Simple Seismic Evaluation Methodology for Gravity-Designed Reinforced Concrete Building

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Abstract

This paper presents a simple seismic evaluation method for reinforced concrete building constructed as beam-column rigid frame. The proposed method is intended for practicing engineers as guidance for seismic evaluation of existing buildings. The proposed seismic evaluation methodology consists of force check in terms of demand to capacity (DCR), reinforcement detailing check and failure mode investigation. The failure mode flowchart consists of load flowchart and yielding flowchart. The use of flowchart requires structural indices and DCR. The load flowchart is intended to check the failure mode of existing buildings under the code-specified earthquake load. The yielding flowchart is intended to check the failure mode when some members of the building yield. A case study is presented to demonstrate the applicability of the method. The applicability of the method is partly verified by experiment of beam-column joint conducted in the past.

1. Introduction

Recently, several foreign earthquakes have caused severe vibration of buildings in Bangkok and created a public concern on seismic safety of existing buildings. Almost all buildings in Bangkok were not designed against seismic loading. These buildings may be subject to severe damages in the event of large earthquake magnitude. The buildings should be evaluated for seismic rating and necessary preparedness is required.

This paper presents a simple, yet effective, method for seismic evaluation of reinforced concrete buildings. It aims to provide guidance for practical designers to evaluate the seismic performance of existing buildings based on the results of linear elastic analysis of the building.

Currently, there exist some preliminary evaluation methods. Gulkan and Sozen [1] presented a procedure for determining seismic vulnerability of building structures. The method essentially requires only the dimensions of the structure as input, and is expressed in terms of their locations in a two-dimensional plot of masonry wall and column percentages. The ranking of damage observed in a group of institutional buildings in Erzincan during the March 13, 1992, earthquake shows that the data is in broad agreement with the proposed method.

Capacity spectrum method is originally developed by Freeman et. al.[2]. This concept has been introduced for seismic evaluation and retrofitting of existing building in FEMA-273 [3]. The capacity spectrum method incorporates the inelastic quasi-static response of the structure in analysis.

The analytical method can be broadly classified into four categories, linear static, linear Dynamic, nonlinear static and nonlinear dynamic. The most realistic analysis procedure is the nonlinear dynamic analysis. However, this method is considered overly complex and impractical for general use. This paper presents a practical method based on Linear Static Procedure to obtain structural indices that will be used with proposed load and yielding flowchart to evaluate the seismic performance and failure mode of existing buildings.

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2. Structural indices

Structural indices are defined as the parameters that characterize the behavior of beam, column and joint under the seismic action. Structural indices of buildings are calculated from design configurations such as sectional dimensions (Fig.1), quantity of longitudinal and transverse reinforcements, strength of concrete and reinforcement and others. The prominent structural indices used in predicting the failure modes are as follows.

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

In the index, a is the shear span which is defined as length of a column or beam measured from the joint face to inflection point (Fig.1), M_n and V_n are nominal flexural and shear strength of the reinforced concrete section, respectively. This index indicates a possibility of shear failure in the member. With the assumption that the inflection point is located at the mid-height of column or beam, the value of the index equal to one indicates that shear force and moment reach the shear strength and flexural yield strength simultaneously. Larger value of this index indicates higher nominal flexural strength compared to shear strength, and a possibility of shear failure before flexural failure.

2.2 Join shear stress over joint shear strength ratio, V_j / V_{jn}

In this index, V_j is the joint shear force and V_{jn} is the joint shear strength. This index indicates the possibility of joint shear failure. The calculation of V_j is conducted by the following formula [4].

$$V_j = \left(1+\beta\right)\lambda_0 f_y A_{s1} - V_{col} \qquad (1)$$

where, $\beta = A_{s2}/A_{s1}$

A_{s1} = area of top beam reinforcement

A_{s2} = area of bottom beam reinforcement

λ_0 = over strength factor (= 1.0 for intermediate moment resisting frame)

f_y = nominal yield strength of steel

V_{col} = column shear force which is calculated by the following formula,

$$V_{col} = 2\left(\frac{l_1}{l_{1n}} M_{0,1} + \frac{l_2}{l_{2n}} M_{0,2}\right) \Big/ (l_c + l_c') \qquad (2)$$

where,

$M_{0,1}$ = negative moment capacity of the right beam

$M_{0,2}$ = positive moment capacity of the left beam

Other notations are as shown in Fig. 2.

