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The New Method in Calculating Columns and Beams Dimensions That Meets Requirements of The Strong Column - Weak Beam and Non - Soft Story

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Abstract. Situated at an earthquake prone area, buildings planning in Indonesia must implement earthquake resistant building principles. One of these principles is determining dimensions of columns and beams in the process of architectural designing.This act eventually affects the behaviour of the strong column - weak beam and the probability of bending failure due to soft story. At present time, there are no simple rules architects can use in calculating the dimensions of beams and columns that meet the criteria for strong column - weak beam and non - soft story. This paper is an effort to provide an input to the architects in designing the dimensions of the columns and beams. This research is a review result of three theories namely: 1). The theory of columns and beams preliminary design, 2). The theory of the strong column - weak beam concept, and 3). The theory of soft story and column slenderness. Those theories were then synthesized into a spreadsheet. To meet the criteria for strong column - weak beam and non - soft story, the following procedures must be done : 1). Determine the columns' dimensions according to 0.15% of the columns' cumulative tributary area, 2). Determine the beams' dimensions according to 1/12 of the beams' span and the beams' plastic modulus, 3). Determine the columns' dimensions and the columns'plastic modulus, 4). Determine the columns' height based on the column slenderness criteria, and 5). Compare the columns plastic modulus and the beams plastic modulus and check whether they meet the criteria "the columns'plastic modulus ≥ 1.2 * the beams' plastic modulus".
Keywords: strong column - weak beam, soft story, column slenderness

1. Introduction

Indonesia is an earthquake prone area, so buildings planning in this country must be in accordance with earthquake-resistant building principles. The planning process for earthquake resistant buildings should start from its architectural design process, and the determination the columns and beams dimensions should be the first step because this important step influences the behaviour of the strong column - weak beam and the probability of bending failure as a result of the soft story. Strong column - weak beam is a concept that describes a condition where plastic hinge occurs only in beams and not in columns when a strong earthquake happens, hence avoiding sudden collapse (BSN, 2013). On the other hand, soft story is a form of geometric irregularity of a building where one story has lower lateral stiffness than the other stories (Arnold, 2001).
At present there are no simple rules architects can apply in calculating the dimensions of the beams and columns to meet the criteria for strong column - weak beam and to avoid the soft story. This paper strives to provide input to architects in creating preliminary design of beams and columns dimensions that satisfies the principles of making earthquake resistant building.

The concept of a strong column - weak beam is that the calculation result of nominal moments of the upper and lower columns must be 1.2 times bigger than the sum of nominal

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moments of the left and right supporting beams (see figure 1.1). The purpose of this concept is to prevent the occurrence of the plastic hinge in the columns that serve as the main component of lateral load supports. Therefore, melting should only occur in the beams so that when there is very large inelastic deformation, no collapse happens.

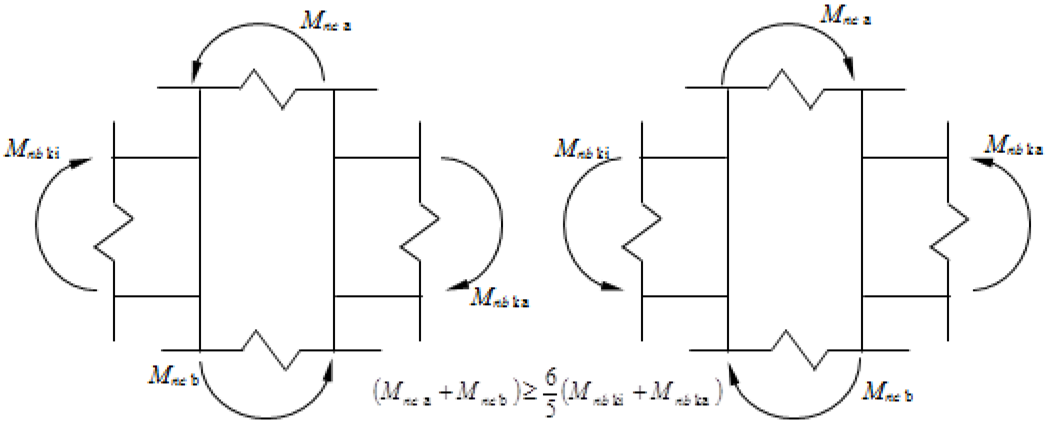


Figure 1.1. The concept of strong column - weak beam (source: BSN, 2013)

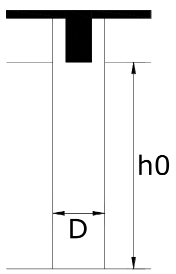
To simplify its application in the structure preliminary design, the following formula is used (Bisch et al., 2012) :

Wp of columns ≥ 1.2*Wp of beams (1)

In which,
Wp = plastic modulus (cm3 or m3)
Wp = 1/4xbxh2
b = the beams'/columns' width
h = the beams/columns' height

Soft story occurs if there is a story having lateral stiffness 70% (soft story) or 60% (excessive soft story) less than the lateral stiffness of the story above it (FEMA, 2007). Soft story is usually related to the height of the floor and the slenderness of the column. Soft story may occur if the height of a floor is higher than the height of other floors; in other words this floor is less stiff than the other floors (Arnold, 2001). To overcome this problem,the slenderness of the column must be limited (see table 1.1).

