DEVELOPMENT OF COMPUTATIONAL TECHNIQUES FOR SERVICE LOAD ANALYSIS OF STEEL-CONCRETE COMPOSITE STRUCTURES

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by

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Dedicated

to those selfless, who silently contribute to the society

&

to the memories of my late parents

CERTIFICATE

This is to certify that the thesis entitled, **"Development of Computational Techniques for Service Load Analysis of Steel-Concrete Composite Structures"** being submitted by **Mr. M. P. Ramnavas** 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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(M. P. RAMNAVAS)

ABSTRACT

Structural members with concrete slab placed above steel sections and connected together with shear connectors is a common form of steel-concrete composite beams with high structural efficiency in resisting flexure, and are used in buildings and bridges. Cracking of concrete slab occurs in the support regions of continuous composite beams due to hogging moments, under service loads. This cracking of the concrete at the service loads causes inelastic behaviour due to the reduction in the stiffness of members which results in redistribution of moments from the supports to the mid-span and increase in curvatures and deflections. Appropriate analysis of structures with composite beams, considering cracking of concrete is important. There are many numerical and analytical methods available in the literature, of which the numerical methods require large computational efforts whereas the analytical methods do not consider all the aspects. Therefore, there is need for procedures that require minimal computational effort but provides accuracy that is acceptable for practical applications.

In the present work, a cracked span length beam element has been proposed that accounts for cracking in the concrete slab, for the instantaneous analysis of composite beams and composite frames which are subjected to service loads. This element consists of two cracked zones at the ends and one uncracked zone between the cracked zones and has been used to develop an analytical-numerical procedure. The procedure is analytical at the element level, whereas it is numerical at the structural level. Analytical expressions have been obtained for flexibility and stiffness coefficients, end displacements, load vector and mid span deflections of the cracked span length beam element. To keep the procedure analytical at the element level, average tension stiffening characteristics are arrived at for the cracked zones. An iterative process is used to establish the cracked zone lengths. The procedure yields cracked lengths, interpolation coefficients (for tension stiffening) and inelastic deflections as well as

redistributed moments. The procedure with the proposed element has been validated by comparisons with experimental results available in literature and also by comparisons with the results from Finite Element Analysis. The procedure requires a fraction of the computational effort required for the numerical methods available and gives sufficiently accurate results. Therefore, the reduction in the computational efforts in the case of large composite structures, e.g. tall building frames would be considerable.

For rapid evaluation of various inelastic quantities considering cracking of concrete for multi-storey composite frames, a methodology based on neural network approach has also been proposed in the present work. Huge number of data sets required for training of neural networks have been generated using the analytical-numerical procedure mentioned above. Closed form expressions based on weights and biases of the neural networks, are used to predict the inelastic moments and deflections from the parameters obtained in the elastic analysis. These expressions have been validated with results obtained from the analytical-numerical procedure.

Similar closed form expressions, have also been developed for prediction of cracked lengths and interpolation coefficients (tension stiffening) in composite beams of multi-storey frames of various classifications viz. low rise, medium rise and high rise frames duly taking into account the effects of change in column sections between storeys and also the effects of differential axial shortening of columns.

A two stage procedure has also been proposed in the present work, by combining the analytical-numerical procedure and the methodology of predicting inelastic quantities mentioned above, for the analysis of multi-storey composite frames, considering cracking. In this procedure, the prediction models for cracked zone parameters (cracked lengths and interpolation coefficients) have been embedded in the analytical-numerical procedure. In the first stage, an elastic analysis is performed and from the results and using the prediction models (i.e. closed form expressions based on neural networks), the cracked zone parameters are evaluated. In the second stage (cracked stage), iterations are performed starting from these predicted values which result in comparatively faster convergence. For using the two stage procedure for low rise, medium rise and high rise frames, the relevant closed form expressions, have been embedded in the procedure. The results from the two stage procedure have been compared with that obtained by the analytical-numerical procedure proposed in the present work, for four storey, twenty storey and forty storey example frames, and the results have been found to match exactly with very less number of iterations and thus the saving in computational efforts is considerable.

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A, B, I	area, first moment of area and second moment of area, respectively, of the composite section
A_{sr}	area of the steel reinforcement in the slab
A_{ss}	area of the steel section
b, D_c, D_s, D_{na}	breadth and depth of the concrete slab, depth of the steel section and depth of the neutral axis of the steel section from its top fibre, respectively
b_h	bias between input layer and hidden layer for hidden neuron h
b_{out}	bias of output neuron
C_i	distance from the end A to the centre of the typical i^{th} zone
CS	Column section
CS_1, CS_2, CS_3	Column section for topmost storey of any frame, for bottom storey of 20 storey frame and bottom storey of 40 storey frame
$CS_{1,1}^{20,eq}$, $CS_{1,1}^{40,eq}$	Column section with an equivalent area to simulate the effects of differential axial shortening, with CS_1 in 1st and 2nd storeys and also in 3rd and 4th storeys, and the moment of inertia equal to that of CS_1, in the case of 20 storey frame and 40 storey frame, respectively.
$CS_{2,1}^{20,eq}$, $CS_{2,1}^{40,eq}$	Column section with an equivalent area to simulate the effects of differential axial shortening, with CS_2 in 1st and 2nd storeys and CS_1 in 3rd and 4th storeys, and the moment of inertia equal to that of CS_2, in the case of 20 storey frame and 40 storey frame, respectively.
$CS_{2,2}^{20,eq}$, $CS_{2,2}^{40,eq}$	Column section with an equivalent area to simulate the effects of differential axial shortening, with CS_2 in 1st and 2nd storeys and also in 3rd and 4th storeys, and the moment of inertia equal to that of CS_2, in the case of 20 storey frame and 40 storey frame, respectively.
d^e, d^i	deflection at mid-span obtained in elastic and inelastic analysis, respectively
d^{cr}	deflection at mid-span of a fixed beam and carrying a uniformly distributed load just sufficient to cause cracking

