Assessment of Seismic Deficiency of Existing Reinforced Concrete Buildings in Bangkok

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Abstract

This paper presents a result of assessment of seismic deficiency of buildings in Bangkok. The target buildings are mid-rise reinforced concrete beam-column frames having 5-15 stories. The occupancy type is essential and assembly facilities including schools, university, governmental offices and apartments. Many of these buildings with more than 6 stories are usually provided with reinforced concrete lift core. The seismic evaluation methodology consists of demand to capacity ratio determination (DCR), reinforcement detailing check and failure mode investigation. Eight buildings are examined. The seismic deficiency is checked against earthquake loading specified in No.49 Ministerial Law [1] and the ACI [2] requirements for Intermediate Moment Resisting Frame. The region of interest is the first floor sub-frame where the lateral shear is supposed to be highest. The moment frames in both transverse and longitudinal directions are considered. The result shows that all eight buildings do not satisfy reinforcement detailing criteria. Five out of eight buildings do not satisfy DCR criteria. Based on the failure mode investigation, the result shows 44% of beam flexural failure, 41% of joint shear failure and 15% of beam shear failure. It is seen that shear failure covers 66% of the total. The majority of failure is found in beams. The reason why the DCR criteria is not critical is due to traditional working stress design approach for RC structures in Thailand with lower allowable compressive strength of concrete and steel compared to more modern ultimate strength design codes. Another reason is the presence of lift core that reduces the forces transmitted to beam-column frame.

1. Introduction

Although Bangkok, the capital city of Thailand is not directly located on fault, it is not safe from distant earthquakes. On 26th December 2004, the Sumatra earthquake of 9.3 magnitude on Richter scale has caused a devastating Tsunami and hit the coast of Thailand with more than 5,000 lost of lives. In that event, though approximately 800 km away from Bangkok, many high rises in Bangkok were severely shaken. This caused a widespread public concern on the safety of building in seismic events.

Bangkok is vulnerable to earthquake because the city is founded on soft marine clay which can amplify earthquake up to three to four times [3]. Moreover, almost all buildings in Bangkok have not been traditionally designed against seismic loading. In order to mitigate the possible seismic hazard, buildings should be evaluated for seismic rating and necessary preparedness is required, especially public buildings such as academic buildings, apartment buildings, governmental buildings and hospital should be able to withstand earthquake as they are supposed to provide post earthquake rescue operation.

A study on seismic evaluation of RC buildings in Bangkok is presented in this paper. In this study, existing reinforced concrete buildings constructed as beam-column frames are investigated to identify the typical characteristics of building designed for gravity load only, especially the reinforcement detailing. This study focuses on reinforced concrete frames having 5-15 stories. According

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to past studies, the buildings of this range will have a natural period around 1.0 second which corresponds to the peak acceleration response curve. For the buildings of this height, the fundamental vibration is supposed to play a dominant role. Hence the first floor is supposed to be critical under earthquakes. Thus, the research conducted herein emphasizes the first floor sub-frame in both transverse and longitudinal directions of the buildings.

In this study, a practical method to investigate seismic performance of the building is proposed. It aims to provide a guidance for practicing engineers to evaluate the seismic performance of the buildings. The method requires building geometry, cross sectional dimension, reinforcement details, material properties as input to construct the computer model of the buildings. The linear static analysis is employed to obtain shear force and bending moment at critical sections or members. The Demand Capacity Ratio (DCR) is then calculated. The capacity can be based on any structural design code. In this paper, the ACI318 [2] requirement for Intermediate Moment Resisting Frames is adopted as most Thai engineers are familiar with the American code. The proposed evaluation methodology consists of DCR determination, reinforcement detailing check and failure mode investigation.

2. Data collection of existing buildings.

The architectural and structural drawings of 8 existing buildings constructed in Bangkok are collected. These buildings are listed in Table 1. As seen, the buildings have the number of stories ranging from 5-15 stories. They are constructed as beam-column rigid frame. The buildings are generally classified as essential and public facilities that cover apartments, schools, universities and governmental offices. In most buildings, the floor system consists of precast solid plank (PC plank) or precast hollowcore slab which is topped by cast-in-place concrete. Almost all buildings are provided with lift core for vertical transportation.

Table 1 General data of investigated buildings.

