Modern Engineering Design:
Analytical and Numerical Modelling of Semi-rigid Connections

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Abstract

The concept of semi-rigid connection and steel-concrete composite action has been extensively researched in the past. However, they are not widely used in practice due to the lack of detailed information, not only about the advantages of the semi-rigid design philosophy, but also about the potential risks if its effect is not accounted for. The above considerations were the motivations in taking up this research.

Firstly, a numerical study to investigate the effect of connection stiffness on the natural frequency of semi-rigid frame was carried out using ABAQUS software. The results of this numerical study confirmed the necessity of incorporating this effect to get safe and economical design. Consequently, an analytical procedure for a beam with semi-rigid connections under gravity load was developed which overcomes the limitations of previously published procedures. The frequency of a steel beam was also calculated using effective length concept. Furthermore, two new analytical "hand'' calculation methods to estimate the first three frequencies of a semi-rigid frame were developed. Both methods were developed by modifying or improving for existing methods in the literature for rigid-jointed plane steel frame to incorporate the effect of connection stiffness. Fist method is suitable only for a semi-rigid plane steel frame which has uniform properties along its height so as it can be modelled as equivalent flexural-shear cantilever beam. The proposed second method is suitable for non-uniform plane steel frame. Both the above methods can be extended to composite structure using the equivalent stiffness concept of composite beam. Moreover, examples of steel frame were used to demonstrate the application of the proposed analytical methods. It was shown that the proposed methods not only can predict the difference in frequency of rigid and semi-rigid frames, but they are also simple enough to be used in day-to-day design practices.

Secondly, as the stiffness of connection is essential in the calculation of natural frequency of a semi-rigid frame, a new simple mechanical component-based model was developed to determine the initial rotational stiffness of commonly used flush end-plate steel or composite connection incorporating the partial interaction effect. The traditional axial spring of shear connectors was replaced by rotational spring to make the model suitable to extending further than the linear region. A chart was developed to estimate the appropriate values of the secant stiffness and strength of a shear stud, since the empirical equations that researchers have used in the past can lead to unrealistic results in some cases.

Thirdly, a simplified model, which combined three components of a composite connection in one "lump'' component (RCCS), was developed. It can be used in the finite element modelling of a composite connection to overcome the convergence problems associated with cracking of concrete and also it will reduce the computational time significantly with adequate accuracy. A new procedure to determine the number of "active'' studs was developed. The relationship between the number of "active'' shear studs and the maximum number of shear studs required for a full shear connection was derived.

Finally, the relationship between connection ductility and frame ductility was investigated. It was found that the moment resistance and ductility of connection affect significantly the whole behaviour of a frame. Consequently, a simple flowchart to predict the failure mode of a flush end-plate composite connection was developed. A procedure to estimate the moment resistance of a flush end-plate composite connection by modifying the existing procedures in the literature to incorporate the partial shear connection effect was proposed. Also, the proposed mechanical model was further extended using the appropriate post-linear values of its components in order to calculate the rotational ductility of a connection.

All the suggested procedures have been validated with the numerical results using ABAQUS, the results from other existing models and experimental tests in the literature where available.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Notations