d_m	mid-span deflection
d_{sr}	effective concrete cover to the steel reinforcement from the top fibre
$\{d^{er}\},\{d^*\}$	error or difference in the displacement vector and the revised displacement vector, respectively
E	modulus of elasticity
E_c, E_s	modulus of elasticity of concrete and steel, respectively
$f_{ij}, k_{ij}, [k]$	flexibility coefficients, stiffness coefficients and stiffness matrix, respectively, of a skeletal member
$f_c^{'}$	cylinder compressive strength of the concrete at 28 days
f_t	tensile strength of the concrete, respectively
I_{cr}	transformed second moment of area of cracked section (consisting of steel section and reinforcement only), about its neutral axis
I_{un}	transformed second moment of area of uncracked composite section about its neutral axis
I_g	input neuron g
K_{col}, K_b	stiffness of column and beam respectively, in a frame
L	span of the beam
L_i	length of the typical i^{th} zone (cracked or uncracked)
$L_{i,cr}$	length of the typical cracked i^{th} zone
n, m	number of degrees of freedom and half bandwidth, respectively
M	moment
M_A, M_B	moment at end A and end B, respectively
N	axial force
N_A, N_B	axial force at end A and end B, respectively
$\{p\}$	revised force vector of element
$\{P^0\}$	fixed end force vector for the uncracked beam
$\{P^{er}\},\{p^{er}\}$	residual force vector of the structure and element, respectively
P_O	output parameter
p	distance between concentrated load and end A

r	number of input neurons
q	number of hidden neurons
R	reaction force
R_A, R_B	reaction force at end A and end B, respectively
$R^l_{i,j}, R^r_{i,j}$	inelastic moment ratio, at the left l or right r end respectively, of the beam in bay i and floor j
S_i	stiffness of beam in bay i
S_{i+1}/S_i	stiffness ratio
w, W	uniformly distributed load and concentrated load on the span, respectively
w^{cr}	uniformly distributed load at cracking of a beam
w_i	load on beam in bay i
w_i/w_{i+1}	load ratio
w_h	weights between hidden and output layers for hidden neuron h
w_{hg}	weights between input neuron g and hidden neuron h
u	axial displacement
x	distance of the cross-section from end A in a beam
x'	distance of the cross-section from C in a typical zone
y	distance from the reference axis
$y_{act}, y_{\min}$ $y_{\max}, y_{norm}$	actual, minimum, maximum and normalized value respectively, of a parameter in the data set
$\alpha^l_{i,j}, \alpha^r_{i,j}$	stress ratio at the left l or right r end respectively, of the beam in bay i and floor j
$\beta^l_{i,j}, \beta^r_{i,j}$	joint stiffness ratio of a beam at left l or right r end of a beam, in bay i and floor j
$\gamma^l_{i,j}, \gamma^r_{i,j}$	shortening parameter at left l or right r end of a beam in bay i and floor j
$\delta^d_{i,j}$	inelastic deflection ratio for the beam in bay i and floor j
θ	end rotation
τ	tolerance value
ξ, η	average interpolation coefficients
ξ_i, η_i	average interpolation coefficients in a typical i^{th} zone

κ	coefficient that represents the influence of the duration of application or repetition of loading on the interpolation coefficient
$\lambda^{l}_{i,j}, \lambda^{r}_{i,j}$	cracked length ratio at the final cracked state at left l or right r end of a beam in bay i and floor j
$\rho, \varepsilon, \sigma$	curvature, strain and stress, respectively
$\sigma_0, \sigma_{un}, \sigma_{un,i}$	stress at the reference axis, stress at the tensile face (top fibre), average of the stress at the tensile face for i^{th} region respectively
ε_t, ε_u	cracking strain and maximum tensile strain of concrete, respectively
$\varepsilon_0, \varepsilon_y$	strain at a distance zero and y from the reference axis
ω	transverse displacement

Subscript

A, B	ends A and B of a cracked span length beam element, respectively
b, col	Beam and column, respectively
c, s	concrete and steel, respectively
cr, un, ts	cracked state, uncracked state and tension stiffening, respectively
i	i^{th} zone of cracked span length beam element when used in analytical-numerical procedure & i^{th} bay of frame when used in neural networks
j	j^{th} storey/floor of frame
p	predicted value
ss	steel section
sr	steel reinforcement
y	distance from the reference axis

Superscript

C, D, E	locations in a typical zone
cr	cracking limit
e	elastic
i	inelastic
m, n	moment and axial force, respectively