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Effect of Confinement on Load – Moment Interaction Behavior of Reinforced Concrete Column

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Abstract— **Provision of ductility is of particular importance in the design and detailing of reinforced concrete structures subjected to seismic loads. To fulfill this requirement, the recent design code specified the use of transverse reinforcement or stirrups in the structural member such as column. However, the design is based on the simplified stress block of unconfined concrete, and does not account for the strength gain due to the presence of confinement. To investigate the effects of lateral confinement on column capacity an analytical study is carried out. In this study the design stress-strain diagrams for confined concrete are developed by considering different proposed confined models and its effect on column capacity is studied in terms of load – moment interaction diagram of column. The presence of lateral reinforcement expands the interaction diagram of the column particularly when it is in the compression-controlled region.**

Keywords— **RC column, concrete confinement, confined stress strain relationship, load moment interaction, transverse reinforcement,**

I. INTRODUCTION

Transverse reinforcement specified in the design code for beam and column has three main function: 1) Prevent buckling of longitudinal bars; 2) avoid shear failure; 3) Confine the concrete to provide sufficient deformability (ductility).In a column these transverse reinforcement are provided in the form of rectangular, circular or spiral rings from top to bottom which confine the concrete. This results in higher capacity and ductility of the column and helps to prevent the column from brittle failure. The higher capacity of the laterally confined column is due to gain in strength of concrete core of the column from the mobilization of lateral confinement and the yielding of the confining steel contributes to increased ductility (ability to undergo large deformation prior to failure) . In the present construction world we often require higher capacity and ductility of structural member, particularly in reinforced concrete structure. Provision of ductility is of particular importance in the design and detailing of reinforced concrete structures subjected to seismic loads.

The present code for the design of column does not consider the effect of confinement due to the lateral reinforcement. Up to now, the design of the structural column based on the simplified stress block of unconfined concrete since the design stress-strain diagram proposed, by considering the unconfined concrete block. Thus the existing interaction diagrams developed for the column capacity are also based on this assumption that does not account for the strength gain from the presence of confinement. Since the lateral confinement results in higher strength and not considered in design practice, and thus the code is in conservative side.

A considerable amount of work has been carried out to find out the lateral confinement effect on RC column which indicate that the presence of confinement on concrete column would affect the actual stress-strain curve of concrete. This effort gives a more accurate prediction on the compressive force of concrete in a column thus, resulting further in more efficient column cross section. With advancement of computer programming and technology, the computational effort can be much accelerated by implementing the numerical procedure to solve the stress-strain curve.

To investigate the effects of lateral confinement on the column capacity, an analytical study is carried out. In this study the column interaction diagrams are developed for confined concrete by considering three different models namely Modified Kent-Park, Mander et al. and Hong-Han, and compared with the existing interaction diagram.

II. LITERATURE REVIEW

Recent code of practice for the design of column disregard the effect of confinement and the stress-strain diagram given in the code is based on unconfined concrete and simplified for the design purpose. An acceptable stress-strain diagram given in the code is a parabolic curve up to the concrete strain of 0.002 and then it is horizontal up to the maximum strain of concrete. The confined concrete models adopted in this study are Modified Kent-Park, Mander et al. and Hong-Han.