No.	Occupancy type of Building	No. of story	Total height (m)	Dimension W x L (m^2)	Type of Slab	Lift Core
1	Apartment (AP1)	6	17.20	11x17.85	PC plank	none
2	Apartment (AP2)	9	22.90	13.2x29.2	PC plank	2x2m
3	Apartment (AP3)	15	40.00	21x30.8	PC plank	4.2x2.15m
4	Academic (AC1)	5	29.80	18.6x40.5	Cast in place	2.55x2.9m
5	Academic (AC2)	6	26.00	18.8x58.5	PC hollowcore	2.4x4.0m
6	Academic (AC3)	6	27.50	16.5x77.0	PC hollowcore	2.5x4.3m
7	City hall (CH1)	5	25.34	24.0x77.0	PC hollowcore	2.8x5.0m
8	City hall (CH2)	5	24.35	23.0x77.0	PC hollowcore	2.8x5.0m

3. Structural indices

Structural indices are defined as parameters that indicate the behavior of beam, column and joint under seismic action. Structural indices of buildings are calculated from design configurations such as sectional dimensions, area of longitudinal and transverse reinforcing bars, strength of concrete and reinforcement steel, and others.

The prominent structural indices that are used to predict the expected failure modes are as follows.

3.1 Nominal moment capacity to nominal shear capacity ratio, $\frac{M_n}{a \cdot V_n}$

In this index, a is the length measured along the column or beam axis from the joint face to inflection point, M_n and V_n are nominal moment and nominal shear capacity of reinforced concrete section, respectively. This index indicates a possibility of shear failure in the member before yielding. In the calculation of this index, it is assumed that the inflection point is located at the mid-length of column or beam.

3.2 Join shear force over joint shear capacity ratio, V_j / V_{jn}

In this index, V_j [4] is the joint shear force and V_{jn} [5] is the joint shear capacity. The index indicates the possibility of joint shear failure.

3.3 Column to beam moment capacity, M_{nc}/M_{nb}.

In this index, M_{nc} is nominal moment capacity of column and M_{nb} is nominal moment capacity of beam. This index indicates the possibility of plastic hinge forming in column. The summary of overall structural indices in each direction is shown in Table 2, 3 and 4.

Table 2 Average of structural indices for column

Direction	a_c/h_c	$\frac{M_n}{aV_n}$	$\frac{P}{f_c' A_g}$	ρ_t	$\rho_s\sqrt{\frac{b''}{S}}$	$\frac{V_a}{b_w d\sqrt{f_c'}}$ [5]	Expected mode of failure
Transverse Interior	3.60	0.44	0.335	0.050	0.0065	3.72	Flexural failure
Transverse Exterior	3.49	0.60	0.306	0.053	0.0067	4.69	Flexural failure
Longitudinal Interior	5.11	0.29	0.267	0.043	0.0082	2.18	Flexural failure
Longitudinal Exterior	5.11	0.27	0.208	0.037	0.0074	1.84	Flexural failure

Table 3 Average of structural indices for beam

Direction	a_b/h_b	$\frac{M_n}{aV_n}$	ρ	ρ'	$\rho_s\sqrt{\frac{b''}{S}}$	$\frac{V_a}{b_w d\sqrt{f_c'}}$ [5]	Expected mode of failure
Transverse Interior	4.34	0.76	0.010	0.012	0.0039	2.06	Flexural failure
Transverse Exterior	3.61	0.72	0.010	0.012	0.0038	2.00	Flexural failure
Longitudinal Interior	4.34	0.47	0.009	0.011	0.0038	1.45	Flexural failure
Longitudinal Exterior	4.58	0.53	0.012	0.012	0.0042	1.80	Flexural failure

Note: a_c/h_c and a_b/h_b are column and beam shear span ratio; $P/(f_c'A_g)$ is column axial force ratio; ρ_t is longitudinal column reinforcing index; ρ and ρ' are bottom and top longitudinal beam reinforcing index; $\rho_s\sqrt{b''/s}$ is transverse steel index and $V_a/b_w d\sqrt{f_c'}$ is normalized associated shear force index (V_a is associated shear force is dependent on a mode of failure. If member is expected to fail in flexural mode $V_a = M_n / a$ or fail in shear mode $V_a = V_n$ from ATC40 [5])

Table 4 Average of structural indices for joint

Direction	*BI*	$\frac{h_c}{d_b}$	$\frac{b_b}{b_c}$	$\frac{h_b}{h_c}$	$\frac{M_{nc}}{M_{nb}}$	$\frac{V_j}{V_{jn}}$	ρ_s	Expected mode of failure
Transverse Interior	5.15	22.48	0.73	1.27	1.94	1.11	0.00	Joint shear
Transverse Exterior	5.24	23.92	0.74	1.24	7.15	0.65	0.00	Flexural beam
Longitudinal Interior	5.37	21.69	0.47	1.50	3.47	1.31	0.00	Joint shear
Longitudinal Exterior	6.06	19.13	0.46	1.55	4.50	0.74	0.00	Flexural beam

