TRANSVERSE REINFORCEMENT REQUIREMENTS FOR PRECAST LOAD BEARING WALL PANELS WITH LARGE OPENINGS

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ABSTRACT

Precast concrete load bearing walls panels have been used for decades with unparalleled success due to its architectural versatility, thermal insulation (if insulated), ease of production and erection, and structural performance. According to ACI 318, structural walls do not need transverse ties if vertical reinforcement ratio is less than 1% or where vertical reinforcement is not required as compression reinforcement. Also, minimum reinforcement requirements do not apply to structural walls with average effective prestress of 225 psi or greater. Elimination of transverse ties in structural precast walls simplifies the production of the panels. The presence of large openings in precast walls is very common in the design of modern buildings. This results in a significant reduction of panel cross section. Most designers tend to design the remaining portion of the panel cross section as a column not a wall, which requires minimum transverse ties according to ACI 318. The requirement complicates wall detailing and reduces efficiency and economy of panel fabrication. This paper summarizes the literature review conducted to determine when precast load bearing walls should be designed as columns/walls with respect to transverse reinforcement. The requirements of transverse reinforcement in walls and columns in various building codes were studied.

Keywords: Transverse reinforcement, Stirrups, Ties, Precast Walls Panels, Large Openings.

INTRODUCTION

Precast/prestressed concrete load bearing walls have been used for decades with unprecedented success due to its architectural versatility, thermal insulation (if insulated), ease of production and erection, and structural capacity and performance. Solid load bearing walls panels consist of one layer of concrete with no insulation, while sandwich load bearing walls panels consist of two concrete layers (wythes) separated by a layer of rigid foam insulation. The presence of large openings in wall panels is becoming a trend in the modern buildings architecture to obtain natural light and provide vehicular access when needed. Figure 1 shows examples of precast wall panels with large openings (e.g. storage and parking structures). This trend represents a challenge for the structural design and detailing of wall panels because large openings consume most of the panel cross sectional and eventually the remaining parts of the panel behave as columns. The openings are sometimes very wide, which results in a very small cross section for the remaining part of the wall. This "column-like" cross section must have enough capacity to resist dead loads, wind loads, and superimposed loads. The design and detailing of these sections is not clear especially with respect to transverse reinforcement requirements. These requirements complicate the walls detailing and reduce the efficiency and economy of panel fabrication without clear justification.

Figure 1: Precast walls with large openings: truck entrance (top); parking structure (bottom)

Thus this paper aims to answer the following two questions:

1. What are the criteria for classifying the remaining portions of a wall panel with large openings as a column rather than wall with respect to reinforcement requirements?
2. What are the recommended design and detailing of transverse reinforcement for the remaining portions of a wall panel with large openings?

In order to answer these two questions, the criteria adopted by different building codes to differentiate between walls and columns are reviewed. Also, the function of transverse reinforcement in compression members and the historical development of their code requirements are studied.