Tabel 1.1. The criteria for slenderness of columns (Sources : compiled from Seki 2015; Okada et al. 2005).

Types of Lateral Elements	Requirements	
Columns	The columns' net height/dimensions; h0/D	Definition h0/D
a). Slender	6≤h0/D	
b). Normal	2<h0/D<6	
c). Short	h0/D≤2	

In which,
h0 = the columns'net height
$h = h0 - h_b$
D = the reviewed columns' width
For columns, the minimum dimensions are based on the consideration of their shear strength (Ersoy, 2013) :

$$A_c \geq 0.0015 \sum A_o \quad (2)$$

$$b_c = h_c = \sqrt{A_c} \quad (3)$$

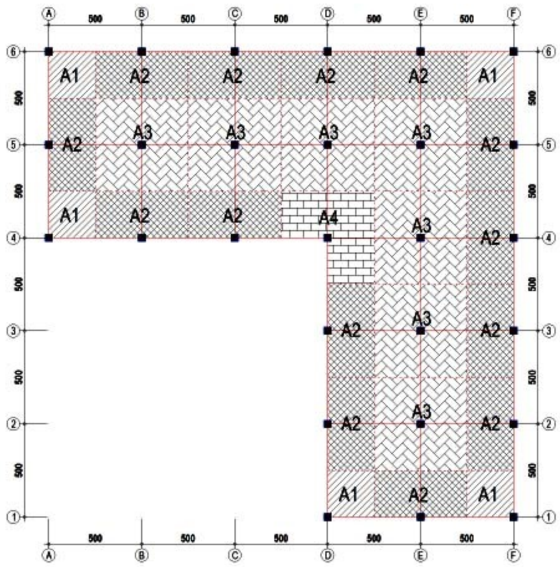
In which,
A_c = the columns' cross-sectional area
A_o = the columns' tributary area (see figure 1.2)
$\sum A_o$ = the columns' cumulative tributary area
$A_c \geq 0.09$ m2 (min 30x30 cm)
b_c = the columns' width
h_c = the columns' height

In general, the preliminary dimensions of one-way and two-way beams can be calculated with the following formula:

$$h_b = 1/10 - 1/14*L \quad (4)$$

$$b_b \geq ½*h_b \quad (5)$$

In which,
h_b = the beams' height
b_b = the beams' width (min $b_b \geq 25$ cm)
L = the beams' span



Ground Floor (0.00)

Figure 1.2. The columns' tributary area of A1, A2, A3 & A4

2. Methods

This research is the result of a literature review. The theories reviewed were : 1). The theory of columns and beams preliminary design, 2).The theory of the strong column - weak beam concept, and 3).The theory of soft story and column slenderness. These theories were then synthesized into a spreadsheet to be a new proposal for calculating dimensionsof columns and beams able to fulfil the requirements for the strong column - weak beam and non - soft story.

3. Result & Discussion

3.1. Calculate The Dimensions of The Beams and Columns

Table 3.1. Determining of the columns cross-sectional area

Floors	A_o (m^2)	$\sum A_o$ (m^2)	A_c (m^2)
1st	35	350	0.525
2nd	35	315	0.473
3rd	35	280	0.420
4th	35	245	0.368
5th	35	210	0.315
6th	35	175	0.263
7th	35	140	0.210
8th	35	105	0.158
9th	35	70	0.105
10th	35	35	0.053

It is assumed that a building consists of 10 floors with a 5x7 meters structure module, and we need to calculate the dimensions of the beams and columns that meet the criteria for the strong column - weak beam and non - soft story. To solve this problem, we need to do following steps:

- Step 1, see table 3.1 and determine the columns' tributary area (A_o) and the columns' cumulative tributary area ($\sum A_o$). Next, obtainthe columns' cross-sectional area (A_c) based on formula (2). For example, for the 1st floor (A_o) = 5 * 7 = 35 m^2, it is assumed that the typical column tributary area per floor ($\sum A_o$) = 35 * 10 = 350 m^2, next the columns' cross-sectional area of the 1st floor (A_c) = 0.15% * ∑Ao = 0.15% * 350 = 0.525 m^2.
- Step 2, see table 3.2. For the beams'span (Lx), determine the beams' height (h_b) based on formula (4) and the beams' width (b_b) based on formula (5). Then obtain the beams' plastic modulus (Wp_b) based on formula (1). For example, the 1st floor (Lx) = 7 m. Calculate the height and the width of the beams, h_b = 1/12 * Lx = 1/12 * 7 = 0.58 ≈ 0.6 m and b_b = 1/2 * h_b = 1/2 * 0.6 = 0.3 m. Calculate the plastic modulus of the beams (Wp_b) = 1/4 * b_b * h_b^2 = 1/4 * 0.3 * 0.6^2 = 0.0270 m^3.
- Step 3, see table 3.2. For the columns' cross-sectional area (A_c) obtained in step 1, determine the columns' dimension (b_c) based on the formula (3) and determine the columns'plastic modulus(Wp_c) based on the formula (1). For example, for the columns' cross-sectional area of the 1st floor (A_c) = 0.525 m^2 and their dimensions (b_c) = $\sqrt{A_c}$ = $\sqrt{0.525}$ = 0.72 ≈ 0.75 m. Calculate the their plastic modulus (Wp_c) = 1/4 * b_c * h_c^2 = 1/4 * 0.75 * 0.75^2 = 0.1055 m^3.

- Stage 4, see table 3.2. Limit the columns' maximum height to 5 m and the columns' minimum height to 3 m. Determine the maximum and minimum height of the columns based on the formula (b) table 1. For example, the maximum columns' height for 1st (h_{max}) = (6 * b_c) + h_b = (6 * 0.75) + 0.6 = 5.1 ≈ 5 m while the minimum columns' height (h_{min}) = (2 * b_c) + h_b = (2 * 0.75) + 0.6 = 2.1 ≈ 3 m.
- Stage 5, see table 3.2. Compare the columns' plastic modulus (W_{pc}) and the beams' plastic modulus (Wp_b) based on the formula (1). For example, for the 1st floor, Wp_c = 0.1055 m^3 and Wp_b = 0.0270 m^3, in which 0.1055 > 1.2 * 0.0270 = 0.0324 hence fulfilling Wp_c's requirements > 1.2xWp_b.

Table 3.2. Determining of the beams and columns dimensions on the x-axis

	Beams				Colums			Columns' height		Columns> beams
Floors	Lx (m)	h_b (m)	b_b (m)	Wp_b (m^3)	A_c (m^2)	b_c (m)	Wp_c (m^3)	h max (m)	h min (m)	Wp_c>1.2xWp_b
1st	7	0.60	0.30	0.0270	0.525	0.75	0.1055	5.00	3.00	Fulfil
2nd	7	0.60	0.30	0.0270	0.473	0.70	0.0858	4.80	3.00	Fulfil
3rd	7	0.60	0.30	0.0270	0.420	0.65	0.0687	4.50	3.00	Fulfil
4th	7	0.60	0.30	0.0270	0.368	0.60	0.0540	4.20	3.00	Fulfil
5th	7	0.60	0.30	0.0270	0.315	0.55	0.0416	3.90	3.00	Fulfil
6th	7	0.60	0.30	0.0270	0.263	0.50	0.0313	3.60	3.00	Does not fulfil
7th	7	0.60	0.30	0.0270	0.210	0.45	0.0228	3.30	3.00	Does not fulfil
8th	7	0.60	0.30	0.0270	0.158	0.40	0.0160	3.00	3.00	Does not fulfil
9th	7	0.60	0.30	0.0270	0.105	0.35	0.0107	2.70	3.00	Does not fulfil
10th	7	0.60	0.30	0.0270	0.053	0.25	0.0039	2.10	3.00	Does not fulfil

From stage 1 to stage 5, the overall results can be seen in table 3.2. From the 1st floor to the 10th floor, only the 1st floor until the 5th floor that meet the criteria for the strong column - weak beam. With the same span (Lx) = 7 m, the dimensions of the beams from the 1st to the 10th floors are same, namely b_b = 0.3 m and h_b = 0.6 m. The columns' dimensions (b_c) from1st floor until the 5th floor may vary according to the weight they support. The columns' dimensions can be determined based on the criteria for the strong column - weak beam and the columns' height. If it is based on the criteria of the strong column - weak beam and it is assumed that the height of the column for each floor (h) = 4 m, then only the 1st floor to the 4th floor that meet the criteria. Therefore, the dimensions of the columns can be simplified, for example, for the 1st floor to the 4th floor = 0.75x0.75 m and for the 5th floor until the 10th floor = 0.60x0.60 m.

