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SIMPLIFYING EUROCODE 8 DUCTILE DETAILING RULES FOR REINFORCED CONCRETE STRUCTURES

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Abstract

The use of ductile detailing for the seismic design of reinforced concrete (RC) structures is effective in increasing overall deformability of the structure through plastic hinge formation thereby resulting in a potentially well controlled failure mechanism in an extreme event. The prescriptive approach to seismic design typifying various international seismic design codes has become the norm in high seismicity regions. However, there can be reservations expressed by the engineering community practicing in a low to moderate seismicity region to abide by the rules, as was experienced by the authors when drafting the National Annex to Eurocode 8 for Malaysia where seismic design had never been mandated. This paper presents simplified models that were developed by the authors for the ductile design of RC to address the challenges. The model aims at simplicity and transparency (to demystify complex looking equations), taking Eurocode 8 Ductile Detailing Medium (DCM) as benchmark reference. Limiting dimensions of RC member, cover thickness, steel rebar diameter, concrete strength, steel strength and axial stress have been undertaken to identify limits of DCM compliance as presented in (six types of) graphs. Complex ductile detailing provisions are accordingly translated into simple design recommendations that are easy to comprehend and are pragmatic. The importance of carefully controlling the axial load ratio in RC columns and walls irrespective of their ductility category has been highlighted.

Keywords: ductile detailing, reinforced concrete structures, Eurocode 8, axial load ratio

1. Introduction

Various major international seismic design codes including EN 1998-1-1 [1], commonly referred as Eurocode 8 (EC8), adopts a prescriptive approach to ductile detailing as is the norm in high seismicity regions. In regions of low-to-moderate seismicity, where knowledge and experience in incorporating ductile detailing into the design of reinforced concrete (RC) structures is lacking, the strength based design approach (based on trading off strength with ductility) ought to be a viable alternative approach to adopt. Unfortunately, EC8 has mandated ductile design in certain regions depending on their seismicity classification [2]. For example, only structures that are located in areas where the value of design ground acceleration on rock (a_g, being product of a_{gR} with importance factor, γ_I), is lower than 0.08g or where $a_g S$ is lower than 0.10g (where S is the soil factor), may be designed to Ductility Class Low (DCL) requirements. In areas of higher seismicity structures would need to conform to Ductility Class Medium (DCM) or Ductility Class High (DCH) requirements. It is noted that DCH requirements are so onerous that there are issues in implementing the code stipulated requirements even in high seismicity regions. This paper presents a simple ductile design model which aims at simplicity and transparency to demystify complex rules, taking DCM in EC8 [1] as benchmark reference. Complex provisions are accordingly translated into simple design recommendations that are presented in the form of design charts and are easy to comprehend.

2. Background of EC8 DCM

Rules that are stipulated in Chapter 5 of EC8 [1] for the seismic design and detailing of RC buildings are founded on the concept of providing the structure with adequate capacity to dissipate energy without substantial loss in strengths both horizontally and vertically. In addition to dissipating energy within the elastic limit (which is dependable on strength), ductility is achieved through the formation of plastic hinges that are highly deformable thereby resulting in a potentially well controlled failure mechanism in an extreme event. There are a few textbook references which present worked examples to illustrate applications of DCM provisions [3, 4] but engaging engineers to abide by the stipulated rules remains to be a challenge. Explanations for the key terminologies, concepts and models are presented in below to facilitate discussion of DCM provisions in the later part of this article.

2.1 Curvature ductility factor (μ_ϕ)

Moment-curvature (M-ϕ) relationship is regularly used to characterize the ductility capacity of flexural RC members. Elementary theories of flexure is applicable within the elastic limit, and yield curvature (ϕ_y) is simply the reciprocal of the radius of curvature. In contrasts, plastic curvature (ϕ_p) of a RC member is defined by Eq. (1).

$$\phi_p = \theta_p / L_p \tag{1}$$

where θ_p denotes plastic hinge rotation and L_p is the plastic hinge length.

The ductility factor characterises the ability of an RC member to undergo deformation beyond yield. The curvature ductility factor (μ_u) is defined by Eq. (2).

$$\mu_\phi = \phi_u / \phi_y \tag{2}$$

where ϕ_u is total curvature (= $\phi_{y+}\phi_p$) and ϕ_y is yield curvature.