Note: $BI = \frac{f_y d_b}{2h_c\sqrt{f'_c}}$ *is bond index;* h_c/d_b *is column depth-to-bar diameter ratio;* b_b/b_c *is beam with-to-column width ratio;* h_b/h_c *is beam depth-to-column depth ratio;* M_{nc}/M_{nb} *is column flexural capacity-to-beam flexural capacity ratio;* V_j/V_{jn} *is joint shear force over joint shear capacity ratio;* ρ_s *is joint reinforcement ratio*

4. Seismic evaluation methodology

The seismic evaluation methodology adopted in this study consists of Demand Capacity Ratio (DCR) determination, reinforcement detailing check, and failure mode investigation.

4.1 DCR determination

To determine Demand Capacity Ratio (DCR), the structure is analyzed by linear static procedure under the equivalent lateral static load specified by No. 49 Ministerial Law [1], which is based on UBC 1985 [6]. The load combination considered is U1 = 0.75(1.4DL+1.7LL±1.87E), where DL is dead weight, LL is live load and E is earthquake load. At critical sections of beam, column and joint, demand is obtained in terms of shear force and bending moment. Corresponding capacities are calculated based on ACI318 [2] structural concrete design code. The member is said to fail if DCR is larger than 1.0. In the analysis, the emphasis is placed on the first floor sub-frame as it is assumed that buildings of less than 10 floors are governed by the fundamental mode of vibration where the forces shall be highest at the column of the first floor. As a majority of buildings are constructed using precast floor slab system, the structure will therefore be stronger in the direction transverse to the span of slab, and weaker in the other direction. Hence, the structure is analyzed for both transverse and longitudinal direction. The DCR considered in this research consists of

$\frac{M_{ub}}{M_{nb}}$ DCR for moment in beam

$\frac{V_{ub}}{V_{nb}}$ DCR for shear in beam

$\frac{V_{ju}}{V_{jn}}$ DCR for shear in joint.

$\frac{V_{uc}}{V_{nc}}$ DCR for shear in column

$\frac{M_{uc}}{M_{nc}}$ DCR for moment in column

The meaning of subscribe *u* is based on No.49 Ministerial Law [1] demand, subscribe *n* is capacity of each member and subscribe *c*, *b* and *j* are location of members, column, beam and joint, respectively.

The results of DCR comparison are shown in Fig.1 to 5. Summary of DCR check is shown in table5.

DCR for moment in beam (Fig.1) shows that almost beam sections pass this criterion in transverse direction. In longitudinal direction, there are a few sections that do not pass the criterion. This is because of the slab system using precast concrete slab spanning in the longitudinal direction of building, thus making the beam much stronger in transverse than in longitudinal direction. DCR for shear in beam (Fig.2) show that some sections of buildings AP3, AC3 and CH2 do not pass this criterion because of the same reason as for moment.

As for DCR for moment in column (Fig.3), almost all building pass this criteria except building CH2 at the exterior joint in the longitudinal direction which has too small longitudinal reinforcement ratio in column.

As for DCR for shear in column (Fig.4), all sections of the column have DCR less than 0.5 indicating that the sections have sufficient shear capacity to resist code-specified earthquake load. There are two reasons to support this, that is, the presence of lift core that reduces the lateral load transmitted to column and the traditional working stress design approach with low code-specified allowable material stresses.

The DCR for shear in beam-column joints is shown in Fig.5. As shown, all building pass this criterion because column has large size as explained above.

It is found that almost critical elements of lateral force resisting system have strengths greater than computed actions based on code specified earthquake load. However, it should not be concluded the structure is safe against earthquake. As a matter of fact, the force that can develop in a structure depends on structural capacity itself. Hence, the structure should be investigated under the condition that some members reach yielding. Moreover, the reinforcement detailing should be checked too.