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TABLE I
SUMMARY OF STRESS STRAIN CONFINED MODEL

Model	Equations
Modified Kent and Park (1982)	$f_c = \mathrm{K} f_{ck}[(2\varepsilon_c/0.002\mathrm{K})/(\varepsilon_c/0.002\mathrm{K})^2]$ if $\varepsilon_c \leq 0.002K$ $f_c = K f_{ck}\,[1 - \mathrm{Z}_m(\varepsilon_c - 0.002\mathrm{K})]$if if $\varepsilon c \geq 0.002K$ but not less than $0.2K f_{ck}$ $Zm = \frac{0.625}{\varepsilon_{50u}+\varepsilon_{50h}-0.002\mathrm{K}}$, $\mathrm{K} = \left[1.251 + \frac{\rho_s f_{yh}}{f_{ck}}\right]$ $,\varepsilon_{50u} = \frac{3+0.29 f_{ck}}{145 f_{ck}-1000}$,
Mander et al. *(1988)*	$f_c = \frac{\mathrm{xr} f_{cc}}{r-1+\mathrm{x}^r}$, $\mathrm{x} = \frac{\varepsilon_c}{\varepsilon_{cc}}$,$\mathrm{r} = \frac{E_c}{E_c - E_{sec}}$, $\mathrm{E}_c = 5000\sqrt{\mathrm{f}_{ck}}$, $\mathrm{E}_{sec} = \frac{\mathrm{f}_{cc}}{\varepsilon_{cc}}$, $\varepsilon_{cc} = \varepsilon_{c0}\left[1 + 5\left(\frac{\mathrm{f}_{cc}}{\mathrm{f}_{ck}} + 1\right)\right]$, $\varepsilon_{c0} = 0.002, f_{lx} = K_e \rho_x f_{yh}$ $,f_{ly} = K_e \rho_y f_{yh}$ $\mathrm{f}_{cc} = \mathrm{f}_{ck}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94 f_l}{f_{ck}}} - 2\frac{f_l}{f_{ck}}\right)$ $,\mathrm{K}_e = \frac{\left(\sum_{i=0}^{n}\frac{(\mathrm{w}_i)^2}{6 b_c d_c}\right)\left(1-\frac{s}{2d_c}\right)\left(1-\frac{s}{2b_c}\right)}{1-\rho_{cc}}$,
Hong-Han *(2005)*	$f_c = f_{ck}\left\{1 - \left(1 - \frac{\varepsilon_c}{\varepsilon_{cc}}\right)^{\alpha}\right\}$ for $\varepsilon_c \leq \varepsilon_{cc}$, $f_c = f_{ck} - E_{des}(\varepsilon_c - \varepsilon_{cc})$ for $\varepsilon_c > \varepsilon_{cc}$, $E_{des} = 0.026\frac{f_{co}^3}{f_{le}^{0.4}}, \alpha = E_c\frac{\varepsilon_{cc}}{f_{cc}}$, $f_{co} = 0.85 f_{ck}, E_c = 3320\sqrt{f_{co}} + 6900$, $\frac{f_{cc}}{f_{co}} = 1.0 + 4.1\left(\frac{f_{le}}{f_{co}}\right)^{0.70}, k_3 = {}^{40}/{}_{f_{co}} \leq 1.0$, $\varepsilon_{cc} = \varepsilon_{co} + 0.0015\left(\frac{f_{le}}{f_{co}}\right)^{0.56}, f_{le} = K_e \rho_s f_{hcc}$, $\mathrm{K}_e = \frac{\left(1-\sum_{i=0}^{n}\frac{(\mathrm{w}_i)^2}{6 b_c d_c}\right)\left(1-0.5\frac{s}{d_c}\right)\left(1-0.5\frac{s}{b_c}\right)}{1-\rho_{cc}}$ $,f_{hcc} = E_s\left\{0.45\varepsilon_{co} + 0.73\left(\frac{K_e \rho_s}{f_{co}}\right)^{0.70}\right\} \leq f_{yh}$

TABLE II
SUMMARY OF EFFECT OF CONFINEMENT PARAMETERS ON STRESS-STRAIN CURVE OF CONCRETE

Confinement Models	**Parameters**	**Confinement parameters**					
		Lateral reinforcement				**Longitudinal reinforcement**	
		Diameter	**Spacing**	**Yield strength**	**configuration**	**Number**	**configuration**
Modified Kent and Park	Peak stress	N	N	Y	N	N	N
	Peak strain	N	N	Y	N	N	N
	Ultimate strain	Y	Y	Y	Y	N	N
Mander at al.	Peak stress	Y	Y	Y	Y	Y	Y
	Peak strain	Y	Y	Y	Y	Y	Y
	Ultimate strain	Y	Y	Y	Y	Y	N
Hong-Han	Peak stress	Y	Y	Y	Y	Y	Y
	Peak strain	Y	Y	Y	Y	Y	Y
	Ultimate strain	Y	Y	Y	Y	Y	Y

Y -> affecting , N-> not affecting

Kent and Park (1971) made provisions in their stress-strain model to accommodate the behavior of confined concrete. It was assumed in their model that the maximum stress reached by confined concrete remained the same as the unconfined concrete strength f_{ck}. However after the experiment conducted by Scott et al. (1982), the Kent and Park model was modified in order to incorporate the increase in compressive strength of confined concrete. The maximum concrete stress attained is assumed to be Kf_{ck} and the strain at maximum concrete stress is 0.002K, where 'K' is a factor that depends on the yield strength of lateral reinforcement and unconfined strength of concrete.