2.3 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 before in beam.

3. Evaluation Methodology

The proposed evaluation methodology consists of linear static analysis of structures to obtain demand capacity ratio (DCR), reinforcement detailing check and flowcharts for failure mode investigation.

To obtain demand capacity ratio (DCR), the linear static analysis is conducted and the seismic demand and capacity are calculated and compared. Seismic demands include shear force and moment in beam, column and joint which are calculated from analysis of structures under the action of earthquake loading specified in governing code. In Thailand, the No.49 Ministerial Law [5] is adopted which is based on UBC85 [6]. Other more recent codes can be used as well. Capacities are calculated based on accepted design codes, such as ATC-40 [7] and ACI318 [8]. In each building, the analysis should be conducted for both transverse and longitudinal directions. The procedure to evaluate DCR is described below,

1. Approximate weight (W) of building, including likely live load, for example 40% of specified live load.

2. Calculate base shear force based on No.49 Ministerial Law [5] by the following formula,

$$V=ZIKCSW \tag{3}$$

Where V = base shear force

Z = Zone factor

I = Importance factor

K = Horizontal force factor

C = Coefficient of building natural frequency

S = Soil factor

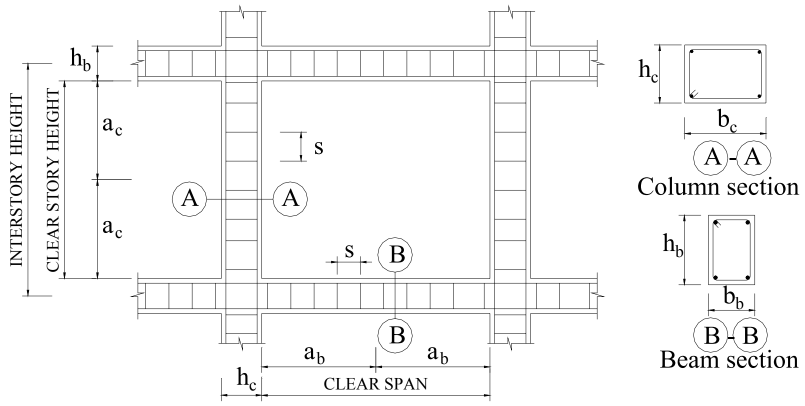


Fig.1 Definition of geometry parameters of structural indices

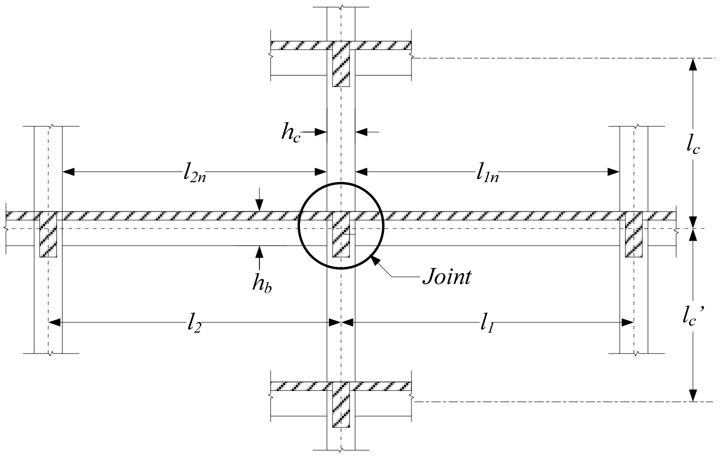


Fig. 2: Interior beam-column sub-assemblage

3. Distribute base shear V to each frame based on relative stiffness. For each frame, distribute lateral forces along building height.

4. Model and analyze the structure in computer for moment and shear forces in beam, column and joint. There are two load cases in the analysis.

Load combination 1:

$U\,1 = 0.75(1.4DL+1.7LL \pm 1.87E)$

Load combination 2:

$U\,2 = DL+0.4LL \pm 1.87E$

Load combination 1 is stated in the ACI318 [6] building code. This load shall be used to check DCR compatible with forces specified in the No.49 Ministerial law [5]. Load combination 2 is considered to represent the more realistic situation under earthquake where actual live load is assumed to be 40%. Shear, moment and axial force obtained from this load combination will be used in examination of possible failure modes.

5. Calculate corresponding capacity of beam, column and beam-column joint based on ACI318 [8] seismic requirement for Intermediate Moment Resisting Frame (IMRF) and ATC-40 [7].