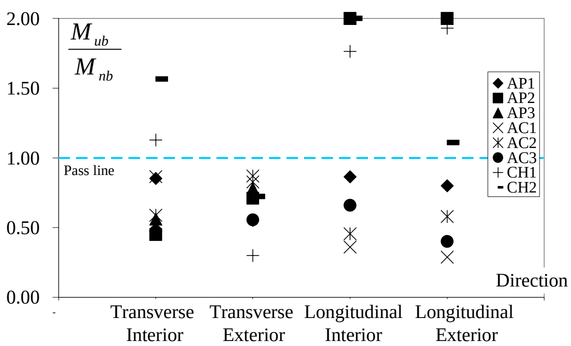

Fig.1 DCR for moment in beam

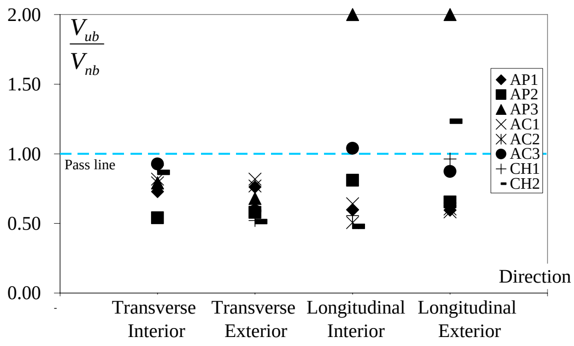

Fig.2 DCR for shear in beam

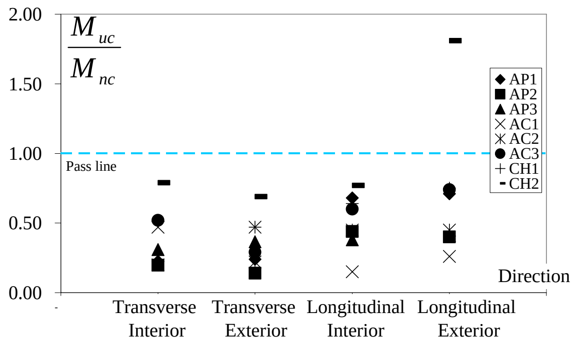

Fig.3 DCR for moment in column

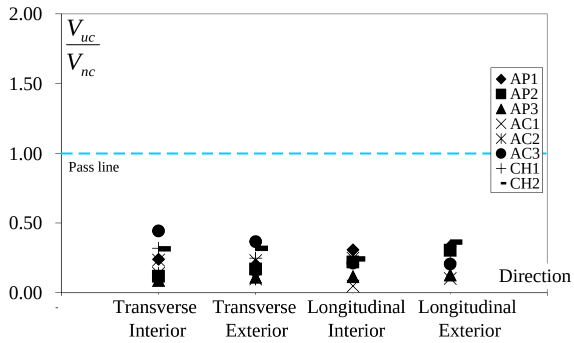

Fig.4 DCR for shear in column

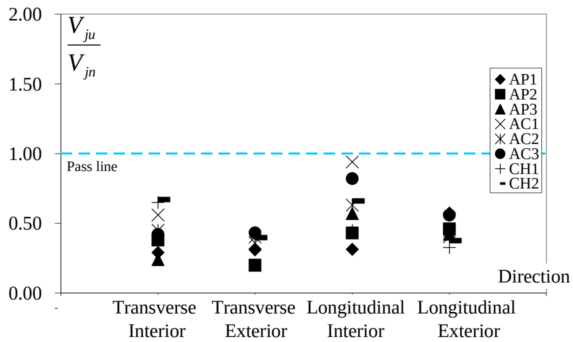

Fig.5 DCR for shear in beam-column joint

4.2 Reinforcement detailing check

The DCR determination is a check for load level specified in the code. Usually, the load level is lower than that actually occurs and the structure is assumed to demonstrate some reversed yielding behavior. As a result, all modern codes of earthquake design states the minimum requirement for reinforcement detailing to provide a certain level of ductility in structural members. In Thailand which is considered to be low to moderate seismic zone, the ACI [2] requirement for Intermediate Moment Resisting Frame (IMRF) is adopted. The requirement for reinforcement detailing is shown in Figure 6 for beam, column and joint.

The results of reinforcement detailing check show that all buildings do not satisfy the reinforcement detailing. All present transverse steels are simply tie without end details as seismic hook. There are not enough transverse steels in beam and column, especially in plastic hinge zone (zone1). More over there are no transverse steel in beam-column joint in all buildings. This means that all investigated buildings lack ductility. An example of detailing check list is shown in table 6.