2.2 Behaviour factor (q_o)

In the conventional force-based approach, as stipulated in EC8 [1], for determining the seismic demands on the structure, the base shear demand is reduced by the behaviour factor (q_o) which can be expressed as product of overstrength and ductility. A minimum (default) value of 1.5 for q_o is stipulated for typical RC design to EN 1992-1-1 [5] which is commonly referred as EC2. A higher value of q_o which implies a higher reserve in the seismic resistance capacity of the building is specified depending on its structural classification [1]. In the deemed-to-satisfy provision of EC8 the required value of μ_u can be estimated for any given value of q_o using Eqs. (3a-3b).

$$\mu_\varphi = 2q_o - 1 \qquad \text{for } T_1 \geq T_C \tag{3a}$$

$$\mu_\varphi = 1 + 2(q_o - 1)\, T_C/T_1 \qquad \text{for } T_1 < T_C \tag{3a}$$

where T_C is the first corner period of the elastic response spectrum (i.e. upper limit of the constant acceleration region) and T_1 is the fundamental natural period of vibration of the building.

2.3 Rebar class

Only steel rebar of Class B or C (as categorized in Table C.1 of EC2 [5]) are permitted for use in a building which has been designed for seismic resistances, but EC8 [1] requires the curvature ductility factor to be at least 1.5 times the value calculated in Eqs. (3a-3b) should Class B rebars be used. Rebars that are commonly used in low-to-moderate seismicity regions are of Class B, having yield strengths of 400 MPa to 600 MPa, overstrength of 1.08 to 1.15 and characteristic strains (at ultimate force) of 5% to 7.5%.

2.4 The effective confinement area model

This section presents the (untold) rationale of the EC8 provisions for quantifying the confinement capacity of a RC cross-section involving use of Eq. (6) and Eq. (9) for the design of a RC column and the boundary elements of a RC shear wall, respectively. Details of the provisions can be found in the later part of the article. The effective area of confinement which is based on recommendations by Mander et al. [6] is best illustrated using Fig. 1. The cross section of a RC column which is confined by closed-loop stirrups is shown in Fig. 1(a). The confined concrete (coloured in red) has excluded areas that are enclosed by the parabolas (i.e. $2/3\ b_i \times b_i/4 = b_i^2/6$, where b_i is clear distance between consecutive longitudinal rebars constrained by the stirrups). The front and side elevations of the column showing the parabolas on the sides between two adjacent stirrups are presented in Fig. 4(b-c). The effective area of the cross section can be calculated using Eq. (4a). The second expression in Eq. (4a) is to refine the estimates by incorporating the geometric reduction ratio such as the effective width to total width ratio: $(b_o - s/2)/b_o$ or $(h_o - s/2)/h_o$.

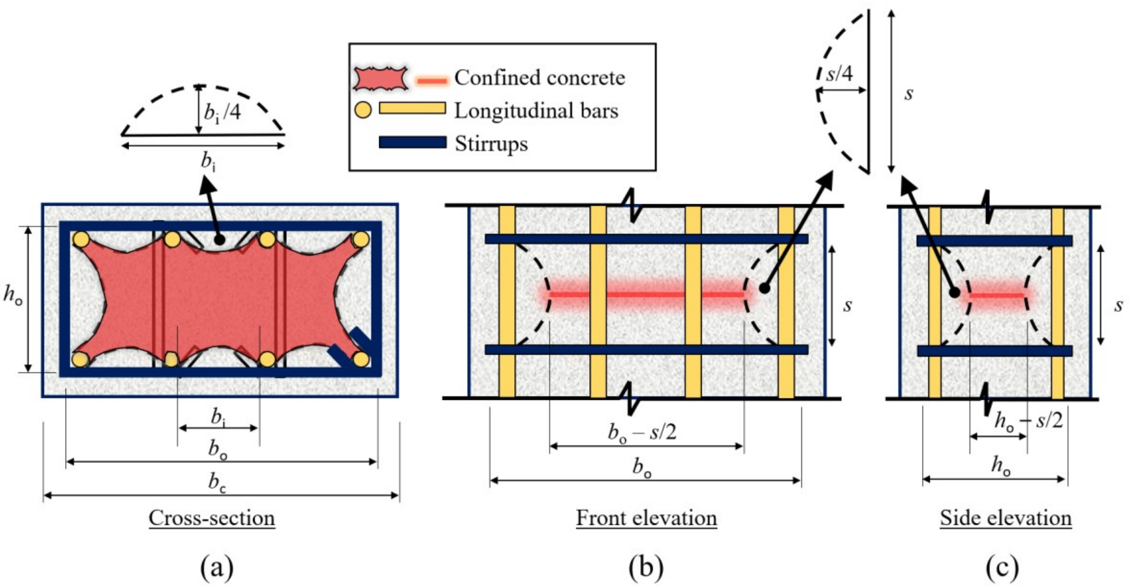

Fig. 1 – Confined concrete area for column and boundary element of shear wall

The α parameter as defined by Eq. (4b) is the effective area (A_{eff}) that has been normalised with respect to $b_o h_o$. The α parameter can be decoupled into two factors: α_n and α_s, where α_n refers to reduction of the cross-section of the column and α_s refers to the reduction as shown on the elevation.