6. Compare existing reinforcement detailing in beam, column and beam-column

joint with ACI requirement for Intermediate Moment Resisting Frame (IMRF).

7. Calculate Demand Capacity Ratio (DCR). Failure is considered to take place when DCR is greater than 1.0. The values of DCR used in this method consist of,

$\frac{M_{ub}^{-}}{M_{nb}^{-}}$ where M_{nb}^{-} is negative moment capacity of beam and M_{ub}^{-} is negative moment demand of beam.

$\frac{V_{ub}}{V_{nb}}$ where V_{nb} is beam shear capacity of section and V_{ub} is shear force demand of beam.

$\frac{V_{ju}}{V_{jn}}$ where V_{jn} is joint shear strength of beam-column joint, V_{ju} is joint shear force demand from associated moment. V_{ju} can be calculated from equation (4)

$$V_{ju} = (M_{ub}^{+} / jd + M_{ub}^{-} / jd) - V_{col} \qquad (4)$$

$\frac{V_{uc}}{V_{nc}}$ where V_{nc} is column shear capacity of section and V_{uc} is shear force demand of column.

$\frac{M_{uc}}{M_{nc}}$ where M_{nc} is moment capacity of column and M_{uc} is moment demand of column.

4. Acceptance Criteria

A building is considered seismically acceptable if both of the following two conditions are satisfied.

4.1 Acceptance for Force criteria

All critical elements of lateral force resisting elements have strengths greater than computed actions, that is, DCR is less than 1. This represents the strength check under code-specified load level.

4.2 Acceptance for Detailing criteria

All reinforcement detailing satisfies the code requirement. The detailing check is intended to check ductility and energy dissipation capacity of critical members of the building.

5. Investigation of failure mode

The DCR analysis presented above relies on the force specified in No.49 Ministerial law [5]. This force may or may not occur in a real earthquake since the actual forces developed in a structure depend on its capacity. Hence, using the force level specified in the code for the evaluation of existing structures may not be fully rational. A more meaningful approach is to determine the possible failure modes when the structure is displaced until yielding takes place in some members of the structure. The staged failure mode is very important to the building retrofit. For example, when flexural DCR exceeds 1.0, it may simply mean that the member yields without failure. The retrofit for flexural DCR exceeding 1.0 may not be important as long as the member can yield with some ductility. The secondary failure mode such as beam or column shear failure after yielding and post-yield joint shear failure is more significant. In this respect, this paper presents two flowcharts for identifying the failure modes of the structure.

5.1. Load flowchart.

The load flowchart is for checking the possible failure modes under code-specified lateral load. It is applied with load combination 2 (U= DL+0.4LL±1.87E) with likely live load acting on the structure. The load flowchart is shown in Fig.3.

5.2 Yielding flowchart

This yielding flowchart is intended for a situation when earthquake motion moves the structure until yielding develops in some members of the structure. This allows an opportunity to investigate staged failure modes. The yielding flowchart is shown in Fig. 4.

6. Case Study and Example of Seismic Evaluation

Example of seismic evaluation of existing building (Fig.5) is provided here. The base shear force is calculated following the No.49 Ministerial Law [5](based on UBC85 [6]) as *V*=*ZIKCSW*, where *Z*=3/16(Zone 1), *I*=1.25 (Academic building), *K*=1 (Moment resisting frame), *S*=2.5 (Bangkok soft clay). The natural period of the building is calculated using $T = 0.09h_n\sqrt{D}$ =0.62 s, where h_n is the total building height =29.8 m and *D* is width of building =18.6 m. The coefficient $C = 1/15\left(\sqrt{T}\right)$ =0.085. The weight (*W*) of building is *W*=2,965.86 Tons. The base shear (*V*) is calculated to be 146.91 Tons.

