

**INVESTIGATIONS INTO BEHAVIOR OF ADHESIVE
BONDED STEEL-CONCRETE COMPOSITE FLEXURAL
MEMBERS**

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INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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STEEL-CONCRETE COMPOSITE FLEXURAL MEMBERS**

by

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Submitted

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परिवार को समर्पित

CERTIFICATE

This is to certify that the thesis entitled, “**Investigations into Behaviour of Adhesive Bonded Steel-Concrete Composite Flexural Members**” being submitted by **Mr. Ankit Bhardwaj** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a bonafide record of research work carried out by him under our supervision and guidance. The thesis work, in our opinion, has reached the requisite standard fulfilling the requirement for the degree of **Doctor of Philosophy**.

The results contained in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

Steel-concrete composite flexural members are widely adopted in the construction of bridges and buildings. For the advancement of steel-concrete composite construction techniques, bonding of steel girder and precast concrete slab at their interface using epoxy-based adhesive to construct bonded steel-concrete composite flexural members (BFMs) is being explored as an alternative to mechanical shear connectors. Adaptation of adhesive bonded connection is only possible when the behavior of interfacial connection has been examined in every aspect. Concrete in continuous BFMs experiences tensile creep at internal supports and compressive creep in the span under sustained load.

Research on BFMs is in its preliminary stage. Among various unexplored aspects of BFMs, some of which have been addressed here are: (i) long-term behavior of continuous BFM, (ii) tensile strength of concrete under tensile creep, (iii) effect of location of load on shear lag behavior, (iv) behavior of bond connection and (v) analytical formulas of slip and shear stress in bond layer.

In the present research work, first, a relationship between effective tensile strength of concrete and creep coefficient is proposed, which is valid for flexural members under sustained load. Using the proposed relationship, a computationally efficient effective modulus method based procedure to predict the long-term behavior of mechanically connected steel-concrete composite flexural members using three-dimensional (3D) finite element (FE) analysis has been proposed.

Next, an experimental program to select an epoxy based adhesive suitable for BFMs has been presented. Then after, short-term and long-term full-scale experiments on BFMs have been presented. The research work also presents 3D FE models to predict short-term and long-term behavior of BFMs.

Further, a numerical study on shear lag and effective width of BFMs has been presented. The study focuses on effect of location of load on shear lag and effective width for (a) deflection at service load, (b) maximum stress at service load and (c) plastic analysis at ultimate load.

Present research work also includes numerical investigation on adhesive bond layer of BFM in order to understand the effect of load proportion factor, loading arrangement, concrete slab width, concrete slab thickness and Young's modulus of adhesive. This investigation focuses on variation of shear and normal stresses and strains along the length at service load and ultimate load.

Also, the present research work presents analytical solutions to interfacial slip of BFMs at service load for common load and boundary conditions, which can be used for preliminary design. The presented analytical solutions have been validated with the help of 3D FE analysis.

सार

इस्पात-कंक्रीट संयुक्त धरन को व्यापक रूप से पुलों और इमारतों के निर्माण में अपनाया जाता है। इस्पात-कंक्रीट संयुक्त निर्माण तकनीकों की उन्नति के लिए, इस्पात के गर्डर और पूर्व निर्मित कंक्रीट पटिया को उनके अंतराफलक पर इपोकसी-आधारित आसंजक का उपयोग कर श्लिष्ट इस्पात-कंक्रीट संयुक्त धरन (बीएफएम) का निर्माण, यांत्रिक कतरनी योजक के विकल्प के रूप में अन्वेषित किया जा रहा है। चिपकने वाले जोड़ का अनुकूलन केवल तभी संभव है, जब हर पहलू में अंतराफलक जोड़ के व्यवहार की जांच की गई हो। निरंतर बीएफएम में कंक्रीट आंतरिक संबल पर तन्यता रेंगने का अनुभव करता है और निरंतर भार के तहत असंबल स्थान में संकुचित शिथिलता अनुभव करता है।

बीएफएम पर शोध अपने प्रारंभिक चरण में है। बीएफएम के विभिन्न अस्पष्टीकृत पहलुओं में से कुछ को यहां संबोधित किया गया है: (i) निरंतर बीएफएम का दीर्घकालिक व्यवहार, (ii) तन्य शिथिलता के तहत कंक्रीट की तन्यता शक्ति, (iii) कतरनी अंतराल व्यवहार के लिए भार के स्थान का प्रभाव, (iv) चिपकने वाले जोड़ का व्यवहार और (v) चिपकने वाले जोड़ में सरक और कतरनी तनाव के विश्लेषणात्मक सूत्र।