$$A_{eff} = A_{eff,n} \times \text{(reduction in elevation)}$$
$$= [b_o\, h_o - \Sigma_i^n (b_i^2 / 6)]\, [(b_o - s/2)/b_o\, (h_o - s/2)/h_o] \quad (4a)$$

where s is hoop spacing, b_o and h_o are distances confined by the stirrups, and b_i has been defined.

$$\alpha = [1 - \Sigma_i^n (b_i^2 / 6)]\, [(1 - s/2\, b_o)\, (1 - s/2\, h_o)]$$
$$= \alpha_n\, \alpha_s \quad (4b)$$

where α_n is cross-sectional area reduction factor and α_s is elevational reduction factor.

3. Simplified design rules for DCM compliant RC frames

The structural types recommended for DCM compliant RC frames in this articles include frame systems (defined herein as frames which are to resist over 65% of the total base shear of the building) and frame-equivalent dual systems (defined herein as frames which are to resist 50 – 65 % of the total base shear of the building).

3.1 Minimum hoop distance for DCM compliant RC beams

EC8 [1] contains provisions for local ductility and this includes Eq. (5) for specifying the spacing of hoop (s) at the critical regions of a beam (i.e. at the plastic hinges).

$$s = \min\{h_w/4;\ 24\, d_{bw};\ 225;\ 8\, d_{bL}\} \quad (5)$$

where h_w is beam depth, d_{bw} is stirrups diameter and d_{bL} is longitudinal rebar diameter.

Stipulations by Eq. (5) can be presented graphically as shown in Fig. 2 in which the y-axis is hoop spacing (s) at the plastic hinge regions of the beam and x-axes are the controlling parameters. This figure will be used for deriving recommendations for DCM beam detailing, to be presented in the later section of this article.

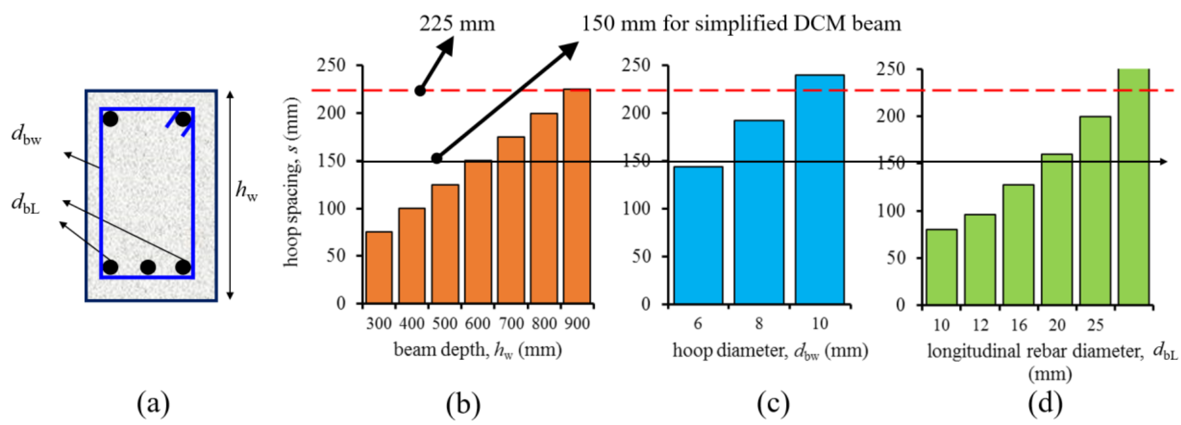

Fig. 2 – Hoop distance for DCM beam

3.2 Confinement capacity and demand for DCM compliant RC columns

The key requirements of EC8 [1] in the confinement design of the critical regions of a RC column is defined by Eq. (6).

$$\text{Confinement capacity, } C_c \geq \text{Confinement demand, } C_d$$
$$\alpha\, \omega_{wd} \geq (30\, \mu_\phi\, \nu_d\, \varepsilon_{sy,d}\, b_c/b_o) - 0.035 \tag{6}$$

where α has been explained in Section 2.4 with reference to recommendations by Ref.[6]; ω_{wd} is mechanical volumetric ratio of the confining hoops; μ_ϕ is curvature ductility ratio, ν_d is normalised design axial force ($N_{Ed}/A_c\, f_{cd}$, where N_{Ed} is design axial force including seismic action, A_c is cross-sectional area of RC column and f_{cd} is design concrete cylinder strength), $\varepsilon_{sy,d}$ is design tensile yield strain of the rebars, and b_c and b_o are as defined in Fig. 1.