COMPARING BUILDING CODES/STANDARDS FOR WALL DEFINITION AND REINFORCEMENT

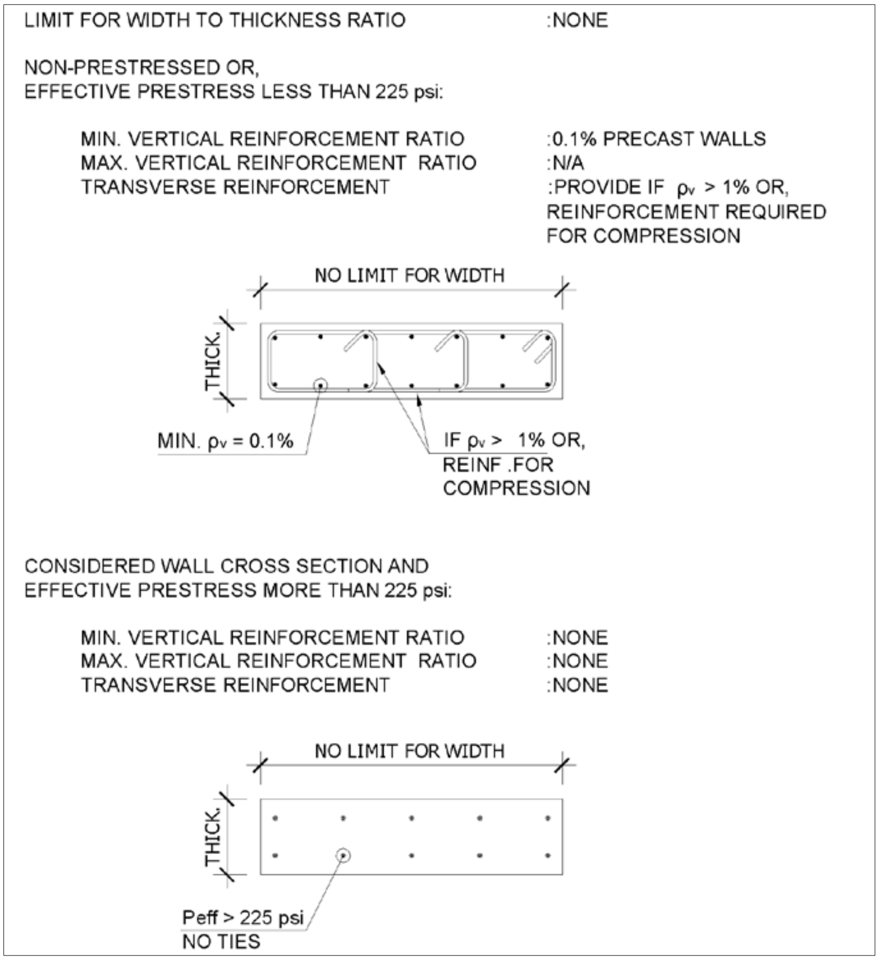
BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE AND COMMENTARY [ACI 318-11][1]:

The notations and definitions chapter of ACI 318-11 defines a "wall" as a member, usually vertical, used to enclose or separate spaces. While a wall always encloses or separates spaces, it may also be used to resist horizontal or vertical forces or bending. Meanwhile the same chapter defines a "column" as a "compression member" in which the primary stress is longitudinal compression. Such a member need not to be vertical but may have any orientation in space. Bearing walls, columns, pedestals, and walls piers qualify as compression members under this definition. The differentiation between columns and walls in the code is based on their principal use rather than the ratio between height and cross-sectional dimensions. The code, however, permits walls to be designed using the principles stated for column design (see section 14.4), as well as by the empirical method (see section 14.5).

The ACI 318-11 sets a minimum reinforcement ratio for the vertical and horizontal reinforcement in walls equals to 0.12% for cast-in-place walls reinforced with Grade 60 bars less than #5 (section 14.3.2). This limit is to eliminate early age shrinkage cracks generated by the inherent constraints of walls from being connected to other elements in structure. The minimum reinforcement ratio becomes 0.15% for cast-in-place walls reinforced with larger reinforcement or with welded wire reinforcement up to D31/W31. For precast walls were panels are free to move at early ages, the code sets a limit of 0.1% for vertical and horizontal reinforcement ratios (see section 16.4.2). The code waives the minimum reinforcement requirement for prestressed walls with average effective prestressing not less than 225 psi (see section 18.11.2.3). The ACI 318-11 code doesn't have a maximum reinforcement ratio for walls.

For both cast-in-place and precast walls, where vertical reinforcement ratio exceeds 1% or when bars are required as compression reinforcement, it is required by the code to provide "transverse reinforcement" (see section 14.3.6). However the code didn't provide quantitative estimate for the recommended transverse reinforcement. In the commentary section (R7.10.3), the code mentions the wall-like columns as one of the special designs, where it may be permitted to waive the transverse reinforcement requirements if tests and structural analysis show adequate strength and feasibility of construction.