वर्तमान शोध कार्य में, पहले, कंक्रीट के प्रभावी तन्यता शक्ति और शिथिलता गुणांक के बीच एक संबंध प्रस्तावित है, जो निरंतर भार के तहत धरन के लिए मान्य है। प्रस्तावित संबंध का उपयोग करते हुए, तीन-आयामी (3 डी) परिमित तत्व (एफई) विश्लेषण का उपयोग करके यांत्रिक रूप से जुड़े इस्पात-कंक्रीट संयुक्त धरन के दीर्घकालिक व्यवहार का अनुमान लगाने हेतु एक संगणक रूप से प्रभावी प्रभावी मापांक विधि आधारित प्रक्रिया प्रस्तावित की गई है।

आगे, बीएफएम के लिए उपयुक्त एपॉक्सी आधारित आसंजक का चयन करने के लिए एक प्रयोगात्मक कार्यक्रम प्रस्तुत किया गया है। उसके बाद, बीएफएम पर अल्पकालिक और

दीर्घकालिक, पूर्ण पैमाने पर प्रयोग प्रस्तुत किए गए हैं। शोध कार्य बीएफएम के अल्पकालिक और दीर्घकालिक व्यवहार के अनुमान लगाने हेतु 3 डी एफई मॉडल भी प्रस्तुत करता है।

इसके अलावा, कतरनी अंतराल और बीएफएम की प्रभावी चौड़ाई पर एक संख्यात्मक अध्ययन प्रस्तुत किया गया है। अध्ययन में (क) सेवा भार पर विस्थापन (ए) सेवा भार पर अधिकतम तनाव और (ग) अंतिम भार पर प्लास्टिक विश्लेषण के लिए प्रभावी चौड़ाई पर भार के स्थान पर प्रभाव पर ध्यान केंद्रित किया गया है।

वर्तमान शोध कार्य में भार अनुपात कारक, भार व्यवस्था, कंक्रीट पटिया की चौड़ाई, कंक्रीट पटिया की मोटाई और आसंजक का यंग मापांक के प्रभाव को समझने के लिए बीएफएम के चिपकने वाली बांड परत पर संख्यात्मक जांच भी शामिल है। यह जांच कतरनी और सामान्य तनावों और सेवा भार और अंतिम भार पर लंबाई के साथ रूपांतर की भिन्नता पर केंद्रित है।

इसके अलावा, वर्तमान शोध कार्य आम भार और सीमा स्थितियों के लिए सेवा भार पर बीएफएम की अंतराफलक सरक के लिए विश्लेषणात्मक समाधान प्रस्तुत करता है, जिसका उपयोग प्रारंभिक रचनात्मक गणना के लिए किया जा सकता है। प्रस्तुत विश्लेषणात्मक समाधानों को 3 डी एफई विश्लेषण की सहायता से मान्य किया गया है।

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LIST OF NOTATIONS

Notation	Description
b_0	Width of the upper flange of the steel I-section
b_{ei}	Effective width of concrete slab on each side of upper flange
b_i	Actual width of concrete slab on each side of upper flange
d	Cohesion of adhesive
d	Distance between centroids of steel and concrete elements
e	Eccentricity defined in CDP
e_L	Distance of the centroid of the load from the mid-width
$e(z)$	Longitudinal strain at centroid of steel element
f_{ys}	Yield compressive strength of adhesive
f_{cr}^-	Tensile strength
f_u^+	Ultimate cylindrical compressive strength
k	Bond stiffness
l	Left segment
p	Hydrostatic stress
\bar{p}	Effective hydrostatic stress
p_u	Pressure intensity due to applied load at ultimate load state
q	Von-Mises equivalent stress
\bar{q}	Von-Mises equivalent effective stress
r	Third invariant of deviatoric stress
r	Right segment
s_{max}	Maximum slip in the BFM
$s(z)$	Slip between steel top surface and concrete bottom surface
$v(z)$	Shear flow in the bond layer
w	Uniformly distributed load