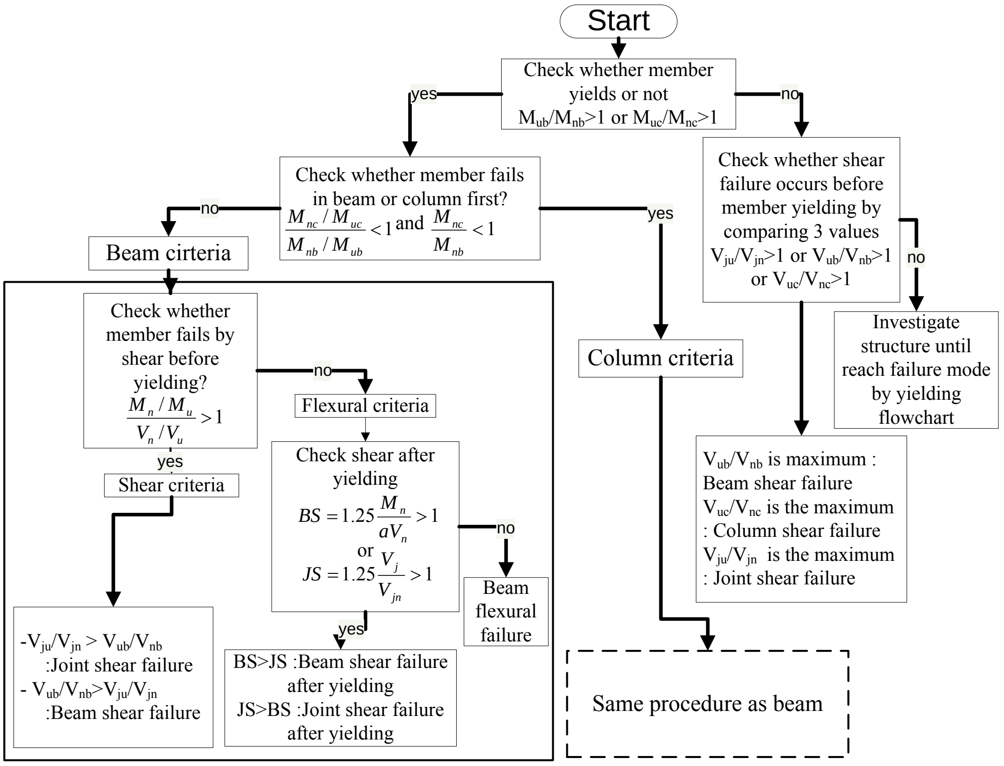


Fig. 3: Load flowchart

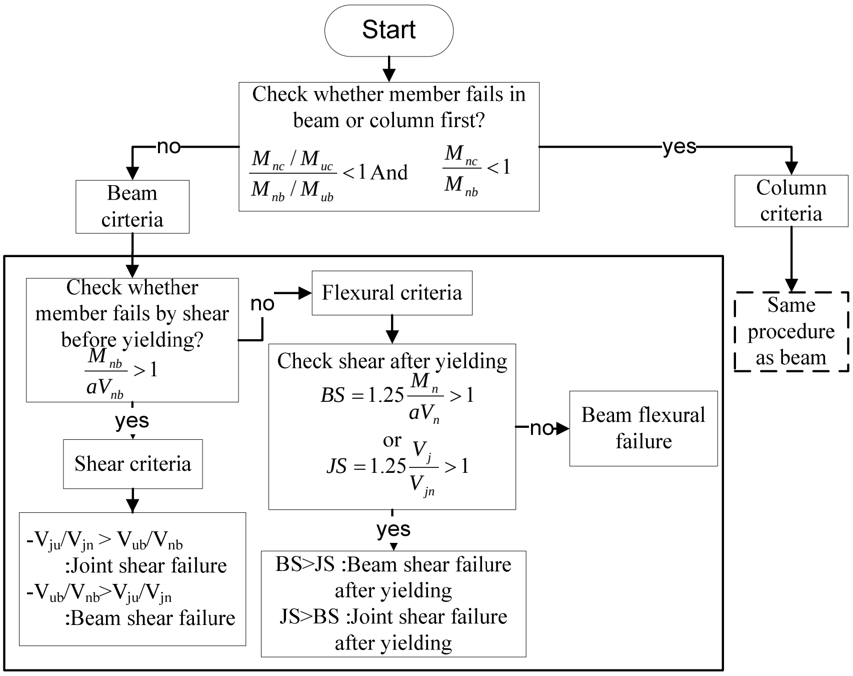
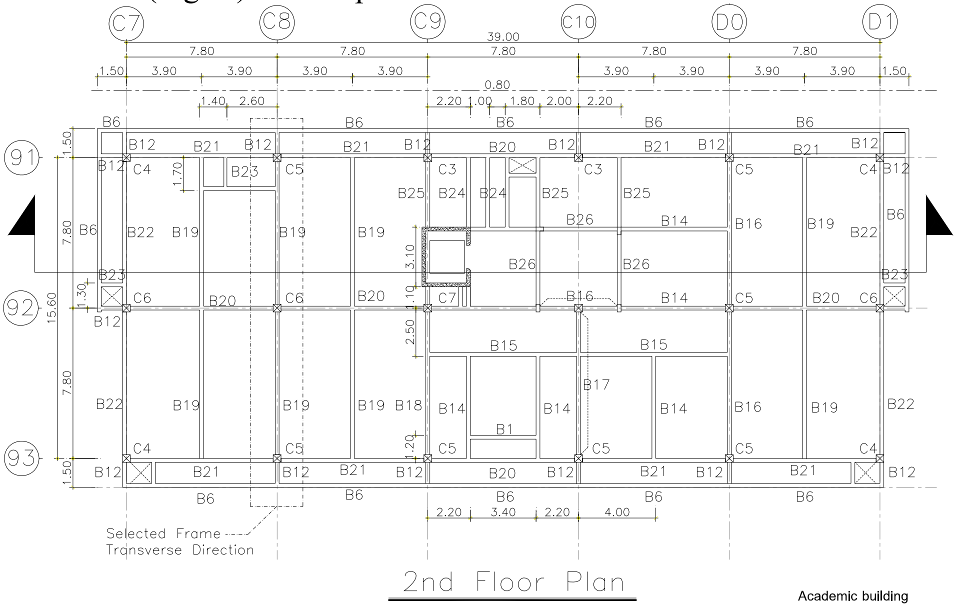