Mander et al. (1988) first tested circular, rectangular and square full scale columns at seismic strain rates to investigate the influence of different transverse reinforcement arrangements on the confinement effectiveness and overall performance.

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Due to its generality, the Mander et al. model has enjoyed widespread use in design and research. Notwithstanding this it has several shortcomings. The Mander et al. model does not handle the post-peak branch of high strength concrete particularly well and requires some modification.

Hong, K. N., and Han (2005) proposed the stress-strain model of high-strength concrete confined by rectangular Ties which considered all the different confined parameters.

The equations used in these models to find out the stress-strain relation are summarized in Table I. Also the Table. II presents the summary of confinement parameters considered in various stress-strain curve of confined concrete proposed by different investigators.

III. Present Investigation

The effects of confinement directly influence the safe and magnitude of stress-strain curve of concrete. This in turn will affect the compressive force per unit width of concrete. The increase in compressive force of concrete will automatically improve the nominal capacity of column subjected to axial force and bending moment, or in other words, the interaction diagram of the column is enlarged. In the present study the effect of lateral confinement on reinforced concrete column is investigated in terms of load-moment interaction curve (including the partial safety factors). The lode-moment interaction curves are developed by considering above confined stress-strain models and compared with the lode-moment interaction curve for unconfined concrete as per the IS code.

To investigate the amount of capacity gain in axial load and bending moment due to the confinement effects, an analytical study is conducted for a uniaxially eccentrically loaded column with a rectangular cross-section (b X D). The design strength of an eccentrically loaded short column depends on the eccentricity of loading. Corresponding to a given eccentricity of loading there exist a unique strain profile at the ultimate limit state and corresponding to this distribution of strains, the stresses in concrete and steel, and hence, their respective resultant forces C_c and C_s can be determined. Applying the condition of static equilibrium, it follows that the two design strength components are obtainable as

$$P_{uR} = C_c + C_s$$
$$M_{uR} = M_c + M_s$$

The coordinates (M_{uR}, P_{uR}) can be derived considering internal value of x_u/D, using the above equilibrium equations.

A. Construction of Load – Moment Interaction Curve

Initial Assumptions:

i. Maximum limiting compressive strain ε_{cu} in confined concrete under flexure is assumed as strain corresponding to 85% of ultimate/maximum compressive stress f_{cc} of confined concrete or 0.01 which one is less.

ii. The maximum compressive strain in concrete under axial loading at limit state of collapse in compression is assumed as $\varepsilon_{cc} =$ stain corresponding to maximum compressive stress f_{cc} .

iii. For the design purpose, the compressive strength of concrete in the structure shall be assumed to be 0.67 times the actual strength. The partial safety factor $\Upsilon_m = 1.5$ shall be applied in addition to this.

For unconfined concrete, it is assumed that $\varepsilon_{cu} = 0.0035$ and $\varepsilon_{cc} = 0.002$ (as per IS code).The design stress-strain diagram for confined concrete are developed for different models by considering the above assumptions and compared with the design stress-strain diagram for unconfined concrete as per the IS code.

The construction of lode-moment interaction curve, both for unconfined concrete (as per IS code) and confined concrete are described in a step by manner. A uniaxially eccentrically loaded column with a rectangular cross-section $(b\ x\ D)$ is considered for the detail calculation. The distributions of strains in a rectangular column section are depicted in Fig.1. Two different cases needed to be distinguished, first case: when the neutral axis is located inside the column section $(x_u \le D)$ and the second case: when the neutral axis is located outside the section $(x_u > D)$. The equations used to find out the design strength component are summarized in Table III.

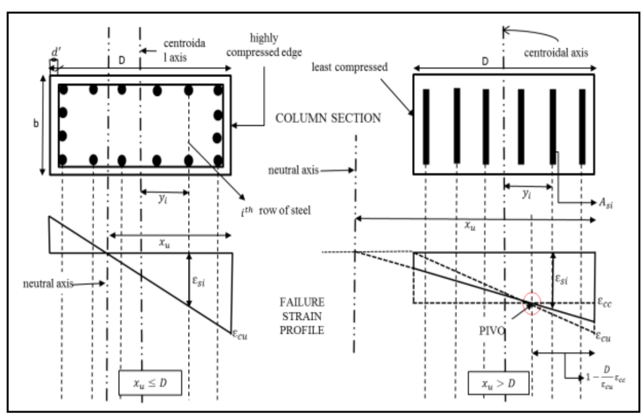

Fig. 1: Failure strain distribution in a rectangular column section

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TABLE III
ANALYSIS OF DESIGN STRENGTH OF A RECTANGULAR SECTION UNDER ECCENTRIC COMPRESSION