$w_{cb}(z)$	Longitudinal displacement of concrete slab's bottom surface,
$w_{st}(z)$	Longitudinal displacement of steel-I section's top surface,
z	Distance along longitudinal
z_{c0}	Depth of the neutral axis of the concrete slab from top at mid-width
A_c	Area of the concrete element
A_s	Area of steel element
B	Width of the BFM
B_a	Width of the bond layer
B_c	First moment of area of the concrete element
B_{eff}	Effective width
$B_{eff,u}$	Effective width for bending moment capacity at ultimate load
$B_{eff,\delta}$	Effective width for deflection at service load
$B_{eff,\sigma}$	Effective width for maximum stress at service load
D_a	Depth of adhesive layer
D_c	Depth of concrete slab
D_s	Depth of steel I-section
D_{sc}	Height of centroid of steel I-section from bottom
D_0^{el}	Undamaged initial elastic modulus
E_{it}	Initial Young's modulus
E_A	Young's modulus of the adhesive
F_{CDP}	Yield function of CDP
F_{DP}	Yield criterion of DP
G_{CDP}	Plastic flow of CDP
G_{DP}	Plastic flow of DP
I	Identity matrix
I_c	Second moment of area of concrete element about its centroid

I_s	Second moment of area of steel element about its centroid.
K_c	Ratio of the second deviatoric stress invariant
K_{DP}	Ratio of the second deviatoric stress invariant
L_0	Total length of the flexural member
L_e	Effective span length of BFM
L_s	Span length of BFM
L_{Load}	Longitudinal location of load in general
M_l	Bending moment in left segment
$M_c(z)$	Internal moment of concrete element
M_r	Bending moment in right segment
$M_s(z)$	Internal bending moment of steel element
$M_{ti}(z)$	Total internal moment in the composite cross-section
$M(z)$	Applied bending moment
$N_c(z)$	Internal longitudinal force in concrete element cross-section
$N_s(z)$	Internal longitudinal force in steel element cross-section
$N_{ti}(z)$	Total internal longitudinal force in the composite cross-section
P	Applied concentrated load
$P_{u,EC}$	Ultimate load resisted by the BFM using Eurocode 4 (2004) for each loading arrangement
$P_{u,FE}$	Ultimate load resisted by the BFM using the FE model
\bar{S}	Effective deviatoric stress tensor
U_x	Displacements in X directions
U_z	Displacements in Z directions
X	Lateral horizontal distance from mid-width of bond layer
X, Y and Z	Directions along width of cross-section
α	A composite cross-section parameter
α_u	Ratio of effective depth of PNA to total depth

α_{CDP} ,	CDP parameters
$B_{\text{eff},\delta}(x, 0.00, 0.00)$	Effective width for deflection at service load at end support
$B_{\text{eff},\sigma}(x, 0.00, 0.00)$	Effective width ratio for maximum stress at service load at mid-width
β_u	Ratio of effective width to total width
β_{CDP}	CDP parameters
β_{DP}	A Drucker-Prager parameters
β_{EC}	Effective width ratio according to EC4
β_{δ}	Effective width ratio for deflection at service load
$\beta_{\delta}(x, 0.00, 0.00)$	Effective width ratio for deflection at service load at mid-width
$\beta_{\delta}(x, 0.00, L_0/2)$	Effective width ratio for deflection at service load at end support
β_{σ}	Effective width ratio for maximum stress at service load
$\beta_{\sigma}(x, 0.00, 0.00)$	Effective width ratio for maximum stress at service load at mid-width
$\beta_{\sigma}(x, 0.00, L_0/2)$	Effective width ratio for maximum stress at service load at end support
$\gamma_{yz}(0.00, D_c + 0.50D_a, z)$	Shear strain in bond layer element located at mid-width at mid-span
$\gamma_{yz}(x, D_c + 0.50D_a, z)$	Shear strain in bond layer element located at distance x from mid-width at mid-span
ε	Strain
$\varepsilon(y, z)$	Longitudinal strain
$\varepsilon_{\text{cb}}(z)$	Longitudinal strain of concrete element's bottom surface
$\varepsilon_{\text{st}}(z)$	Longitudinal strain of steel element's top surface
ε^{pl}	Plastic strain
$\dot{\varepsilon}^{\text{pl}}$	Plastic strain rate
$\tilde{\varepsilon}^{\text{pl}}$	Equivalent plastic strain