Fig 4 Yielding flowchart

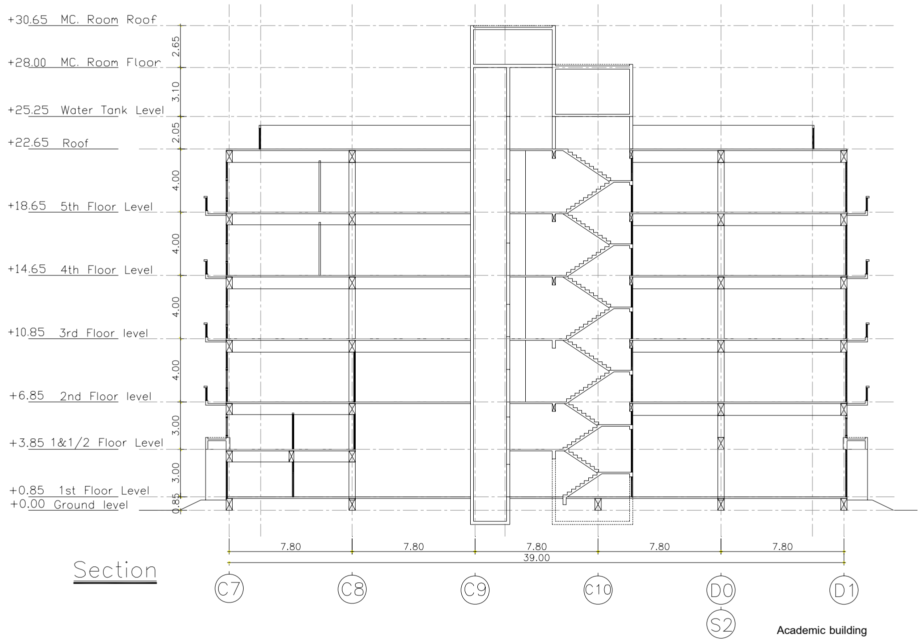
The base shear is distributed to the frame according to the relative stiffness. For this building, the frame stiffness is 4.40 T/cm and the total stiffness of building is 41.06 T/cm.

The Demand Capacity Ratio is shown in Table 1 as an example for the second floor of the frame in the transverse direction. The failure mode is analyzed under load combination 2 using load flowchart (Fig. 3) and yielding flowchart (Fig. 4). The inputs to the flowcharts are DCR and structural indices as calculated before.

For this example building, all DCR values are less than 1.0 (Table 1), indicating that the buildings have sufficient capacity under code-specified lateral load. However, the check of reinforcement detailing shows that no stirrup is provided in the joint and the beam stirrup is insufficient (Table 2).