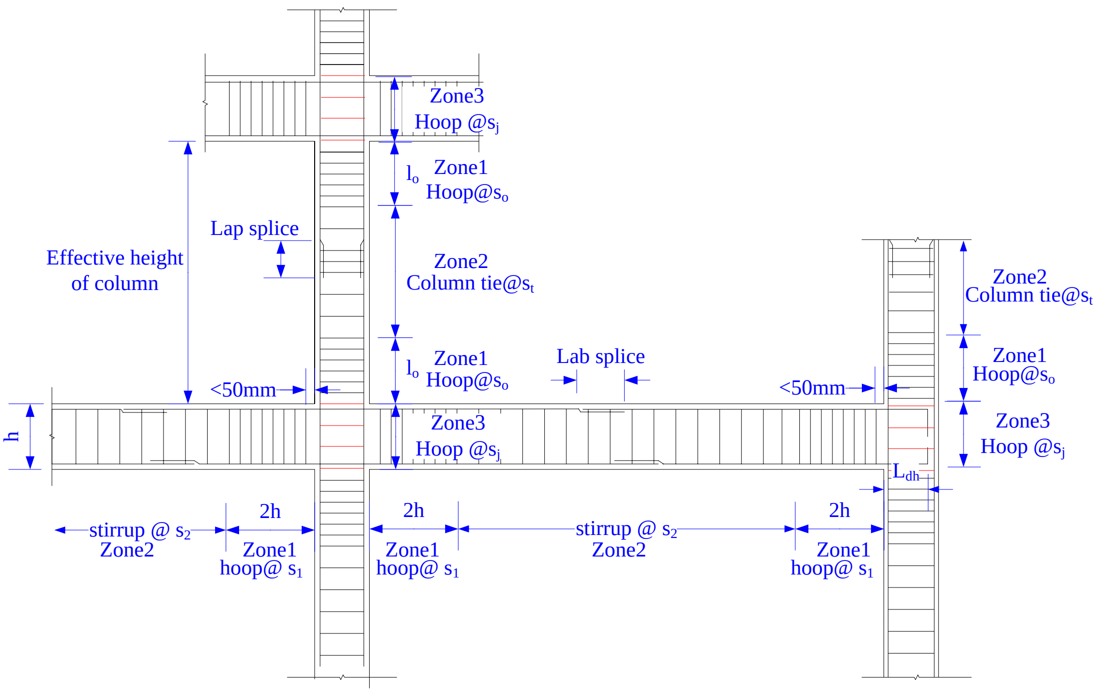

Fig. 6 Detailing criteria for beam, column and joint.

Table 5 Summary of DCR check

Building	Transverse direction		Longitudinal direction	
	Interior span	Exterior span	Interior span	Exterior span
AP1	C	C	C	C
AP2	C	C	NC	NC
AP3	C	C	NC	NC
AC1	C	C	C	C
AC2	C	C	C	C
AC3	C	C	NC	C
CH1	NC	C	NC	NC
CH2	NC	C	NC	NC

Note: C=Compliance, NC=Not compliance

Table 6 Example of Detailing criteria for transverse direction-interior span.