3.3 Limiting dimensions of DCM compliant RC columns

The limiting dimensions in a RC column for DCM compliance are listed in Table 1. The lower and upper limits of the dimensions are defined by Eq. (7a) and Eq. (7b), respectively, showing the range of values for compliance. The lower limit ($b_{o,min}$) is obtained by subtracting the maximum cover ($cover_{max}$ = 60 mm) on both sides from the total width of the cross-section, based on the maximum possible hoop diameter ($d_{hoop,max}$) of 16 mm. The upper limit ($b_{o,max}$) is obtained by subtracting the minimum cover ($cover_{min}$ = 20 mm) on both sides from the total width of the cross-section based on the minimum possible hoop diameter ($d_{hoop,min}$) of 10 mm.

$$b_{o,min} = b_c - 2\, cover_{max} - d_{hoop,max} \tag{7a}$$

$$b_{o,max} = b_c - 2\, cover_{min} - d_{hoop,min} \tag{7b}$$

Table 1 – Limiting dimensions for RC columns and rectangular shear walls for DCM compliance

Element	**Column**																		
	Rectangular shear wall									**Not applicable for shear walls**									
b_c (mm)*	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
$b_{o,min}$ (mm)	60	160	260	360	460	560	660	760	860	960	1060	1160	1260	1360	1460	1560	1660	1760	1860
$b_{o,max}$ (mm)	154	254	354	454	554	654	754	854	954	1054	1154	1254	1354	1454	1554	1654	1754	1854	1954

*For column, b_c is the smaller dimension of the face; for shear wall, b_c is the thickness of the wall.

As for RC beams, EC8 [1] also contains provisions for controlling the hoop spacing (s) for RC columns at the critical regions, as defined by Eq. (8).

$$s = \min\{b_o/2;\, 175;\, 8\, d_{bL}\} \tag{8}$$

where the meaning of b_o and d_{bL} have been defined.

3.4 Design charts for determining the confinement demand (C_d) on DCM compliant RC columns

The confinement demand on RC columns can be presented in the form of design charts (Fig. 3) covering columns of different widths and normalised design axial force (e.g. 0.2, 0.4 to the maximum of 0.65) for ensuring DCM compliance. A higher design axial force requires a higher confinement demand. The four colour bands represent the lower and upper limits of the confinement demands for a range of curvature ductility factors (10.5, 15, 20 and 25), behaviour factors (q_o) and typical values of T_C.

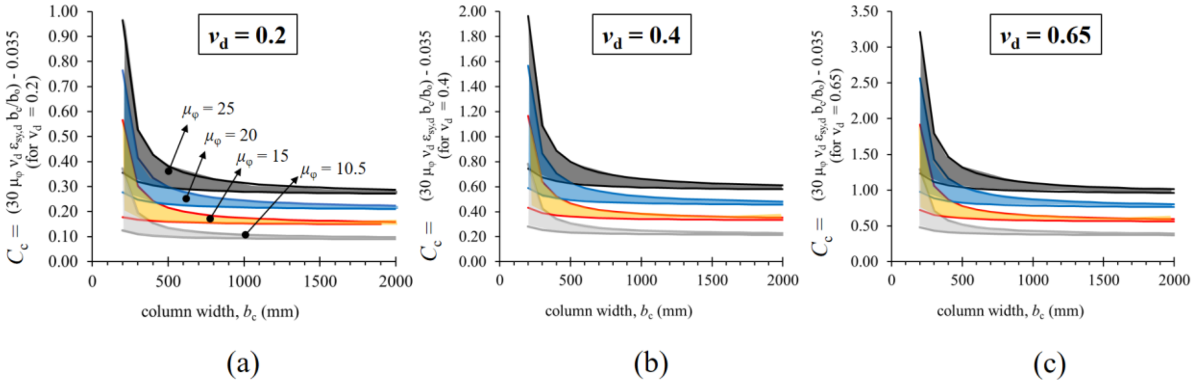

Fig. 3 – Design charts for confinement demand of DCM column
(for selected normalised design axial force with varying curvature ductility)

