, sementara bagi empat rasuk lain, 15% daripada keluasan kabel pra-tegasan telah di putuskan. Selepas pemutusan berlaku, satu spesimen telah diuji sehingga gagal dan tiga spesimen lagi telah diperkukuhkan menggunakan pelbagai teknik pengukuhan dan seterusnya diuji sehingga gagal. Untuk mengembalikan kapasiti rasuk, tiga teknik pengukuhan yang berbeza telah digunakan di bawah kombinasi bebanan yang sama. Teknik yang diambil di dalam kajian ini adalah dengan menggunakan lapisan CFRP yang diikat secara luaran, kabel pra-tegasan dengan pemanjangan tambahan dan kenaan pra-tegasan secara menegak dengan menggunakan sistem bolt dan nat.

Hasil ujian menunjukkan bahawa pemutusan sebanyak 15% bagi kabel pra-tegasan akan mengakibatkan sebanyak 74% peningkatan di dalam ubah bentuk pada beban perkhidmatan dan 22% penurunan keupayaan pada beban muktamad. Tambahan pula, pemutusan dawai pra-tegasan akan meningkatkan tegasan di dalam kabel sebanyak 70% berbanding rasuk yang tidak mempunyai pemutusan. Teknik pengukuhan yang digunakan dapat mengembalikan kapasiti rasuk secara berkesan dan mengatasi kesan pemutusan kabel.

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I certify that an Examination Committee has met on 2nd August 2007 to conduct the final examination of Rachael Bukola Ohu on her Master of Science thesis entitled " Structural

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DECLARATION

I hereby declare that this thesis is based on my original work, except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or any other institution.

RACHAEL BUKOLA OHU

Date: 1st October 2007

TABLE OF CONTENTS

Page

LIST OF TABLES

Table		**Page**
3.1	Properties of CFRP	3.7
3.2	Properties of Sikadur 30 adhesive	3.8
3.3	Mechanical properties of bolts and nuts	3.14
4.1	Loss of prestress	4.2
4.2	Experimental cracking loads	4.31
4.3	Theoretical cracking loads	4.33
4.4	Experimental – Theoretical cracking loads	4.33
4.5	Experimental – Theoretical ultimate loads	4.49

LIST OF FIGURES

Figure		Page

LIST OF ABBREVIATIONS/NOTATIONS

A or A_c = cross sectional area

A_{CFRP} = cross sectional area of CFRP strip

A_{ps} = area of prestressing tendons

A_s = area of tension reinforcement

A_s' = area of steel in compression

A_{st} = area of transverse steel in flange

A_{sv} = cross sectional area of two legs of a link

b = width or effective width of the section or flange in compression zone

b_w = web width

b_f = plate width

d = effective depth to centroid of steel area Aps or nominal diameter of fastener

d_{CFRP} = depth of CFRP

d_n = depth to centroid of compression zone

d_s' = depth of compression reinforcement

d_{st} = depth of tension reinforcement

δ = deflection

e = eccentricity

ε_{cu} = strain at top of concrete fibre

ε_{CFRP} = strain in CFRP

Ec = modulus of elasticity of concrete

E_{CFRP} or E_{fd} = elastic modulus of CFRP or FRP

E_s or E_p = modulus of elasticity of steel

f_{ci} = concrete strength at transfer

f_{cu} = concrete strength at service

f_{cp} = design compressive stress at centroidal axis due to prestress

f_{CFRP} = stress in CFRP

f_{ctm} = tensile strength of concrete

$f_{max}/_{min}$ = principal tensile stress

f_{pb} = design tensile stress in tendons

f_{pe} = design effective prestress in tendons after all losses

f_{pu} = ultimate tensile stress of tendons

f_y or f_{yv} = characteristic strength of reinforcement

$f_{y'}$ = characteristic strength for compression reinforcement

f_{yt} = characteristic strength for tension reinforcement

f_t = maximum design principal tensile stress

F_{bst} = design bursting tensile force

F_T = tensile force in bolt

$h_{max}/_{min}$ = larger or smaller dimension of rectangular section

I_{xx} = net moment of inertia

L or l = span of beam

L_{max} = maximum anchorage length

Mu = ultimate moment of resistance

η = percentage loss

P_i = initial prestressing force

P_{cr} = cracking load

P_T = tensile capacity

P_{ult} = ultimate load

ρbb = bearing strength of bolt

ρbs = bearing strength of connected parts

S_{CFRP} = CFRP spacing

Sv = spacing of links along the member

ti = wall thickness

t_{CFRP} = CFRP thickness

T = applied torque or torsion

T_{CFRP} = torsional strength

T_{max} = maximum force in CFRP bonded to concrete

τv = torsional shear stress

V_{co} = design ultimate shear resistance of section uncracked in flexure

V_{cr} = design ultimate shear resistance of a section cracked in flexure

v = design shear stress

v_{tmin} = minimum torsional shear stress

v_t = torsional shear stress

v_{tu} = maximum combined shear stress (shear + torsion)