Symbol	Definition	Unit
A_b	Area of beam	mm^2
A_{bf}	Area of beam flange	mm^2
A_c	Area of column	mm^2
A_{cf}	Area of column flange	mm^2
A_{cj}	Cross-sectional area of the *j*-th column	mm^2
A_r	Area of reinforcing bars	mm^2
A_{sc}	Area of a stud	mm^2
A_{vc}	Shear area of the column	mm^2
b_{bf}	Breadth of beam flange	mm
b_{cf}	Width of column flange	mm
$b_{eff,cwc}$	Effective width of column web in compression	mm
c_j	Distance of the *j*-th column from the centroid of the column assembly	mm
d	Diameter of shear connector	mm
D_b	Distance from the top row of bolts to the centre of the compression zone	mm
d_{cw}	Width of column web	mm
$D_{i,j}$	Lateral stiffness of the *i*-th storey	N/mm
D_r	Distance from the reinforcement to the centre of the compression zone	mm
d_s	Distance between the centroid of the beam section and the centroid of the reinforcement	mm
E_c	Young's modulus of concrete	N/mm^2
E_m	Mean modulus of elasticity for the embedded reinforcement	N/mm^2
E_{RCC}	Modulus of elasticity of the (RCC) component	N/mm^2
E_s	Young's modulus of steel	N/mm^2
f	Frequency	1/sec
F_b	Tensile force of the top row of bolts	N
F_{base}	Design seismic base shear force	N
F_c	Force in the centre of the compression zone	N
$F_{c,bf,Rd}$	The resistance of beam flange in compression	N
$F_{c,cw,Rd}$	The resistance of column web in compression and buckling	N
$F_{c,t}$	Force of the concrete tension member	N
f_{ck}	Characteristic cylinder compressive strength of concrete	N/mm^2
f_{cm}	Mean compression strength of concrete	N/mm^2
f_{cr}	Crack strength of concrete	N/mm^2
f_{ctm}	Mean tensile strength of concrete	N/mm^2
f_p	Tensile strength of end plate	N/mm^2
F_r	Force in reinforcement	N
$f_{r,u}$	Ultimate strength of reinforcement	N/mm^2
$f_{r,y}$	Yield strength of reinforcement	N/mm^2

F_{RCC}	Force in the (RCC) component	N
F_s	Force acting on the studs	N
$F_{s,T}$	Tensile force of a reinforced concrete uncracked member	N
$F_{sc,k}$	Characteristic resistance of the shear stud	N
$F_{sc,max}$	Ultimate shear strength of the shear stud	N
$F_{sc,y}$	Yield force of shear connector	N
f_u	Ultimate tensile strength of shear stud	N/mm^2
$f_{y,cw}$	Yield strength of column web	N/mm^2
G	Shear modulus	N/mm^2
h	Storey height	mm
H_b	Depth of the steel beam	mm
h_c	Depth of column	mm
h_d	Bending deflection height of the shear connector	mm
h_{sc}	Height of shear connector	mm
h_{sl}	Thickness of the concrete slab	mm
I	Second moment of area of the steel beam	mm^4
$\bar{I}_b$	Modified second moment of area of a beam	mm^4
J	Lowest integer number of shear studs for full shear connection	-
k	characteristic parameter account for the effect of axial rigidity	-
k_b	Stiffness of bolt	N/mm
k_{bfc}	Stiffness of bottom flange of beam in compression	N/mm
k_{bt}	Stiffness of top row bolts in tension.	N/mm
k_{bwt}	Stiffness of beam web in tension	N/mm
k_c	Stiffness of a group of components in series at the level of the centre of the compression	N/mm
k_{cfb}	Stiffness of column flange in bending	N/mm
k_{cwc}	Stiffness of column web in compression	N/mm
k_{cws}	Stiffness of column web panel in shear	N/mm
k_{cwt}	Stiffness of column web in tension	N/mm
k_{pb}	Stiffness of end-plate in bending	N/mm
k_r	Stiffness of reinforcement in the concrete slab.	N/mm
k_{RCC}	Stiffness of an (RCC) spring	N/mm
k_s	Stiffness of shear connection; Stiffness of connection spring	N/mm
$k_{s,p}$	Plastic stiffness of shear connectors	N/mm
k_{sc}	Secant stiffness of one shear connector	N/mm
K_{slab}	Stiffness of composite slab in composite connection	N/mm
L_b	Length of the beam under hogging bending moment adjacent to the connection	mm
l_{bi}	Span of the beam in the i-th bay	mm
l_r	Effective length of bars	mm
l_{RCC}	Length of the (RCC) component	mm
L_t	Transmission length of crack	mm