Building	Location	Transverse steel	Existing	Minimum requirement	Results
AP1	Beam	Zone 1 ($2h_o$)	RB9 @ 0.20	RB9 @ 0.15	NC
		Zone 2	RB9 @ 0.20	RB9 @ 0.16	NC
	Column	Zone 1 (s_o)	3-RB9@0.20	3-RB9 @ 0.20	C
		Zone 2 (s_t)	3-RB9@0.20	3-RB9 @ 0.40	C
	Joint	Zone 3 (s_j)	None	RB9 @ 0.40	NC
AP2	Beam	Zone 1 ($2h_o$)	RB6 @ 0.10	RB6 @ 0.04	NC
		Zone 2	RB6 @ 0.10	RB6 @ 0.05	NC
	Column	Zone 1 (s_o)	3-RB6 @ 0.20	3-RB6 @ 0.20	NC
		Zone 2 (s_t)	3-RB6 @ 0.20	3-RB6 @ 0.20	C
	Joint	Zone 3 (s_j)	None	3-RB6 @ 0.20	NC
AP3	Beam	Zone 1 ($2h_o$)	1-RB 9 @ 0.20	1-RB 9 @ 0.09	NC
		Zone 2	1-RB 9 @ 0.20	1-RB 9 @ 0.09	NC
	Column	Zone 1 (s_o)	3-RB 9 @ 0.20	3-RB 9 @ 0.16	NC
		Zone 2 (s_t)	3-RB 9 @ 0.20	3-RB 9 @ 0.32	C
	Joint	Zone 3 (s_j)	none	3-RB 9 @ 0.32	NC
AC1	Beam	Zone 1 ($2h_o$)	RB 9 @ 0.20	1-RB 9 @ 0.15	NC
		Zone 2	RB 9 @ 0.20	1-RB 9 @ 0.16	NC
	Column	Zone 1 (s_o)	3-RB 9 @ 0.20	3-RB 9 @ 0.21	C
		Zone 2 (s_t)	3-RB 9 @ 0.20	3-RB 9 @ 0.43	C
	Joint	Zone 3 (s_j)	none	3-RB 9 @ 0.43	NC
AC2	Beam	Zone 1 ($2h_o$)	1-RB 9 @ 0.125	1-RB 9 @ 0.09	NC
		Zone 2	1-RB 9 @ 0.125	1-RB 9 @ 0.09	NC
	Column	Zone 1 (s_o)	4-RB 9 @ 0.20	4-RB 9 @ 0.20	C
		Zone 2 (s_t)	4-RB 9 @ 0.20	4-RB 9 @ 0.40	C
	Joint	Zone 3 (s_j)	none	4-RB 9 @ 0.40	NC
AC3	Beam	Zone 1 ($2h_o$)	1-RB 9 @ 0.125	2-RB 9 @ 0.09	NC
		Zone 2	1-RB 9 @ 0.125	2-RB 9 @ 0.09	NC
	Column	Zone 1 (s_o)	3-RB 9 @ 0.30	3-RB 9 @ 0.06	NC
		Zone 2 (s_t)	3-RB 9 @ 0.30	3-RB 9 @ 0.06	NC
	Joint	Zone 3 (s_j)	none	3-RB 9 @ 0.06	NC
CH1	Beam	Zone 1 ($2h_o$)	RB 9 @ 0.20	1-RB 9 @ 0.10	NC
		Zone 2	RB 9 @ 0.20	1-RB 9 @ 0.10	NC
	Column	Zone 1 (s_o)	2-RB 9 @ 0.30	2-RB 9 @ 0.20	NC
		Zone 2 (s_t)	2-RB 9 @ 0.30	2-RB 9 @ 0.27	NC
	Joint	Zone 3 (s_j)	none	2-RB 9 @ 0.27	NC
CH2	Beam	Zone 1 ($2h_o$)	1-RB 9 @ 0.15	1-RB 9 @ 0.10	NC
		Zone 2	1-RB 9 @ 0.15	1-RB 9 @ 0.10	NC
	Column	Zone 1 (s_o)	2-RB 9 @ 0.30	2-RB 9 @ 0.20	NC
		Zone 2 (s_t)	2-RB 9 @ 0.30	2-RB 9 @ 0.40	NC
	Joint	Zone 3 (s_j)	none	2-RB 9 @ 0.40	NC

Note: C=Compliance, NC=Not compliance

5. Investigation of failure mode

As stated, the DCR check under code specified earthquake load does not suffice to determine the actual seismic performance of a structure. The sequence of failure of structure is valuable for the retrofit of the buildings. In this research, the methodology for determining the failure mode is presented. The method uses the information of DCR, structural indices mentioned above together with two flowcharts, that is, load flowchart and yielding flowchart. The purpose of load flowchart is to identify the failure mode under the code-specified load. The purpose of yielding flowchart is to identify the failure mode in case that some members of structure reach yielding with increasing lateral load. The new DCRs are obtained under the load combination U2 = DL + 0.4LL ± 1.87E. It is noted that the only 40% of live load is taken as likely live load to be present when earthquake occurs. The load flowchart is presented in Fig. 7. The yielding flowchart is intended to check the structure when earthquake moves the structure so that some members yield. The concept of yielding flowchart is shown in Fig. 8. The advantage of the yielding flowchart is that it allows the post-yield failure mode to be identified. Usually, the flexural failure caused by member yielding should not be regarded as failure in the sense of earthquake resistance. The failure is usually caused by subsequent shear failure in the member and joint. The retrofitting method should therefore aim to strengthen member and joint in shear rather flexural strengthening. Contradictorily, the flexural strengthening may increase the shear and bond demand, hence the structure may be more brittle than un-retrofitted structure.