3.5 Design charts for α_n and α_s of DCM compliant RC columns

Likewise, estimates for the value of the α_n and α_s parameters that are within the calculated lower and upper limits can be shown for given column dimensions. For example, the range of values for α_n with adjacent clear longitudinal bar spacing (b_i) of 150 mm is shown in Fig. 4(a), whereas the same information for α_s is shown in Fig. 4(b). The aspect ratio of columns is restricted to four in accordance with stipulations found in EC2 [5]. The green band in both figures shows the lower and upper limits for square RC columns.

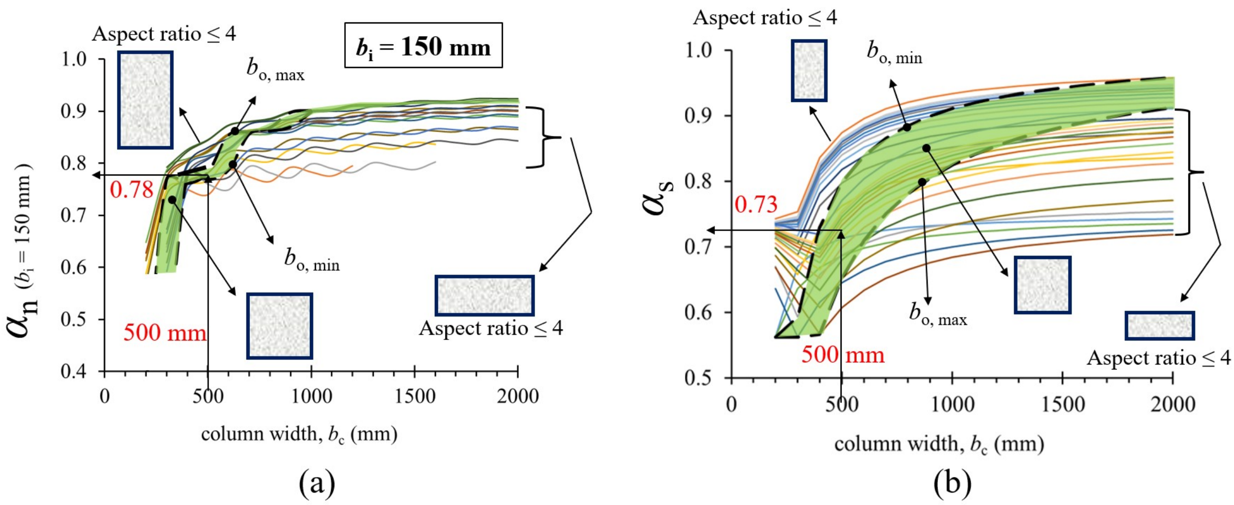

Fig. 4 – Design chart for α_n (with suggested b_i = 150 mm) and α_s for DCM compliant columns

3.6 Design charts for mechanical volumetric ratio (ω_{wd}) of DCM compliant RC columns

Finally, estimates for the value of the mechanical volumetric ratio (ω_{wd}) are shown in Fig. 5 for b_i of 150 mm and hoop diameter of 12 mm. The limits presented are for column dimensions listed in Table 1. The ratio of the design yield strength of rebar to the design cylinder strength of concrete is required for the calculation of the mechanical volumetric ratio. Two examples are presented for concrete strength of 50 MPa and 25 MPa in Figs. 5(a) and 5(b), respectively. The colour band in both figures shows the lower and upper limits for the mechanical volumetric ratio.