I. Design Strength : Axial Load – Moment Interaction	
For unconfined concrete(as per IS code)	**For confined concrete**
$C_c = af_{ck}bD$ $M_c = C_c(D/2 - \bar{x})$ $a = \begin{cases} 0.362x_u/D, & x_u \leq D \\ 0.447(1-4g/21), & x_u > D \end{cases}$ $\bar{x} = \begin{cases} 0.416x_u, & x_u \leq D \\ (0.5-8g/49)\{D/(1-4g/21)\}, & x_u > D \end{cases}$ $g = \frac{16}{(7\,x_u/D-3)^2}$ $P_{u0} = 0.447f_{ck}A_g + (f_{sc} - 0.447f_{ck})A_{sc}$ $f_{sc} = \begin{cases} 0.870f_y forFe\ 250 \\ 0.790f_y forFe\ 415 \\ 0.746f_y forFe\ 500 \end{cases}$ $C_s = \sum_{i=1}^{n}(f_{si} - f_{ci})A_{si}$ $M_s = \sum_{i=1}^{n}(f_{si} - f_{ci})A_{si}y_i$ $f_{ci} = \begin{cases} 0, & \varepsilon_{si} \leq 0 \\ 0.447f_{ck}, & \varepsilon_{si} \geq 0.002 \\ 0.447f_{ck}\left[2\left(\frac{\varepsilon_{si}}{0.002}\right) - \left(\frac{\varepsilon_{si}}{0.002}\right)^2\right] & otherwise \end{cases}$ $\varepsilon_{si} = \begin{cases} 0.0035\left[\frac{x_u - D/2 + y_i}{x_u}\right] x_u \leq D \\ 0.002\left[1 + \frac{y_i - D/14}{x_u - 3\,D/7}\right] x_u > D \end{cases}$	$C_c = abD$ $M_c = C_c(D/2 - \bar{x})$ $a = \begin{cases} \frac{\int_0^{\varepsilon_{cu}} f(\varepsilon)d\varepsilon}{\varepsilon_{cu}}(x_u/D), & x_u \leq D \\ \frac{\int_g^{\varepsilon_{cu}} f(\varepsilon)d\varepsilon}{\varepsilon_{cu}}(x_u/D), & x_u > D \end{cases}$ $\bar{x} = \begin{cases} \left[1 - \left\{\frac{\int_0^{\varepsilon_{cu}} f(\varepsilon)\varepsilon d\varepsilon}{\int_0^{\varepsilon_{cu}} f(\varepsilon)d\varepsilon}\right\}\frac{1}{\varepsilon_{cu}}\right]x_u, & x_u \leq D \\ \left[1 - \left\{\frac{\int_g^{\varepsilon_{cu}} f(\varepsilon)\varepsilon d\varepsilon}{\int_g^{\varepsilon_{cu}} f(\varepsilon)d\varepsilon}\right\}\frac{1}{\varepsilon_{cu}}\right]x_u, & x_u > D \end{cases}$ $g = \left\{1 - \frac{1}{(x_u/D)}\right\}\varepsilon_{cu}$, $C_s = \sum_{i=1}^{n}(f_{si} - f_{ci})A_{si}$ $M_s = \sum_{i=1}^{n}(f_{si} - f_{ci})A_{si}y_i$ $f_{ci} = \begin{cases} 0 & \varepsilon_{si} \leq 0 \\ f(\varepsilon) & \varepsilon_{si} > 0 \end{cases}$ $\varepsilon_{si} = \begin{cases} \left[\frac{x_u - D/2 + y_i}{x_u}\right]\varepsilon_{cu} x_u \leq D \\ \left[\frac{x_u - D/2 + y_i}{x_u - \left(1 - \frac{\varepsilon_{cc}}{\varepsilon_{cu}}\right)D}\right]\varepsilon_{cc} x_u > D \end{cases}$
$P_{uR} = C_c + C_s$ $M_{uR} = M_c + M_s$	

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Step-by-Step Calculation Procedure:

1. The coordinates of the 'Load-Moment interaction curve' that is P_{uR} (on the x-axis) and M_{uR} (on the y-axis) can be determined for any arbitrary neutral axis depth. To begin with, a trial value $x_u = 0.1D$ can be assumed.
2. Once x_u/D is fixed, find out whether it is greater than or less than 1 that is whether the neutral axis is located inside the column ($x_u \le D$) or outside the column ($x_u > D$).
3. Depending upon the location of the neutral axis the strain in i^{th} row of steel ε_{si} can be obtainable from the strain compatibility condition. From the Fig. 1 it can be easily observed (applying similar triangle).
4. Corresponding to the strain ε_{si}, the design stress f_{si} in the i^{th} row of steel can be obtainable from the design stress-strain curve for steel, ε_{si} and f_{si} are assumed to be positive if compressive, and negative if tensile.
5. The design compressive stress level f_{ci} in concrete, corresponding to the strain $\varepsilon_{ci} = \varepsilon_{si}$ adjoining the i^{th} row of steel, obtainable from the design stress-strain curve for concrete. As the tensile strength of the concrete is neglected in the design practice, thus f_{ci} is assumed as zero if the strain is tensile.
6. Now the expression for the resultant force in steel (C_s) as well as its moment (M_s) with respect to the centroidal axis of bending can be easily obtainable from the given equations.
7. The magnitude of the resultant force in concrete C_c and its line of action can be obtainable from the analysis of concrete stress block in compression, which depends on the location of the neutral axis. By means of simple integration, it is possible to derive expression for stress block area factor 'a' and centroidal distance of the stress block area '$\bar{x}$' measured from the highly compressed edge.
8. Now the expression for the resultant force in concrete C_c as well as its moment M_c with respect to the centroidal axis can be obtainable from the above mentioned equations.
9. The co-ordinates (M_{uR}, P_{uR}) for a fixed value of x_u/D (i.e., at a particular depth of neutral axis) can be find out applying the equilibrium conditions.
10. By incrementing x_u/D suitably (in steps of 0.02 or less), up to the point where M_{uR} is zero, the intermediate points of the interaction curve can be traced. This can be more conveniently done on a computer.

Note: For unconfined concrete $P_{uR} = P_{u0}$ *at* $M_{uR} = 0$.

B. Effect of Confinement

To investigate the effect of confinement on load-moment interaction curve of RC column, an analytical study is conducted on a column model with following data: a) unconfined concrete strength or characteristic strength of concrete: M60 b) cross section: D = 400mm, b = 400mm c) longitudinal reinforcement: 6, 25mm bars d) lateral reinforcement: diameter 10mm e) concrete cover 40mm f) spacing of lateral reinforcement: 100mm g) yield strength of lateral reinforcement f_{yl}= 250Mpa and h) yield strength of longitudinal reinforcement f_y= 415Mpa.

The design stress-strain diagrams are developed for confined concrete by considering different models and compared with the design stress-strain diagram for unconfined concrete as per the IS code (2000) and the same is presented in Fig. 2. By considering these design stress strain diagrams the load-moment interaction curves are developed both for confined and unconfined concrete, following the above mentioned steps. The Comparison between confined and unconfined Load-Moment interaction diagram of concrete column is presented in Fig.3.

It is observed that there is a considerable increase in column capacity due to the confinement produced by lateral reinforcement. The load moment interaction diagrams developed by considering Modified Kent Park, Mander et al. and Hong-Han model shows a considerable gain in column capacity is observed. Table IV shows the percentage increase in column capacity due to confinement effect for different confined models considered in this study, over the unconfined concrete column section.

TABLE IV
INCREASE IN COLUMN CAPACITY DUE TO CONFINEMENT EFFECT

Column section	Model	Maximum axial load(KN)	Percentage increase	Max. bending moment (KNm)	Percentage increase
Unconfined	IS code	5178	---	294	---
Confined concrete	Modified Kent park	6143.5	18.65	350.5	19.22
	Mander et al.	5894.2	13.83	337.5	14.8
	Hong-Han	6588.7	27.24	370.6	26.05