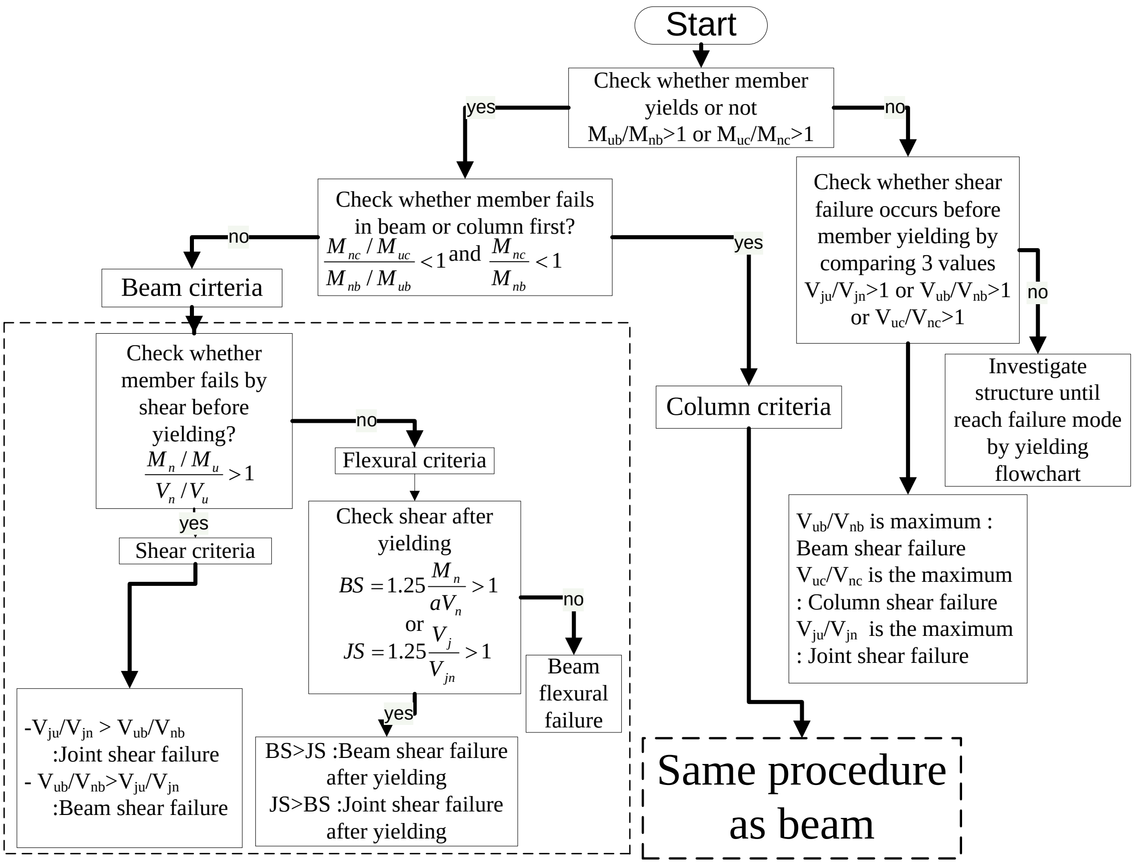

Fig 7 Load flowchart

All eight buildings are examined with the proposed flowcharts. The result shows 44% of beam flexural failure, 41% of joint shear failure and 15% of beam shear failure. It is seen that shear failure covers 66% of the total failure (Fig 9). The total failures can be classified as follows,

In transverse direction and interior span, 62% is joint shear failure, 25% is beam flexural failure and 13% is beam shear failure (Fig.9).

In transverse direction and exterior span, 74% is beam flexural failure and 26% is beam shear failure (Fig 9).

In longitudinal direction and interior span, 75% is joint shear failure and 25% is beam flexural failure (Fig.9).

In longitudinal direction and exterior span, 74% is beam flexural failure and 26% is joint shear failure (Fig.9).

According to the investigation, the majority of failure is found in beams. However, as mentioned, the beam flexural failure is rarely a problem as long as ductility is available. It is also noted that the evaluation with load flowchart shows less failures compared with yielding flowchart. This is due to traditional RC working stress design approach adopted in Thailand with lower allowable compressive strength of concrete and steel compared with ACI [2] codes. Another reason is the presence of lift core that reduces the forces transmitted to beam-column frame.