Figure 2: Recommendations of ACI318-11



STANDARD SPECIFICATIONS FOR CONCRETE STRUCTURES – 2007 "DESIGN" GUIDELINE FOR CONCRETE NO. 15 [JSCE][2]:

The JSCE section 6.1 defines a wall as a planar member, whose width in the direction perpendicular to the principal axis of the member is much larger than its height or thickness. The commentary of section 6.5 defines the wall as a vertical plate with horizontal length not less than 4 times its thickness and it is used mainly to support vertical loads.

JSCE sets the minimum vertical reinforcement ratio to 0.4%. Meanwhile the reinforcement ratio should not exceed 4%. JSCE requires vertical reinforcement located at both sides of the

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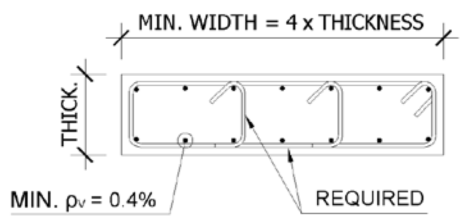
walls shall be tied to each other using tie bars, however there is no quantitative data on the recommended transverse reinforcement or its detailing.

Figure 3: Recommendations of JSCE

LIMIT FOR WIDTH TO THICKNESS RATIO	:> 4 TO 1
MIN. VERTICAL REINFORCEMENT RATIO	:0.4%
MAXIMUM VERTICAL REINFORCEMENT RATIO	:4%
TRANSVERSE REINFORCEMENT	:REQUIRED (NO DETAILS)



EUROCODE 2 DESIGN OF CONCRETE STRUCTURES [EUROCODE][3]:

Eurocode section 9.6.1 defines a wall as a reinforced concrete vertical member with a length to thickness ratio of 4 or more and in which the reinforcement is taken into account in the strength analysis. Also, in section 5.3.1, the Eurocode defines a column as a member for which the section depth does not exceed 4 times its width and the height is at least 3 times the section depth. Otherwise it should be considered as a wall.

Eurocode section 9.6.2 requires a minimum vertical reinforcement ratio in walls of 0.2%, while the maximum reinforcement ratio is 4%. Section 9.6.4 indicates that in cases where vertical reinforcement ratio exceeds 2%, ties similar to those used in columns should be used in walls. Meanwhile the Eurocode waives any requirements for ties in walls reinforced with welded wire mesh or bars less than 16 mm (#5) if concrete cover is larger than twice bar diameter.

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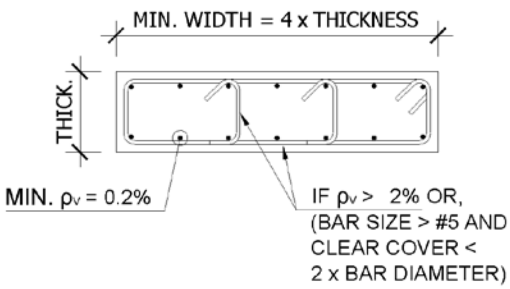
Figure 4: Recommendations of EUROCODE

LIMIT FOR WIDTH TO THICKNESS RATIO	:> 4 TO 1
MIN. VERTICAL REINFORCEMENT RATIO	:0.2%
MAXIMUM VERTICAL REINFORCEMENT RATIO	:4%
TRANSVERSE REINFORCEMENT	:PROVIDE IF $\rho_v > 2\%$ OR (BAR SIZE > #5 AND CLEAR COVER < 2 x BAR DIAMETER)

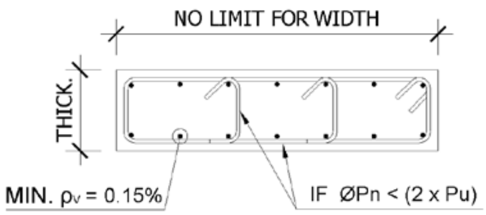


AUSTRALIAN STANDARD [AS 3600][4]:

The Australian standard does not provide a different definition for walls from columns. It sets a lower limit for vertical reinforcement ratio in walls of 0.15% without an upper limit. Different criteria are used to determine the need for transverse ties in walls based on the loading level not the reinforcement ratio. Section 11.6.4 states that for walls designed as columns in accordance with Section 10, the restraint provisions of Clause 10.7.3 do not apply if cross section ultimate capacity is larger than twice the applied ultimate load ($N_u \leq 0.5\ \phi\ N_n$), where section 10 is the column design and Clause 10.7.3 is the tie requirements for columns. This means that if walls are designed using column design provisions and the axial load is less than half the factored nominal capacity, column tie requirements do not apply.