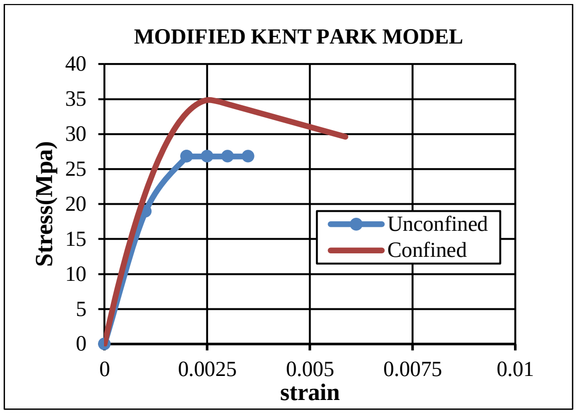

Fig. 2(a)

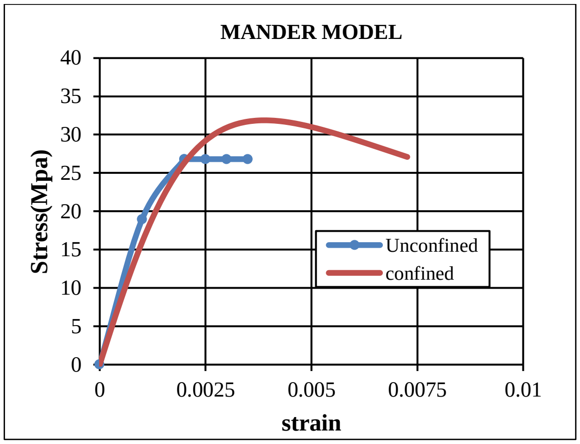

Fig. 2(b)

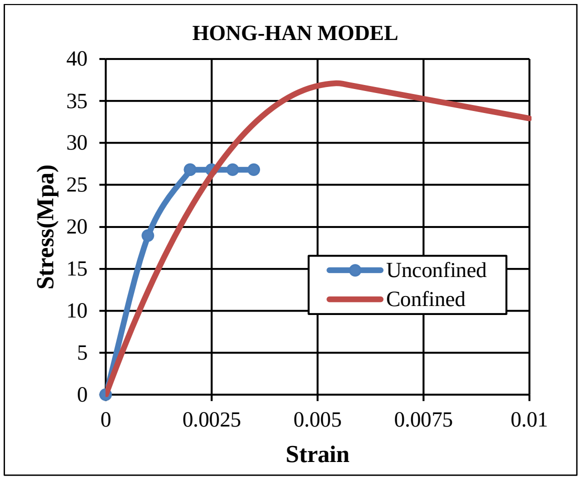

Fig. 2(c)

Fig. 2: Design stress-strain diagram for confined and unconfined concrete

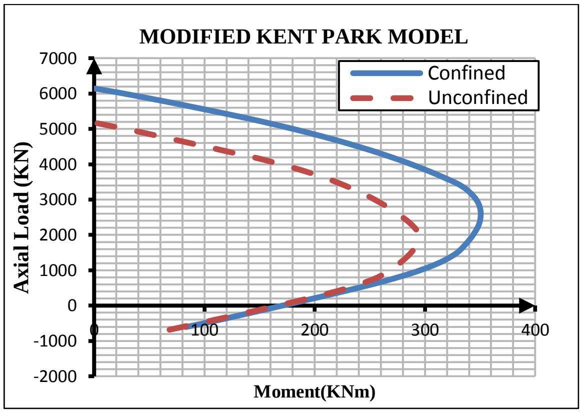

Fig. 3(a)

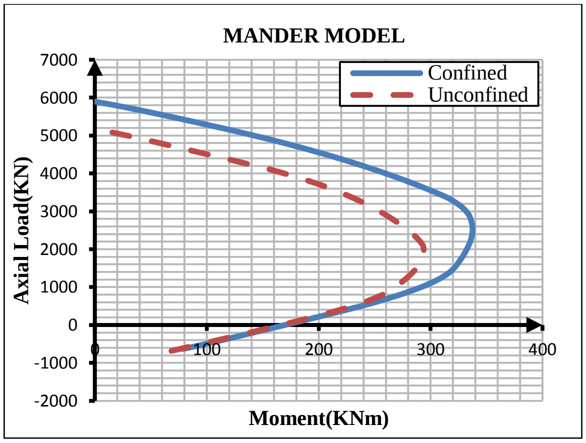

Fig. 3(b)