$\varepsilon_x^-(0.00, 0.00, 0.00)$	Transverse bending tensile strain at top surface of concrete at mid-width at mid-span
$\varepsilon_y^-(0.00, D_c + 0.50D_a, z)$	Normal tensile strain in bond layer of concrete at mid-width at mid-span
$\varepsilon_z^-(0.00, D_c + 0.50D_a, 0.00)$	Longitudinal bending tensile strain in bond layer of concrete at mid-width at mid-span
$\varepsilon_z^-(0.00, D_c + 0.50D_a, 0.48L_0)$	Longitudinal bending tensile strain in bond layer of concrete at mid-width at support
ε^+	Compressive strain in concrete
ε_f^+	Strain corresponding to f_u^+
$\varepsilon_y^+(0.00, D_c + 0.50D_a, z)$	Normal compressive strain in bond layer of concrete at mid-width at mid-span
$\varepsilon_y^+(x, D_c + 0.50D_a, z)$	Normal compressive strain in bond layer of concrete at distance x from mid-width at mid-span
ε_z^+	Longitudinal bending compressive strain
$\varepsilon_z^+(0.00, 0.00, 0.00)$	Longitudinal bending compressive strain at top surface of concrete at mid-width at mid-span
$\varepsilon_z^+(0.00, 0.00, L_0/2)$	Longitudinal bending compressive strain at top surface of concrete at mid-width at end support
$\varepsilon_z^+(0.00, D_c + 0.50D_a, z)$	Longitudinal bending compressive strain in bond layer of concrete at mid-width at mid-span
$\varepsilon_z^+(x, 0.00, 0.00)$	Longitudinal bending compressive strain at top surface of concrete at distance x from mid-width at mid-span
$\varepsilon_z^+(B/2, 0.00, L_0/2)$	Longitudinal bending compressive strain at top surface of concrete at outer edge at end support
λ	Plastic loading factor
λ_ε	Shear lag parameter for longitudinal bending compressive strain

$\lambda_\epsilon(x, 0.00, 0.00)$	Shear lag parameter for longitudinal bending compressive strain at top of concrete at mid-span
$\lambda_\epsilon(x, 0.00, L_0/2)$	Shear lag parameter for longitudinal bending compressive strain at top of concrete at longitudinal end of slab
λ_σ	Shear lag parameter for longitudinal bending compressive stress
$\lambda_\sigma(x, 0.00, 0.00)$	Shear lag parameter for longitudinal bending compressive stress at top of concrete at mid-span
$\lambda_\sigma(x, 0.00, L_0/2)$	Shear lag parameter for longitudinal bending compressive stress at top of concrete at longitudinal end of slab
ξ	Ratio of depth of PNA to depth of neutral axis at mid-width
σ	Stress
$\sigma(y, z)$	Longitudinal stress in section at distance z from origin
σ_{b0}	Equibiaxial compressive strength of concrete
σ_{c0}	Uniaxial compressive strength of concrete
σ_{t0}	Uniaxial tensile strength
$\bar{\sigma}$	Effective stress
$\sigma_x^-(0.00, 0.00, 0.00)$	Transverse bending tensile stress at top surface of concrete at mid-width at mid-span
$\sigma_x^-(0.00, 0.00, L_{Load})$	Transverse bending tensile stress at top surface of concrete at mid-width at location of load
$\sigma_x^-(B/2, 0.00, L_{Load})$	Transverse bending tensile stress at top surface of concrete at concrete slab edge at location of load
$\sigma_y^-(0.00, D_c + 0.50D_a, z)$	Normal tensile stress in bond layer at mid-width
$\sigma_y^-(0.50B_a, D_c + 0.50D_a, 0.00)$	Normal tensile stress in bond layer at outer fiber of bond layer
$\sigma_z^-(0.00, D_c + 0.50D_a, z)$	Longitudinal bending tensile stress in bond layer at mid-width of bond layer
$\sigma_z^-(x, D_c + 0.50D_a, z)$	Longitudinal bending tensile stress in bond layer