Figure 5: Recommendation of AS 3600

LIMIT FOR WIDTH TO THICKNESS RATIO	:NONE
MIN. VERTICAL REINFORCEMENT RATIO	:0.15%
MAXIMUM VERTICAL REINFORCEMENT RATIO	:N/A
TRANSVERSE REINFORCEMENT	:PROVIDE IF ØPn < (2 x Pu)



SUMMARY

It is obvious that building codes and standards use different ways to differentiate between columns and walls based on various aspects. ACI 318-11 uses the spatial function of the element while the JSCE and Eurocode use the dimensions of the cross section. The Australian Standard is silent in this regards.

It is also clear that there is a wide range for vertical reinforcement ratios recommended by different codes. These ratios influence the need for transverse reinforcement. The ACI 318 requires transverse reinforcement only if the vertical reinforcement is effectively contributing to the strength of the cross section capacity, which is defined by a vertical reinforcement ratio of 1%. The ACI 318 code does not specify the type of transverse reinforcement required for walls. JSCE requires both layers of walls vertical reinforcement to be tied with no exception and no details on such tie reinforcement. Eurocode adopted a similar requirement but increased the limit to 2% compared to 1% of the ACI 318. The Australian Standards uses different criteria to judge on the need for transverse ties, if the applied axial load on the walls is more than half its nominal capacity then ties are required. The ties in this case should be similar to the column ties.

REVIEW OF THE ROLE OF TIES IN COLUMNS AND WALLS

The transverse reinforcement requirements presented earlier for columns and walls did not explicitly address the role of this type of reinforcement. In the following section, selected studies are discussed to explain the role of transverse reinforcement (i.e. ties) in column and wall design.

BRESLER ET AL. [1961][5]:

The stringent requirements for ties in ACI 318-56 were the incentive for Bresler et al. to study the buckling likelihood of longitudinal reinforcement. As stated by Bresler et al., it has been suggested by several investigation prior to Bresler et al.'s work that the main role of lateral ties is to restrain the longitudinal bars from buckling. These suggestions were not backed up by analytical formulation of the problem.

The longitudinal bars and restraining lateral ties were studied as a classical statics problem to find out the maximum spacing that allows the longitudinal bars to reach yield stress prior to buckling. Bresler et al. considered a buckling length equal to double the spacing between the ties. By equating the theoretical buckling stress to the material yield stress for the steel used and taking into account the inertia of the longitudinal bar (function of bar diameter) Bresler et al. concluded a dimensional limit of 17 for bars with yield stress equal to 43.6 ksi. This dimensional limit is equal to 14.5 for the typically used bars of 60 ksi, this limit reaches 11 for 100 ksi bars. It is worth mentioning that Bresler et al. used the tangent modules of elasticity of steel close to failure (10,000 ksi) which is nearly 1/3 of the commonly thought modules (29,000 ksi), this assumption was challenged by other researchers and found to be accurate.

The study by Bresler et al. addressed the required stiffness of lateral tie in order to provide the longitudinal bars with enough restrain to limit bucking. First and second buckling modes were considered. Modeling the lateral tie as a spring resulted in a first mode of buckling in a length equal to twice the tie spacing, and the second mode of buckling in a length equal to tie spacing. Using the principles of total potential energy for the system, Bresler et al. developed two expressions for the tie stiffness. The first expression is suitable for the corner bars and the other expression is suitable for the bars tied to a middle of tie. The critical scenario was the intermediate bar case where a much stiffer tie is required to restrain the bar. Bresler et al. proposed a limit on the ratio between spacing of ties to distance between tied bars to be 3. Applying the proposed limit, the equation by Bresler et al. became practical and the tie diameter to longitudinal bar diameter ratio became 1/3. A summary for dimensional limits proposed by the authors:

- Tie spacing = 17 x Longitudinal bar diameter
- Tie spacing = 3 x Distance between tied Longitudinal bar diameter
- Tie diameter = 1 / 3 x Longitudinal bar diameter

Bresler et al. carried out an experimental study to validate the hypothesis. Test results indicated that there is no significant effect for the internal ties on the axial capacity of the tested columns. The study also indicated that the lateral tie enables the concrete core to reach its maximum strain in addition to restraining the longitudinal bars from buckling subsequent to column concrete cover spalling. To prevent buckling of longitudinal bars the proposed dimensional limits should be used to provide a stiff tie and reasonable tie spacing.

PFISTER, J. F. [1964][6]:

Pfister study was initiated to aid the development of 1963 ACI 318 code, where eleven columns, 11 ft long each, were tested under concentric loading condition to capture the influence of tie arrangement and spacing on the strength and behavior of columns. Table 1 lists the cross sectional dimensions, longitudinal bars and ties arrangement of the tested columns. Table 1 also shows the ratio of the test load and the capacity calculated according to ACI 318-1963 code to indicate the effect of tie arrangement on the column capacity and mode of failure. Strain gauges attached to the reinforcing bars were used to calculate the load carried by the steel and concrete solely. Figure 3 shows the cross sections of each series of columns.

Table 1: Dimensions and reinforcement details of the tested columns

Column No.	Specimen details*	Ties arrangement**	P_{test} / P_{calc}	Failure mode
1A	**Series A** 12 x 12” Cross section 12#6 Longitudinal bars #2@12” Exterior ties	FH + interior ties	0.98	Gradual
2A		FH	0.99	
3A		MH	0.99	
4A		no ties	0.92	Sudden
1B	**Series B** 8 x 18” Cross section 12#6 Longitudinal bars #2@8” Exterior ties	FH + interior ties	1.00	Gradual
2B		FH	1.01	
3B		No ties	0.98	
1C	**Series C** 10 x 12” Cross section 6#8 Longitudinal bars #2@10” Exterior ties	FH + interior ties	1.00	Gradual
2C		FH	0.98	
3C		MH	0.93	Sudden
4C		no ties	0.94	Sudden

* All columns had steel bearing plate and 2 ties within 3” from the ends of test specimen