m	Mass per unit length of beam	kg/mm
M_F	Fixed end moment in beam	N-mm
$M_{j,c}$	Moment of composite connection	N-mm
$M_{j,Rd}$	Moment resistance of connection	N-mm
$M_{j,s}$	Moment of bare steel connection	N-mm
$M_{j,sw}$	Moment resistance of steelwork in composite connection	N-mm
$M_{j,y}$	Yield moment of connection	N-mm
N_{act}	Number of active shear studs	-
N_{full}	Maximum number of shear studs for a full shear connection	-
N_{sc}	Number of studs in the hogging moment region	-
N_{spr}	Number of (RCC) springs in series between any two consecutive shear studs	-
p	Spacing between shear studs	mm
p_0	Distance between the column face and the first shear stud	mm
q	behaviour factor	-
R_b	Strength force of top row of bolts	N
R_r	Resistance of reinforcement	N
R_s	Resistance of shear connectors	N
$S_d\ (T_1)$	The ordinate of the design spectrum at period, T_1	m/sec^2
$S_{j,c}$	Rotational stiffness of composite connection	N-mm/rad
$S_{j,s}$	Rotational stiffness of bare steel connection	N-mm/rad
$S_{j,sw}$	Stiffness of steelwork in composite connection	N-mm/rad
s_{sc}	Slip of shear connector	mm
$s_{sc,c}$	Slip capacity of shear connector	mm
$s_{sc,u}$	Ultimate slip of shear connector	mm
t_{bf}	Thickness of beam flange	mm
t_{bw}	Thickness of beam web	mm
t_{cf}	Thickness of column flange	mm
t_{cw}	Thickness of column web	mm
t_p	Thickness of end plate	mm
V_i	Shear force in the *i*-th storey	N
w_{slab}	Width of concrete slab	mm
z	Lever arm between the compressive and the tensile area	mm
H	Height of building	m
I_{bi}	Second moment of area of the beam in the *i*-th bay	mm^4
I_{cj}	Second moment of area of the *j*-th column	mm^4
T	Time period	sec
T_{sf}	Time period of coupled shear-flexural vibration	sec
κ	Effective length factor	-
μ_f	Ductility of frame. and	-
μ_j	Rotational ductility of connection	-
β	Interaction parameter	-

Δ_b	Extension of the top row of bolts	mm
Δ_c	Extension of a group of components at the level of the centre of the compression	mm
Δ_r	Extension of reinforcement	mm
δ_{red}	Reduction in deflection	mm
Δ_s	Slip of shear connection	mm
Δ_u	Top horizontal displacement at ultimate load	mm
Δ_y	Top horizontal displacement at first yield	mm
$\Delta\varepsilon_{sr}$	Increase of embedded reinforcement strain in the cracking state	-
ε_{cr}	Crack strain of concrete	-
ε_{smu}	Ultimate strain for embedded reinforcement	-
ε_{smy}	Yield strain for embedded reinforcement	-
ε_{su}	Ultimate strain of bare reinforcement	-
ε_{sy}	Yield strain of bare reinforcement	-
η	Degree of shear connection	-
κ	shape factor	-
λ	Correction factor that depends on T_1 and number of storeys; Eigenvalue of the free shear flexural vibration of a prismatic cantilever	-
ν	Poisson's ratio	-
τ_{sm}	Average bond stress along the transmission length	N/mm^2
φ_{comp}	Rotation due to the deformation of connection's components	mrad
φ_{sh}	Rotation due to shear panel of column web	mrad
ω	Angular frequency	rad/sec
α	Parameter account for the effect of flexural and shear rigidity of the assumed cantilever	$1/mm^2$
$\phi_{j,c}$	Rotation capacity of connection	mrad
$\phi_{j,ult}$	Rotation of connection at ultimate	mrad
$\phi_{j,y}$	Rotation of connection at yield	mrad
η_u	Shear connection ratio based on the ultimate strength of reinforcement	-
η_y	Shear connection ratio based on the yield strength of reinforcement	-
λ_f	Eigenvalue of purely flexural vibration	-
λ_{sf}	Eigenvalue of coupled shear-flexural vibration	-
ρ	reinforcement ratio	-
$\sigma_{c,t}$	Stress of the concrete in tension member	N/mm^2
σ_r	Stress of the reinforcement in tension member	N/mm^2