σ_{c0}^0	Uniaxial compressive strength of adhesive,
σ_{t0}^0	Uniaxial tensile strength of adhesive
σ^+	Compressive stress in concrete
$\sigma_y(0.00, D_c + 0.5D_a, z)$	Normal stress in bond layer at mid-width
$\sigma_y^+(0.00, 0.00, 0.00)$.	Normal compressive stress at top surface of concrete at mid-width at mid-span
$\sigma_y^+(0.00, 0.00, L_{Load})$	Normal compressive stress at top surface of concrete at mid-width at location of load
$\sigma_y^+(0.00, D_c + 0.5D_a, z)$	Normal compressive stress in bond layer at mid-width
$\sigma_y^+(0.50B_a, D_c + 0.5D_a, z)$	Normal compressive stress in bond layer outer fiber of bond layer
$\sigma_y^+(x, 0.00, 0.00)$	Normal compressive stress at top surface of concrete at mid-span
$\sigma_y^+(x, D_c + 0.5D_a, z)$,	Normal compressive stress in bond layer
$\sigma_y^+(B/2, 0.00, L_{Load})$	Normal compressive stress at top surface of concrete at edge at location of load
σ_z^+	Longitudinal bending compressive stress
$\sigma_{z,max}^+$	Maximum longitudinal bending compressive stress
$\sigma_z^+(0.00, 0.00, 0.00)$	Longitudinal bending compressive stress at top surface of concrete at mid-width at mid-span
$\sigma_z^+(0.00, 0.00, L_0/2)$	Longitudinal bending compressive stress at top surface of concrete at mid-width at longitudinal end of BFM
$\sigma_z^+(0.00, 0.00, L_{Load})$	Longitudinal bending compressive stress at top surface of concrete at mid-width at location of load
$\sigma_z^+(0.00, D_c + 0.5D_a, z)$	Longitudinal bending compressive stress in the bond layer at mid-width
$\sigma_z^+(x, 0.00, 0.00)$	Longitudinal bending compressive stress at top surface of concrete at mid-width
$\sigma_z^+(x, 0.00, z)$	Longitudinal bending compressive stress at top surface of

	concrete
$\sigma_z^+(x, y, 0.00)$	Longitudinal bending compressive stress at mid-width
$\sigma_z^+(B/2, 0.00, 0.00)$	Longitudinal bending compressive stress at edge of top surface of concrete at mid-width
$\sigma_z^+(B/2, 0.00, L_0/2)$	Longitudinal bending compressive stress at edge of top surface of concrete at longitudinal end of BFM
$\sigma_z^+(B/2, 0.00, L_{Load})$	Longitudinal bending compressive stress at edge of top surface of concrete at location of load
$\sigma_{z,SBT}^+(x, 0.00, 0.00)$	Longitudinal bending compressive stress at top surface of concrete at mid-width using simple bending theory
$\bar{\sigma}_c(\tilde{\epsilon}_c^{pl})$	Effective compressive cohesion stress
$\hat{\sigma}_{max}$	The maximum principal effective stress
$\bar{\sigma}_t(\tilde{\epsilon}_t^{pl})$	Effective tensile cohesion stress
τ_{yz}	Shear stress
$\tau_{yz}(0.00, D_c + 0.50D_a, z)$	Shear stress in the bond layer at mid-width
$\tau_{yz}(0.25B_a, D_c + 0.50D_a, z)$	Shear stress in the bond layer at quarter-width
$\tau_{yz}(0.50B_a, D_c + 0.50D_a, z)$	Shear stress in the bond layer at edge
$\tau_{yz}(x, D_c + 0.50D_a, z)$	Shear stress in the bond layer
ν_a	Poisson's ratio of the adhesive
$\chi(z)$	Curvature of the BFM
ψ_{CDP}	The dilation angle measured in p - q plane in high confining pressure condition of concrete
ψ_{DP}	Dilation angle of adhesive

LIST OF ABBREVIATIONS

Abbreviation	Elaboration
B31	Two-node spatial shear flexible beam elements
BFM	Adhesive bonded steel-concrete composite flexural members
C3D8	Three dimensional eight node continuum elements
CDP	Concrete damaged plasticity
CFM	Steel-concrete composite flexural members
DP	Drucker-Prager
EC	Eurocode 4 (2004)
FE	Finite element
LA	Loading arrangement
LDP	Extended linear Drucker-Prager
LPF	Load proportion factor
MCFM	Mechanically connected steel-concrete composite flexural members
PNA	Plastic neutral axis
RB	Reference beam
SBT	Simple beam theory
VB	Validation beam