** FH: ties spaced along full height of specimen MH: ties at mid height section only

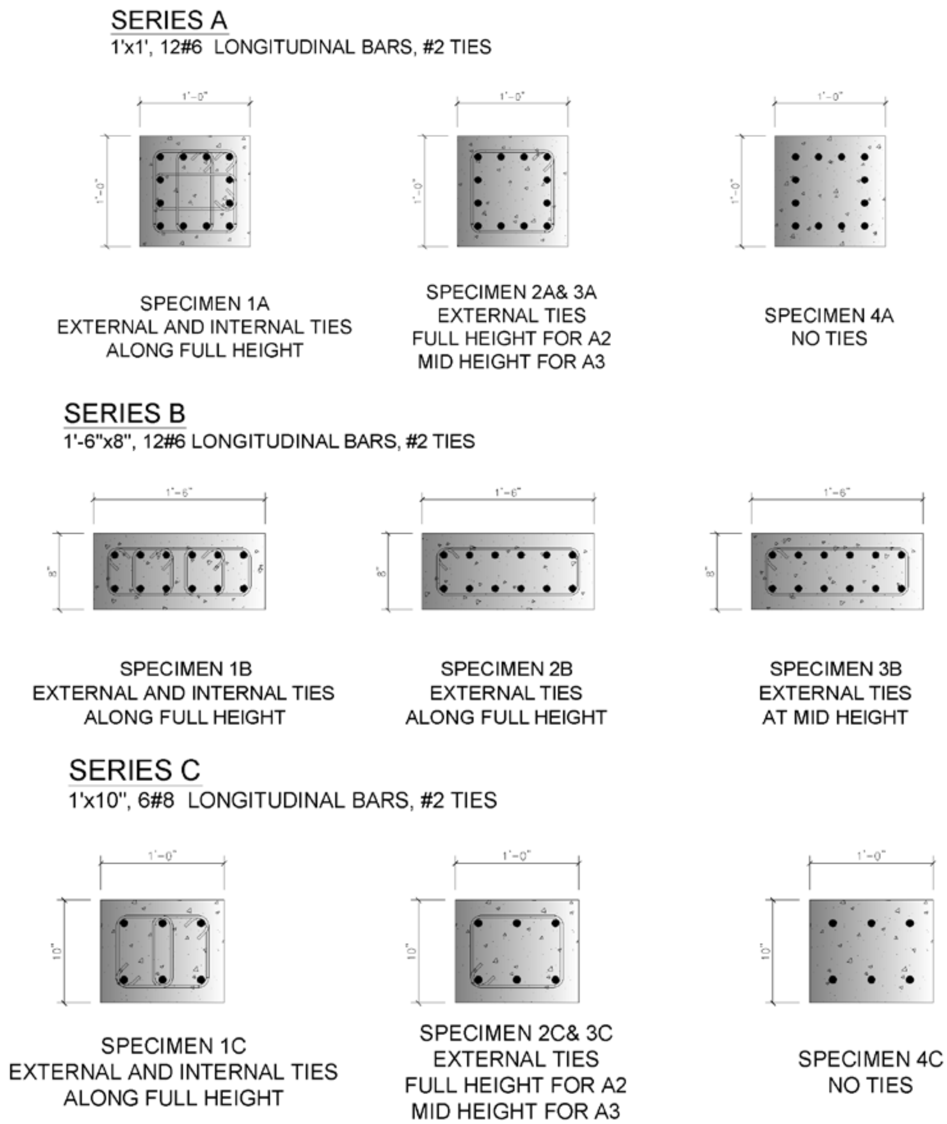


Figure 6: Cross Sections of Tested Column Specimens with Reinforcement Details

The results of testing Series A and C columns indicated that the lateral ties has a signficant role in preventing the bucking of longitudinal bars and confining the cocnrete core, which ensures gradual failure. If no ties were provided, a sudden failure occurs at a load that is 6%-8% less than the calculated load. Internal ties do not have a signficant impact on the strength or the ductility of the columns. The results of testing Series B columns indicated that column 3B that does not have any ties had almost the same capacity and behavior of fully tied column 1B or 2B. Neither was the concrete stress at ultimate strength in column 3B significantly less than that in columns 1B and 2B. This was attributed to elongated "wall-like" cross section of these columns. The longitudinal cracks tend to divide the concrete into narrow strips along the long face of the columns and quite deep into the concrete column parallel to the short faces. These strips are more likely to buckle about its weak direction (parallel to column short face), which results in more resistance to buckling.

HUDSON, F. M. [1966][7]:

Hudson tested 32 columns to investigate the effect of tie spacing on the ultimate strength of columns. Testing variables were the tie spacing, tie size and strength of concrete. The columns were 2'-8" tall and tested in concentric and eccentric loading setups. The test program used 4x4" cross section reinforced with 8#2 longitudinal bars. Concrete strength varied between 3,600 to 4,100 psi. Tie size was 13 gauge wires for the concentric load setup, and 12 gauge wires for the eccentric load setup. The adopted tie spacing was 4, 6, 8 and 31". In the 31" spacing specimen, ties were only used at the ends of the columns near loading head.

The average theoretical capacity is calculated for each group based on its average f'c and the loading conditions (concentric or eccentric) and then compared against the average test failure load. Test results show a 3% less capacity for the columns with ties at 31" spacing compared to that for the columns with closer tie spacing in concentric loading condition. For the eccentric loading condition the columns with 31" tie spacing had 11% less capacity than that with 6" tie spacing.