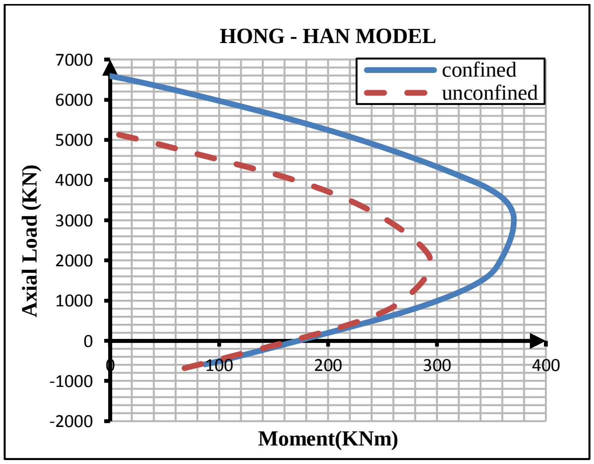

Fig. 3(c)

Fig.3: Comparison between confined and unconfined interaction diagram of concrete column

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IV. CONCLUSION

From the present investigation it can be concluded that the confinement produced by the lateral reinforcement only effect the compression controlled region of the RC column section. The load moment interaction diagram for confined concrete almost coincide with the unconfined concrete in the tension controlled region. Even though IS code ignore the effect of confinement on the strength gain due to the conservative consideration for the design purposes, with the capacity gain due to confinement effects shown in the analysis, it is expected that a reinforced concrete column could resist higher axial load and bending moment in the future design.

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NOTATIONS

f_{ck} = Compressive strength of unconfined concrete
f_c = Compressive strength of confined concrete
ε_c = longitudinal concrete strain
ε_{50u} = unconfined concrete strain when the stress reaches 50 percent of peak stress
ε_{co} = unconfined concrete strain at the peak stress
ρ_s = the volumetric ratio of lateral reinforcement to the confined concrete core measured outer to outer of lateral reinforcement
b'' = the width of confined concrete core measured outer to outer lateral reinforcement
s_h = spacing of lateral reinforcement (centre to centre)
f_{yh} = yield strength of lateral reinforcement
K = a multiplying factor
b_c = cross-sectional dimension of confined concrete core measured center-to-center of lateral reinforcement in the *x* direction
d_c = cross-sectional dimension of confined concrete core measured center-to-center of lateral reinforcement in the *y* direction
s = clear spacing of lateral reinforcement
W_i = i^{th} clear spacing from two adjacent longitudinal reinforcement
ρ_{cc} = ratio of cross-sectional area of longitudinal reinforcement to area of confined concrete core
E_c = modulus of elasticity of lateral reinforcement
f_{hcc} = stress of lateral reinforcement at peak stress of confined concrete
E_{des} = strength reduction factor
b = width of the rectangular column section
D = Overall depth of the rectangular column section in the plane of bending
C_c = resultant forces in concrete
C_s = resultant forces in steel
M_c = resultant moment due to C_c with respect to the centroidal axis
M_s = resultant moments due to C_s respectively with respect to the centroidal axis
x_u = neutral axis depth measured from highly compressed edge of the column
P_{uR} = design axial load corresponding to any arbitrary neutral axis depth
M_{uR} = design bending moment corresponding to any arbitrary neutral axis depth
ε_{si} = strain in i^{th} row of steel
y_i = distance of i^{th} row of the steel from the centroidal axis, measured positive in the direction towards the highly compressed edge and negative towards the least compressed edge
f_{si} = design stress in the i^{th} row of steel
ε_{ci} = strain in concrete level adjoining the i^{th} row of steel
f_{ci} = design compressive stress level in concrete adjoining the i^{th} row of steel
n' = total numbers of rows of steel
A_{si} = area of the steel in the i^{th} row of n' rows
a = stress block area factor
$\bar{x}$ = centroidal distance of the stress block area measured from the highly compressed edge
P_{u0} = Theoretical maximum axial compression (with eccentricity equal to zero)
A_g = gross area of cross section
A_{sc} = cross sectional area of the longitudinal reinforcement
ε_{cu} = maximum limiting compressive strain in concrete under flexure
ε_{cc} = maximum compressive strain in concrete under axial loading at limit state of collapse in compression
f_{cc} = ultimate/ maximum compressive stress in concrete
$f(\varepsilon)$ = the equation of design stress-strain curve of confined concrete as a function of strain ε
f_y = yield strength of longitudinal reinforcement
f_{yl} = yield strength of lateral reinforcement
$\emptyset$ = diameter of longitudinal reinforcement
$\emptyset_l$ = diameter of lateral reinforcement
n = no. of longitudinal reinforcement
d' = concrete cover