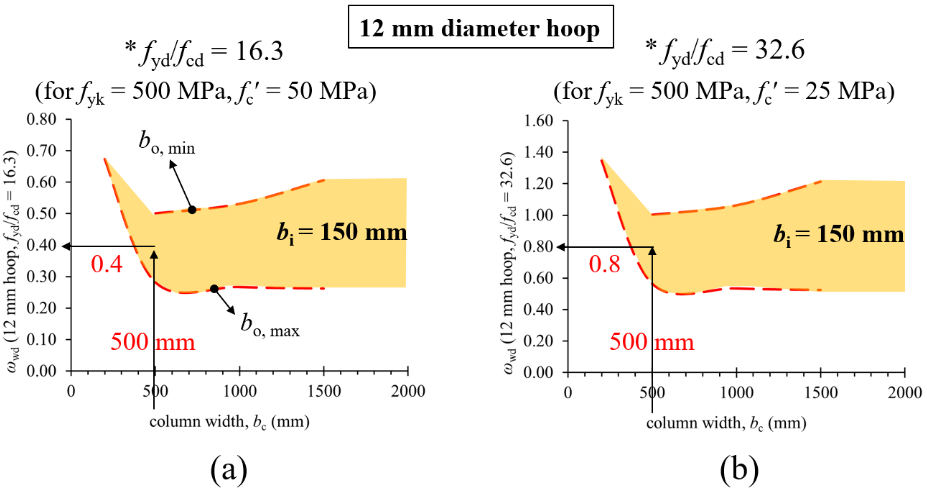

Fig. 5 – Design charts for mechanical volumetric ratio (ω_{wd}) of DCM column (with suggested b_i = 150 mm and hoop diameter of 12 mm)

4. Simplified design rules for DCM compliant RC rectangular shear walls

The structural types recommended for DCM compliant RC walls in this articles include wall systems (defined herein as walls which are to resist over 65% of the total base shear of the building), wall-equivalent dual systems (defined herein as walls which are to resist 50 – 65 % of the total base shear of the building) and coupled wall systems (walls with coupling beams to reduce base moment on the wall).

4.1 Confinement capacity and demand for DCM compliant RC shear walls

Eq. (9) stipulated for shear walls is analogous to Eq. (6) for columns. The confinement capacity for walls and columns of identical dimensions are the same but their confinement demands can be different. The mechanical ratio of the vertical web rebars (ω_v) has been incorporated.

$$\text{Confinement capacity, } C_c \geq \text{Confinement demand, } C_d$$
$$\alpha\,\omega_{wd} \geq [30\,\mu_\phi\,(\nu_d + \omega_v)\,\varepsilon_{sy,d}\,b_c/b_o) - 0.035 \tag{9}$$

4.2 Limiting dimensions of the boundary elements of shear walls

The limiting dimensions of rectangular shear walls of up to 1000 mm thick are also listed in Table 1. The hoop spacing requirement as defined by Eq. (8) is also applicable to shear walls. Only the boundary elements of the walls need be confined. The required length of the boundary element is defined by Eq. (10). It is noted that the boundary element length refers to the cross-sectional length and not up the wall height.

$$l_c = \max\{0.15\,l_w;\ 1.5\,b_w\} \tag{10}$$

where l_w is wall length and b_w is wall thickness.

4.3 Design charts for determining confinement demand (C_d) of DCM compliant RC shear walls

Design charts to facilitate determination of the confinement demand (C_d) of DCM compliant RC shear walls are shown in Fig. 6 for wall dimensions listed in Table 1. Two selected design axial forces are presented, i.e. 0.2 and 0.4. Shear walls are more commonly used in tall buildings; hence the fundamental period (T_1) of wall structure is typically higher than the first corner period (T_c) of the response spectrum. A curvature ductility factor for shear wall (with Class B rebars) of 7 is used as example. Compared to DCM column in Fig. 3, the colour bands in Fig. 6 refer to various typical mechanical ratios of vertical rebars that are located within the web of the shear wall.

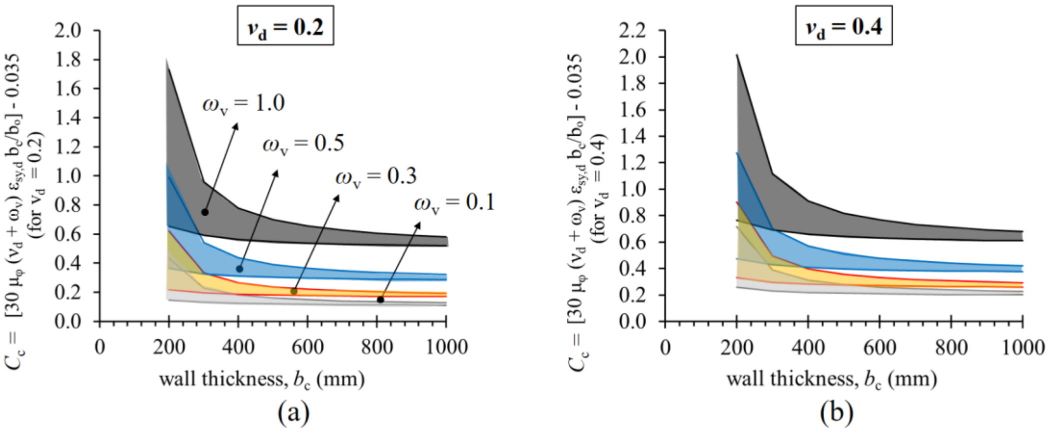

Fig. 6 – Design charts for confinement demand of DCM shear walls
(for selected axial load with varying mechanical ratio of vertical web rebars)

4.4 Design charts for α_n and α_s of DCM shear walls

Figs. 7(a) and 7(b) show the α_n and α_s parameters for shear walls. Compared to Fig. 4, the aspect ratio of boundary elements in a shear wall is required to be more than 1:1.5 in accordance to Eq. (10).