Table 3.3. Determining of the beams and columns dimensions on the y-axis

	Beams				Columns			Columns' height		Columns> beams
Floors	Lx (m)	h_b (m)	b_b (m)	Wp_b (m^3)	A_c (m^2)	b_c (m)	Wp_c (m^3)	h max (m)	h min (m)	Wp_c>1.2*Wp_b
1st	5	0.45	0.25	0.0127	0.525	0.75	0.1055	4.95	3.00	Fulfil
2nd	5	0.45	0.25	0.0127	0.473	0.70	0.0858	4.65	3.00	Fulfil

Table 3.3. Continue...

3rd	5	0.45	0.25	0.0127	0.420	0.65	0.0687	4.35	3.00	Fulfil
4th	5	0.45	0.25	0.0127	0.368	0.60	0.0540	4.05	3.00	Fulfil
5th	5	0.45	0.25	0.0127	0.315	0.55	0.0416	3.75	3.00	Fulfil
6th	5	0.45	0.25	0.0127	0.263	0.50	0.0313	3.45	3.00	Fulfil
7th	5	0.45	0.25	0.0127	0.210	0.45	0.0228	3.15	3.00	Fulfil
8th	5	0.45	0.25	0.0127	0.158	0.40	0.0160	2.85	3.00	Does not fulfil
9th	5	0.45	0.25	0.0127	0.105	0.35	0.0107	2.55	3.00	Does not fulfil
10th	5	0.45	0.25	0.0127	0.053	0.25	0.0039	1.95	3.00	Does not fulfil

On the -y axis (table 3.3), only the 1st floor until the 7th floor meet the criteria for strong column - weak beam. With the same span (Ly) = 5 m, the dimensions of the beams of all floors are the same, namely b_b = 0.25 m and h_b = 0.45 m. The column dimensions (b_c) on the x-axis and y-axis that meet the criteria for the strong column - weak beam and column height vary, so the most critical part is chosen, namely the x-axis with the columns'dimensions of the 1st floor to the 4th floor = 0.75x0.75 m and of the 5th floor to the 10th floor = 0.60x0.60 m.

3.2. The Soft Story is One of The Most Dangerous Types of Building Irregularity

The aforementioned procedure of calculating columns and beams dimensions that fulfils the strong column - weak beam and non-soft requirements are expected to reduce the potential soft story because the soft story is one of the most dangerous types of building irregularity (Mezzi, 2006). Boen researches in Padang, Bengkulu and Yogyakarta (Boen, 2006, 2007a, 2007b) show that the most frequent and deadly structural failure due to large earthquakes is the soft story (see figure 3.1).

Figure 3.1. The Padang earthquake on September 30 & October 1, 2007: a). The Office of DPU Padang experienced soft story on the 1st floor but it was still survived, b). The 3 - story-shophouse experienced severe soft story at the 1st floor. This floor collapsed, and the 2nd & 3th floors fell on it, c). & d). Two commercial buildings experiencing severe soft story both at the 1st floor. The 1st floors collapsed, and the 2nd and 3rd floors fell on them (source: http://www.perencanaanstruktur.com/2010/10/bentuk-keruntuhan-bangunan-saat-gempa.html).

4. Conclusion

To make columns and beams dimensions meet the criteria for the strong column - weak beam and non - soft story, the following steps must be conducted:

- Determine the columns' dimensions based on 0.15% of the columns' cumulative tributary area.
- Determine beams' dimensions based on 1/12 of their span and beams' plastic modulus.
- Determine columns' dimensions and columns' plastic modulus.
- Determine columns' height based on the columns' slenderness criteria.
- Compare the plastic modulus of both columns and beams and find out whether the result satisfies the criteria "columns'plastic modulus ≥ 1.2 * the beams' plastic modulus".

With this new proposed way in calculating dimensions of the columns and beams, we can expect the number of sudden collapse due to the occurrence of plastic hinge and soft stories in the columns can be reduced.

Glossary :

- Column / beam plastic modulus : used for materials where elastic yielding is acceptable and plastic behavior is assumed to be an acceptable limit.
- Plastic hinge : a yielding zone in an structural elements which generally develops at the point of maximum bending moment, support, etc.
- Slender column : if its cross-sectional dimensions are small compared with its length.
- Soft story : if there is a story having lateral stiffness 70% (soft story) or 60% (excessive soft story) less than the lateral stiffness of the story above it.
- Strong column - weak beam : a concept that describes a condition where plastic hinge occurs only in beams and not in columns when a strong earthquake happens, hence avoiding sudden collapse.

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