SUMMARY

Based on the presented literature, the main role of transverse ties is to prevent longitudinal bars from outward buckling after concrete cover spalling and to restrain the concrete core to reach it maximum usable strain. Testing different column sections has shown some effect (2 to 8%) for the external ties on the column load capacity and insignificant effect for the internal ties (<2%) on the column capacity. ACI 318 code agrees with this result in commentary section (R7.10.5). The external transverse ties have major effect on the failure mode and amount of strain available prior to failure (ductility). Internal transverse ties didn't show an effect on the ductility of the columns section prior to failure. Also, testing has shown less effect of transverse tie on cross section with high aspect ratio "walls-like section" than that in near square cross sections. Further analysis and testing need to be conducted to better explain this phenomena.

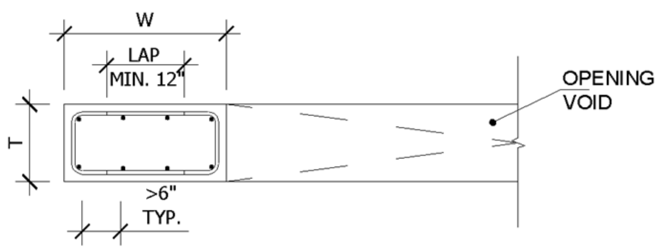
CONCLUSIONS AND RECOMMENDATIONS

Based on the information presented in this paper, the following conclusions and recommendations can be made:

- The use of the aspect ratio of 4 to differentiate between wall and column sections has been adopted by different codes and it is recommended to be used to guide the design of precast walls with large opening.
- Internal transverse ties do not have significant impact on either the capacity or ductility of columns with near-square sections and wall-like sections. These ties could be eliminated in precast walls with large openings without affecting their structural performance.
- External transverse ties have significant effect on the capacity and ductility of columns. This effect decreases as the rectangularity ratio increases. It is recommended that external transverse ties are used in precast wall with large openings except if the design load is less than half the nominal capacity of the section.
- In case external transverse ties are needed, the transverse tie provisions for columns can be adopted. Also, the use of overlapped U-shaped bars according to ACI 315-99 Detailing Manual [8] (see Fig. 14 "Special Wall-Like Column") is recommended to simplify wall fabrication.
- In prestressed wall sections (with effective prestressing in excess of 225 psi), transverse ties does not play significant role as the concrete reaches its maximum usable compression strain -0.003 while the prestressing reinforcement are still subject to tension stresses . Therefore, transverse ties could be eliminated.

Figure 7: Recommendation for Column-like cross sections

CRITERIA	DETAILS	CRITERIA	DETAILS
NON-PRESTRESSED W < (4 x T)	MIN. VERTICAL REINFORCEMENT AS PER COLUMNS LIMITS 1% (ACI318-11 10.9.1) USE EXTERNAL TIES ONLY TIE DIAMETER AS PER COLUMNS LIMITS (ACI318-11 7.10.5.1) TIE VERTICAL AS PER COLUMNS LIMITS (ACI318-11 7.10.5.2) LAP TIES MIN. 12" (ACI 315-99 FIG. 14)	PRESTRESSED W < (4 x T) EFFECTIVE PRESTRESSING > 225 psi	MIN. VERTICAL REINFORCEMENT AS PER (ACI318-11 14.8.2.4) USE EXTERNAL TIES ONLY TIE DIAMETER AS PER (ACI318-11 18.11.2.2- b THROUGH d) TIE VERTICAL AS PER (ACI318-11 18.11.2.2- b THROUGH d) LAP TIES MIN. 12" (ACI 315-99 FIG. 14)



