Cairo University

FLEXURAL BEHAVIOUR OF REINFORCED CONCRETE INVERTED BEAMS STRENGTHENED USING FIBRE REINFORCED POLYMERS AND STEEL PLATES

By

Abdelrahman Medhat Kamal Abdallah

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
STRUCTURAL ENGINEERING

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Under the supervision of

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Thesis Title:

Flexural Behaviour of Reinforced Concrete Inverted Beams Strengthened Using Fibre Reinforced Polymers and Steel Plates

Key Words:
Fibre reinforced polymers – Externally bonded steel plates – Inverted beams – Experimental study –Near surface mounted

Summary:
The flexural behavior of reinforced concrete inverted beams strengthened in flexure was studied in the following thesis. A total of thirteen beams were experimentally tested in flexure. Twelve beams were strengthened in flexure using externally bonded CFRP sheets and steel plates. In addition near surface mounted CFRP strips were also used in strengthening of the inverted beams.

During the tests certain variables were put into consideration. The effectiveness of using different strengthening material such as FRP and steel was investigated. Also, the significance of strengthening an inverted beam at the edges of the web and flange rather than at the centre of the web was analyzed. In addition, the effect of using different bonding lengths covering the whole clear span and half the span was tested. Moreover, the effectiveness of steel bolts and U-anchorage system on the behavior of the strengthening material was also observed and studied.

During the tests the ultimate loads and failure modes of the strengthened beams were recorded and observed. Also, the strains in the main reinforcement and the strengthening material were recorded. In addition the load deflection curve was plotted and the ductility and rigidity of the beams were calculated and induced from the curve. Finally a list of conclusions and observations were identified and recorded at the end of following thesis.

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Dedication

The love, patience and support of my parents, my wife and my son cannot be praised enough; to them this thesis is dedicated.

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Nomenclature

A = Cross-sectional area of a concrete section
A_c = Area of concrete in compression
A_f = Area of CFRP reinforcement
A_s = Area of tension steel reinforcement
$A_{s'}$ = Area of compression steel reinforcement
b = Width of concrete section
b_f = Width of externally bonded FRP sheets/strips
b_s = Width of externally bonded steel plates
c = Depth of the neutral axis from the extreme compression fibres
C = Clear cover of reinforcing bars
$C_{s'}$ = Compression force in steel reinforcement
d = Depth from extreme compression fibre to the flexural reinforcement;
d_f = Depth of near surface mounted CFRP strips from compression fibre
E_c = Modulus of elasticity of concrete
E_f = Modulus of elasticity of FRP reinforcement
E_s = Modulus of elasticity of steel reinforcement
f_{Bottom} = Concrete stress at bottom fibres
f_c = Concrete stress in compression
f_{cu} = Compressive strength of concrete after 28 days
f_{FRP} = Maximum tensile stress in near surface mounted FRP bars
f_f = Stress in CFRP reinforcement
f_s = Stress in tension steel reinforcement
$f_{s'}$ = Stress in compression steel reinforcement
f_y = Yield stress of steel reinforcement
G_a = Shear modulus of the adhesive
h = Total height of a concrete section
L = Total span of the simply supported beam
L_d = Development length of reinforcement
L_e = Effective bond length
M_u = Ultimate moment capacity of a concrete section
N = Normal force acting on the FRP at the two ends of a segment
n = number of FRP Layers
P_U = Ultimate load
P_{CR} = Load at initial crack
T_f = Tensile force in CFRP reinforcement
V_c = Shear force in the concrete at cutoff points due to interfacial shear stresses
V_f = Shear force in the FRP sheets at cutoff points due to interfacial shear stresses
V_u = Ultimate shear capacity of a beam
y = Distance from the FRP laminate to the section neutral axis
β = An empirical constant, depends on the concrete compressive strength
Δ_{cr} = Deflection at cracking

Δ_U = Deflection at ultimate load

ε_c = Concrete strain at the extreme compression fibre; interfacial strain of concrete

κ_m = Reduction factor for the tensile strain in externally bonded FRP reinforcement

$\varepsilon_{main\ steel}$ = Maximum tensile strain of the main reinforcement at failure

$\varepsilon_{steel\ plate}$ = Maximum tensile strain of the steel plate reinforcement at failure

ε_{frp} = Maximum tensile strain of the FRP reinforcement at failure

ρ_f= Reinforcement ratio of FRP

ρ_s= Reinforcement ratio of steel

ϕ = Diameter of bolt or steel bar

Abstract

Strengthening and rehabilitation of concrete structures using externally bonded materials such as steel plates or FRP materials has been the concern of many researchers. Extensive research has been done in this field in order to fully understand the behaviour and the composite action of the concrete structure and the externally bonded material. In fact this strengthening technique has proven to be very effective in fortifying the rigidity and strength of the concrete element. However, most researches have been made on rectangular beams and T-beams; while the information regarding inverted T-beams is rather limited.

Inverted T-beams are found in many structures like residential, commercial buildings and bridges. Nevertheless, limited information regarding the strengthening and rehabilitation of inverted T-beams is available; this was the main concern of the following research. In the experimental program the main concern was to understand in depth the behaviour and performance of strengthened reinforced concrete inverted T-beams in flexure. Based on the research findings; a fundamental criterion was to be identified regarding the techniques implemented in strengthening of such beams. Externally bonded steel plates, externally bonded CFRP sheets and strips and near surface mounted CFRP strips; were used to strengthen the concrete beams

A total of thirteen reinforced concrete inverted T-beams were tested. Twelve beams were strengthened using different techniques. During the experimental tests, the method of bonding of the strengthening element to the concrete substrate, the efficiency of the strengthening material, its length and position were put to the test. Based on the test results the efficiency and applicability of each strengthening technique for each beam was identified.