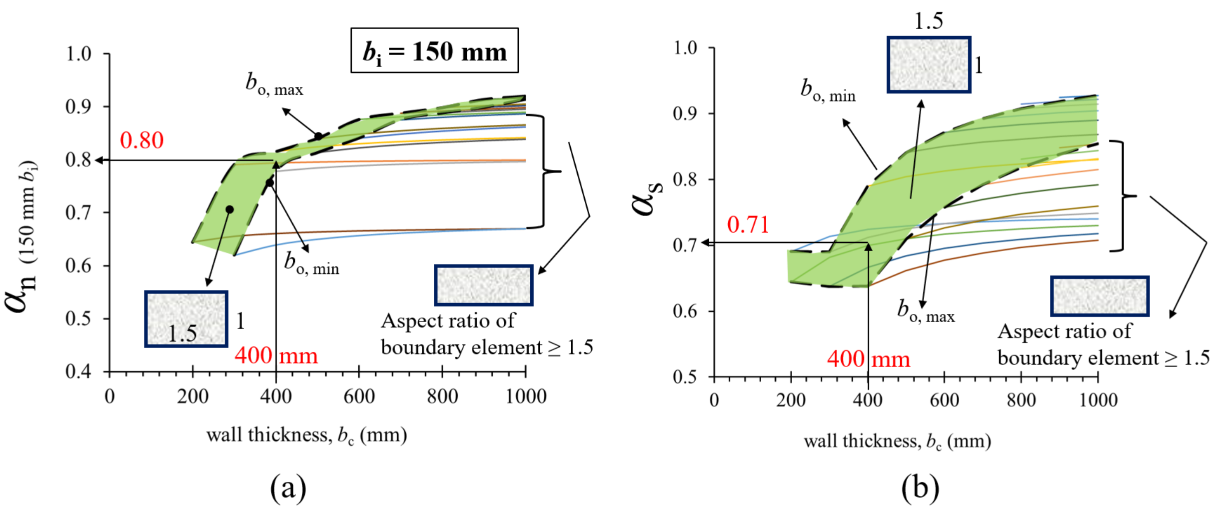

Fig. 7 – Design chart for α_n (with suggested b_i = 150 mm) and α_s of DCM shear wall

4.5 Design charts for mechanical volumetric ratio (ω_{wd}) of DCM shear walls

As for Fig. 5 for the design of DCM compliant RC columns, design charts for determining the mechanical volumetric ratio (ω_{wd}) of DCM compliant RC shear walls are presented in Fig. 8 for b_i of 150 mm and hoop diameter of 16 mm. Design strength of 50 MPa is assumed for the concrete given that shear walls are typically constructed with higher grade concrete.

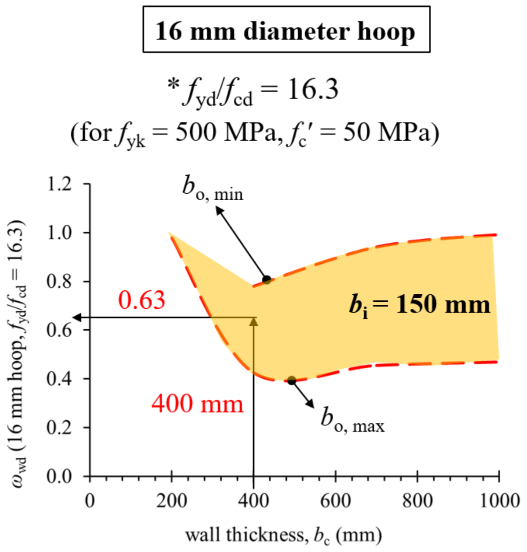

Fig. 8 – Design chart for mechanical volumetric ratio (ω_{wd}) of DCM shear wall (with suggested b_i = 150 mm and hoop diameter of 16 mm)

5. Recommendations

Simple deemed-to-comply design rules for DCM compliant RC frames and shear walls are presented in this section.