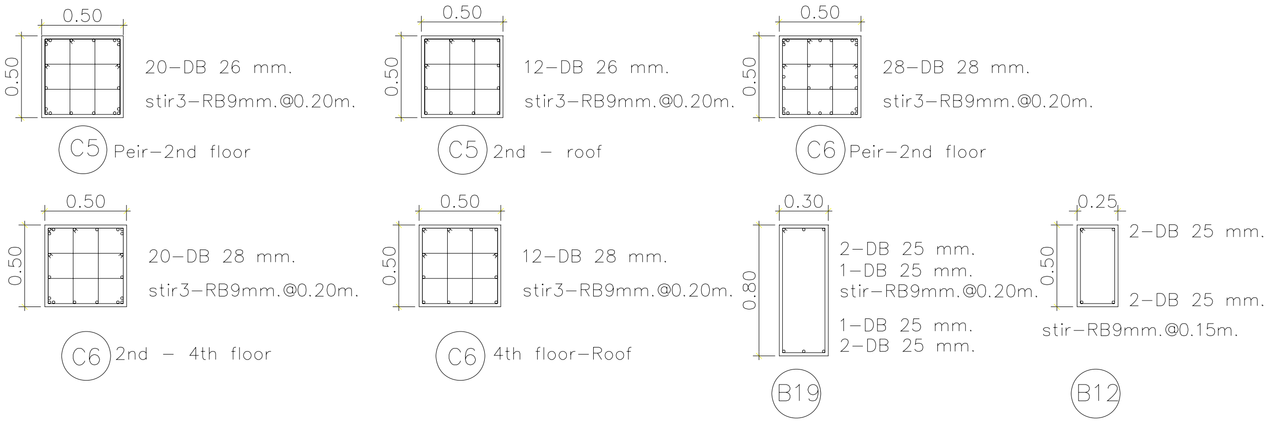


(a) Building plan



(b) Building elevation

Fig.5 Example of seismic evaluation – a case study



(c)Reinforcement detail

Fig.5 Example of seismic evaluation – a case study

Table 1 Demand capacity ratio for 2nd floor interior joint

Selected frame	Joint	Beam		Column		Result
	V_{ju}/V_{jn}	V_{ub}/V_{nb}	M_{ub}/M_{nb}	V_{uc}/V_{nc}	M_{uc}/M_{nc}	
C8	0.56	0.82	0.86	0.23	0.47	Compliant

Table 2 Reinforcement detailing check

Location	Transverse steel	Existing	Minimum requirement	Result
Beam	Zone 1 ($2h_o$)	RB 9 @ 0.20	RB 9 @ 0.15	Not Compliant
	Zone 2	RB 9 @ 0.20	RB 9 @ 0.16	Not Compliant
Column	Zone 1 (s_o)	3-RB9@0.20	3-RB9 @ 0.20	Compliant
	Zone 2 (s_t)	3-RB9@0.20	3-RB9 @ 0.40	Compliant
Joint	Zone 3 (s_j)	None	RB 9 @ 0.40	Not Compliant

Table 3 Failure mode analysis

Joint	
M_{nc}/M_{nb}	1.21
$\frac{M_{nc}/M_{uc}}{M_{nb}/M_{ub}}$	1.50
V_j/V_{jn}	1.21
V_{ju}/V_{jn}	0.56

Beam	
M_{nb}/aV_n	0.44
V_{ub}/V_{nb}	0.62
M_{ub}/M_{nb}	0.85
$\frac{M_{nb}/M_{ub}}{V_{nb}/V_{ub}}$	0.73

Column	
M_{nc}/aV_n	0.11
V_{uc}/V_{nc}	0.22
M_{uc}/M_{nc}	0.56
$\frac{M_{nc}/M_{uc}}{V_{nc}/V_{uc}}$	0.40

Failure mode
1st mode-beam flexural
2nd mode-Joint shear failure

The failure mode analysis is started using load flowchart with the ratio of $M_{ub}/M_{nb} = 0.85$ and $M_{uc}/M_{nc} = 0.56$ in Table 3. These ratios are less than 1, implying that beam and column do not yield. Since the ratio of V_{ju}/V_{jn}, V_{ub}/V_{nb} and V_{uc}/V_{nc} are less than 1.0, beam, column and joint do not fail by shear before yielding. Following yielding flowchart, the ratios of $\frac{M_{nc}/M_{uc}}{M_{nb}/M_{ub}}$ and M_{nc}/M_{nb} greater than 1.0 display that beam fails in flexure before column. The ratio of M_{nb}/aV_n less than 1, indicating that beam fails in flexure first. After yielding in beam, the joint shear failure occurs because the ratio $1.25V_j/V_{jn}$ is greater than 1. The factor 1.25 applies to account for actual yield stress of steel greater than nominal value as well as strain hardening effect. Consequently, the staged failure mode of this interior connection is identified as joint shear failure following beam flexural yielding.