νc = design concrete shear stress

x = depth of neutral axis

y_{po} = half side of loaded area

y_o = half the side of the end block

Zt or Zb = top or bottom section modulus

σb =stress at bottom fibre

σt = stress at top fibre

σci = initial allowable compressive stress at transfer bottom fibre

σcs = allowable compressive stress at top fibre at service

σti = initial allowable tensile stress at transfer in top fibre

σts = allowable tensile stress in bottom fibre at service

CHAPTER 1

INTRODUCTION

1.1 Historical Review of External Prestressing

In 1934, in France, Eugene Freysinnet repaired the Le Havre Station by using stressing wires and went on to develop the art of prestressed concrete to a high level. Franz Dischinger built the first externally prestressed concrete bridge from 1935 – 1937 in Aue, Germany. Steel with tensile strength of 500N/mm^2 was used at the time but due to the low tensile steel, considerable losses in the prestress force occurred and the bridge had to be re-stressed twice in 1962 and in 1980 (Virlogeux, 1989) and (Tandler, 2001) and was finally demolished in 1994 (Landschaftverband Westfalen-Lippe, 2001). Since then, several other bridges have been prestressed using this technique because of its' increased durability effect on concrete which has made it popular.

External prestressing is a special technique of the post-tensioning method of prestressing, where prestress force is applied to the concrete after it has hardened. The external tendons are placed outside the section to be stressed and the forces are only transferred at the anchorage blocks or at the deviators as shown in Figure 1.1.

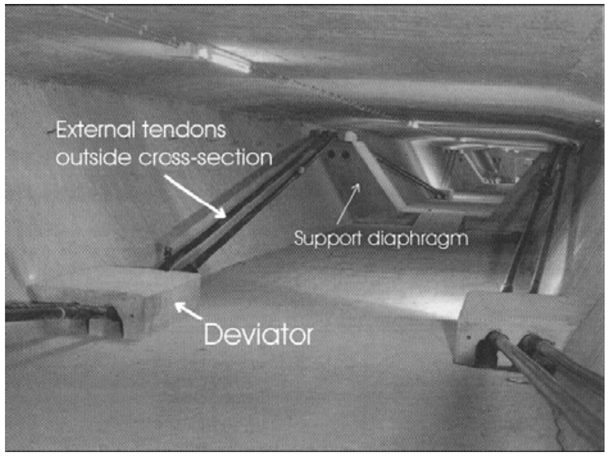

Figure 1.1: Typical view in box Girder Bridge with externally deflected tendons (Tandler, 2001)

In general, there are mainly two post-tensioning techniques available; internal prestressing and external prestressing. Although internal prestressing is similar to external prestressing, the difference between them lies in the position of the tendon layout. Internal prestressing involves the laying of tendons within the cross-section while in external prestressing, the tendons are laid outside the cross-section of the structure. Figure 1.2 shows some of the post-tensioning techniques available.

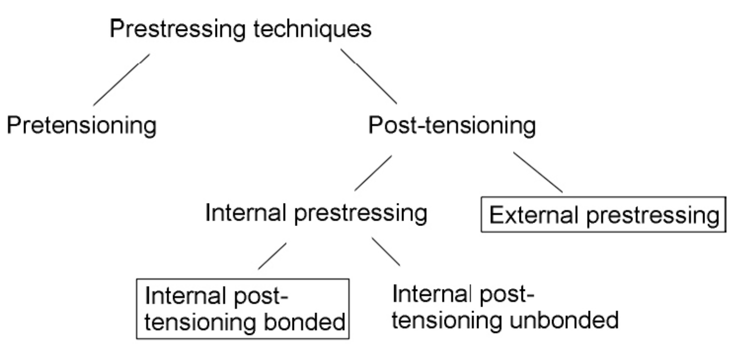

Figure 1.2 Some prestressing techniques (Tandler, 2001)