5.1 Simple design rules for DCM compliant RC beams

For DCM compliant RC beams, a 150 mm hoop spacing is recommended which is in alignment with current construction practices in low-to-moderate seismicity regions. The horizontal line labelled as "150 mm" in Fig. 2 shows a minimum beam depth of 600 mm, minimum stirrup diameter of 10 mm and minimum longitudinal rebar diameter of 20 mm.

5.2 Simple design rules for DCM compliant RC columns

For DCM compliant RC columns, minimum column dimensions of 500 mm x 500 mm are recommended in view of the trends presented in Figs. (3-5). The other recommendations are minimum hoop diameter of 12 mm with spacing of 150 mm, minimum longitudinal rebar diameter of 20 mm with spacing of 150 mm, and average α_n value of 0.78 (Fig. 4(a)) and α_s value of 0.73 (Fig. 4(b)).

A low-rise DCM compliant RC frame (featuring a low fundamental natural period) with concrete strength of 25 MPa and v_d of 0.2 implies a local curvature ductility factor of about 25 and an average confinement demand of 0.35 as shown in Fig. 3(a). Given that the average mechanical volumetric ratio is 0.8 as shown in Fig. 5(b) the confinement capacity is accordingly 0.78 x 0.73 x 0.8 = 0.45 which exceeds the estimated demand value of 0.35.

A medium-rise DCM compliant RC frame (featuring a higher fundamental natural period) with concrete strength of 25 MPa and v_d of 0.4 implies a local curvature ductility factor in the range: 15 - 20 and an average confinement demand of 0.50 as shown in Fig. 3(b). Although the predicted demand is exceeded slightly by the calculated capacity, the design can be fine tuned to address the minor shortfall.

5.3 Simple design rules for DCM compliant RC shear walls

With a DCM compliant RC shear wall, a limiting wall thickness of 400 mm is shown. Design recommendations are boundary element dimensions of 400 mm thick x 600 mm length, minimum hoop diameter of 16 mm with 150 mm spacings, minimum longitudinal rebar diameter of 20 mm with 150 mm spacing, average α_n value of 0.80 (Fig. 7(a)) and α_s value of 0.70 (Fig. 7(b)). A quick assessment by use of Fig. 8 shows that the average mechancial volumetric ratio is 0.63 which gives a confinement capacity of 0.80 x 0.70 x 0.63 = 0.35. With a 2% vertical rebar ratio, 500 MPa steel strength and 50 MPa concrete strength wall, the volumetric ratio of the vertical rebar at the web (ω_v) is equal to 0.3. Axial load is commonly high in shear wall (ν_d = 0.4) as shown in Fig. 6(b). Thus, the confinement demand is predicted to be 0.35 which is nicely met by the calculated confinement capacity. The 400 mm wall thickness as required by EC8 [1] for DCM compliance is understandably perceived to be costly. It is noted that a thinner wall may not be able to provide sufficient core thickness to achieve effective confinement [1, 6].

A summary of the design recommendations is listed in Table 2.

Table 2 – Summary of recommendation for simplified DCM

Elements	**Parameters**	**Recommended values**
Beam	Depth	600 mm
	Hoop diameter	10 mm
	Hoop spacing	150 mm
	Longitudinal rebar diameter	20 mm
Column	Size	500 mm x 500 mm
	Hoop diameter	12 mm
	Hoop spacing	150 mm
	Longitudinal rebar diameter	20 mm
	Longitudinal rebar spacing	150 mm
	α_n	0.78
	α_s	0.73
Shear wall	Thickness	400 mm
	Boundary length	600 mm
	Hoop diameter	16 mm (or bundled rebars)
	Hoop spacing	150 mm
	Longitudinal rebar diameter	20 mm
	Longitudinal rebar spacing	150 mm
	α_n	0.80
	α_s	0.70

6. Conclusion

EC8 has imposed what is widely perceived as strict and complex rules for RC detailing. Preparing a full fledge DCM based design calculations may seem to be a daunting task to many engineers, particularly those practising in low-to-moderate seismicity regions. This less than desirable situation has prompted the authors to develop simple deemed-to-comply rules for achieving DCM compliance for the seismic design of RC beams, colums and shear walls. Experimental research conducted in the past on RC columns [7, 8] and RC shear walls [9, 10] have identified the importance of controlling the amount of axial compression on RC members irrespective of the provisions of confinement for ductility.

7. Acknowledgements

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