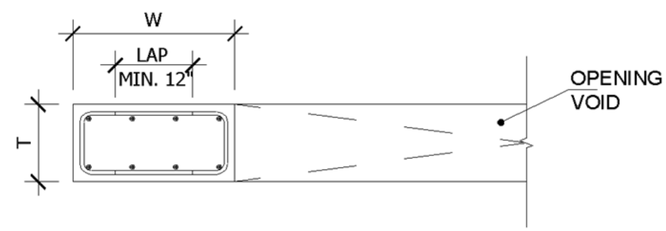
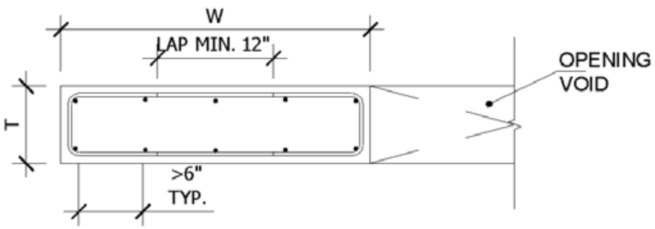


Figure 8: Recommendation for Wall-like cross sections

CRITERIA	DETAILS	CRITERIA	DETAILS
NON-PRESTRESSED W > (4 x T)	MIN. VERTICAL REINFORCEMENT AS PER PRECAST WALLS LIMITS 0.1% (ACI318-11 16.4.2) USE EXTERNAL TIES ONLY TIE DIAMETER AS PER COLUMNS LIMITS (ACI318-11 7.10.5.1) TIE VERTICAL AS PER COLUMNS LIMITS (ACI318-11 7.10.5.2) LAP TIES MIN. 12" (ACI 315-99 FIG. 14)	PRESTRESSED W > (4 x T) EFFECTIVE PRESTRESSING > 225 psi	MIN. VERTICAL REINFORCEMENT AS PER (ACI318-11 14.8.2.4) NO TIES (ACI318-11 18.11.2.3) PROVIDE HORIZONTAL REINFORCEMENT AS PER PRECAST WALLS LIMITS 0.1% (ACI318-11 16.4.2)



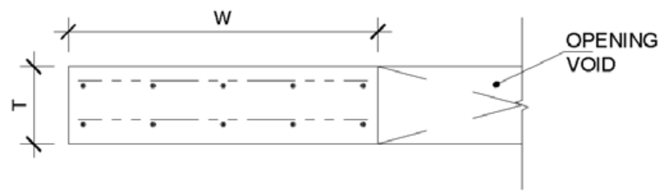
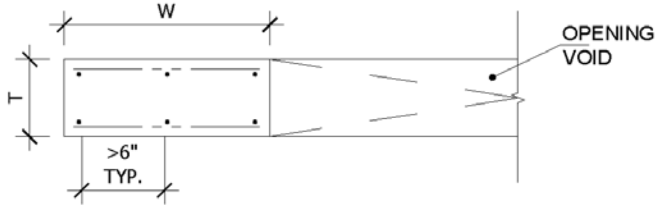
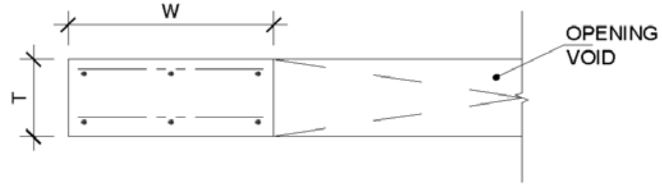


Figure 9: Recommendation for any cross sections with minimal loading

CRITERIA	DETAILS	CRITERIA	DETAILS
NON-PRESTRESSED NO LIMIT FOR W / T RATIO ØPn > (2 x Pu)	MIN. VERTICAL REINFORCEMENT AS PER PRECAST WALLS LIMITS 0.1% (ACI318-11 16.4.2) NO TIES PROVIDE HORIZONTAL REINFORCEMENT AS PER PRECAST WALLS LIMITS 0.1% (ACI318-11 16.4.2)	PRESTRESSED NO LIMIT FOR W / T RATIO ØPn > (2 x Pu)	MIN. VERTICAL REINFORCEMENT AS PER (ACI318-11 14.8.2.4) NO TIES PROVIDE HORIZONTAL REINFORCEMENT AS PER PRECAST WALLS LIMITS 0.1% (ACI318-11 16.4.2)





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