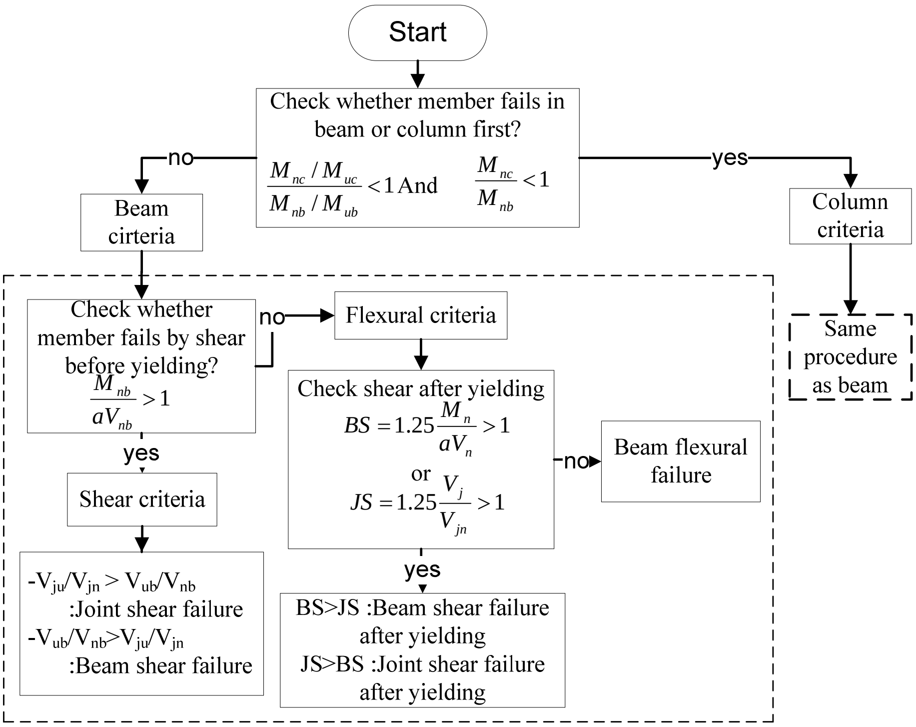

Fig.8 Yielding flowchart

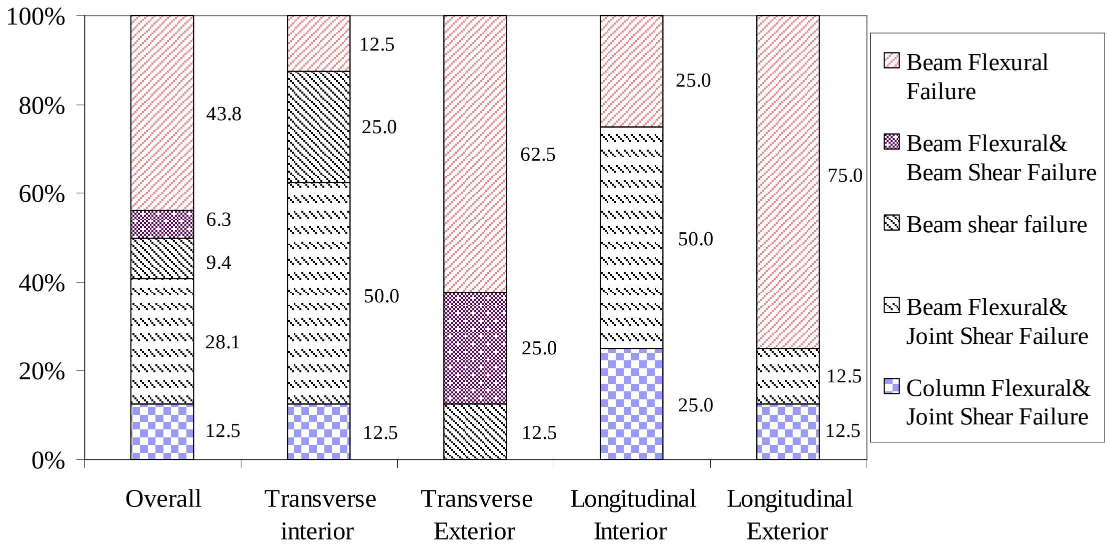

Fig. 9 Failure mode result

7. Conclusion

The paper presents result of seismic assessment of eight existing reinforced concrete buildings in Bangkok. All buildings were constructed as beam-column rigid frame. The building category covers school, apartments and governmental offices. The evaluation method consists of DCR determination, reinforcement detailing check and failure mode investigation. It is found that no buildings satisfy the reinforcement detailing requirement, primarily because of the lack of sufficient transverse reinforcement in beam, column and beam-column joint and non-seismic detail of hook anchorage. Based on DCR, five out of eight buildings show some failures in the members under code-specified earthquake load. The failure mode investigation shows 44% of beam flexural failure, 41% of joint shear failure and 15% of beam shear failure. The load flowchart failure check is less critical than yielding flowchart because of traditional working stress design approach for RC structures in Thailand with lower allowable compressive strength of concrete and steel compared to codes. Another reason is the presence of lift core that reduces the forces transmitted to beam-column frame. According to the investigation, the joint shear failure is identified to be one of the most critical failures of RC buildings.

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