7. Experimental verification

In the previous section, the seismic evaluation methodology is proposed to investigate the failure modes using two flowcharts. A sample building is presented as a case study. In order to partially verify the above method, an experiment on beam-column joint is discussed here for verification. Thinh [9] conducted a reversed cyclic test of substandard interior beam-column connection. The specimen is half-sized, representing the typical beam-column connection of mid-rise (6-15 storey) reinforced concrete frame buildings constructed in Thailand. The member size and reinforcement details of specimen are shown in Fig. 6. The tested concrete compressive strength and steel tensile strength were shown in table 4 and table 5, respectively.

The comparison of structural indices of the joint between that of example building and the specimen is shown in Table 6. As shown, the values are quite close to each other.

The experimental set-up is shown in Fig. 7. Both ends of the beam were supported by rollers that allow horizontal movement to simulate lateral drift. The bottom end of column was pinned to the base. The load was applied by hydraulic actuator at the top of column. The actuator was reacted against 500 kN reaction frame fixed to the strong floor. In order to simulate the axial force on column, prestressing tendons were provided in the column to supply an axial force of 300 kN.

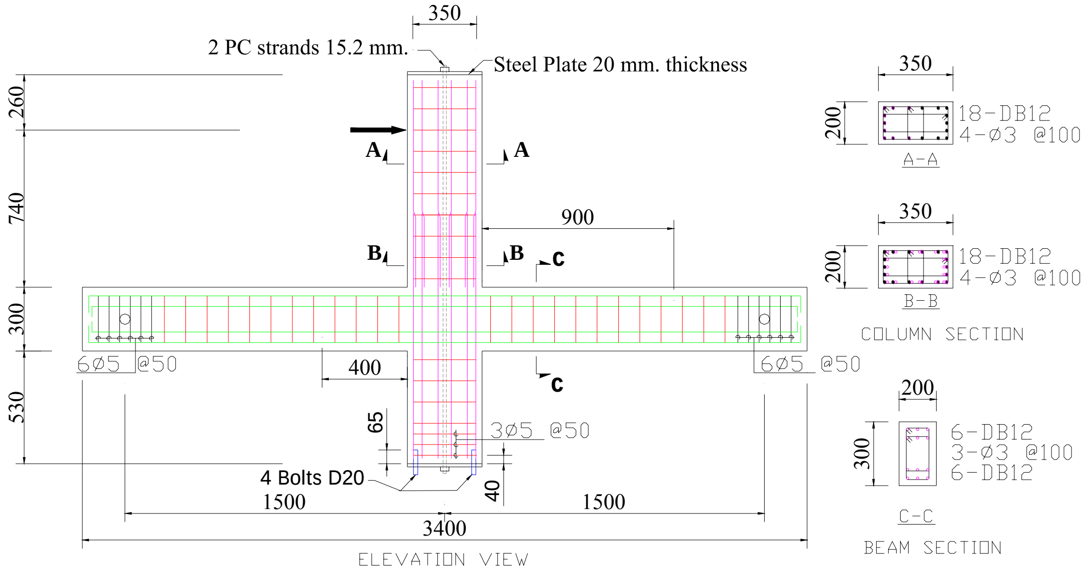


Fig.6 Dimension and reinforcement detailing of specimen

Table 4 Concrete compressive cylinder test results

Average strength (MPa)		
Bottom column	Beam	Top column
27.9	26.6	25.7

Table 5 Steel tensile strength

Type of bar	Average yield strength (MPa)	Average tensile strength (MPa)
Longitudinal reinforcement (DB12 SD40)	498.5	624.3
Transverse reinforcement plain mild steel (3-mm diameter)	284.7	359.3

Table 6 Comparison of structural indices between example building and specimen [9]

Joint	*BI*	h_c/d_b	b_b/b_c	h_b/h_c	M_{nc}/M_{nb}	V_j/V_n	$\rho_{sv}f_{ys}/f_c'$
Example Building	7.23	17.9	0.60	1.60	1.21	1.21	0.00
Specimen [8]	5.24	29.0	1.00	0.86	1.55	1.25	0.00

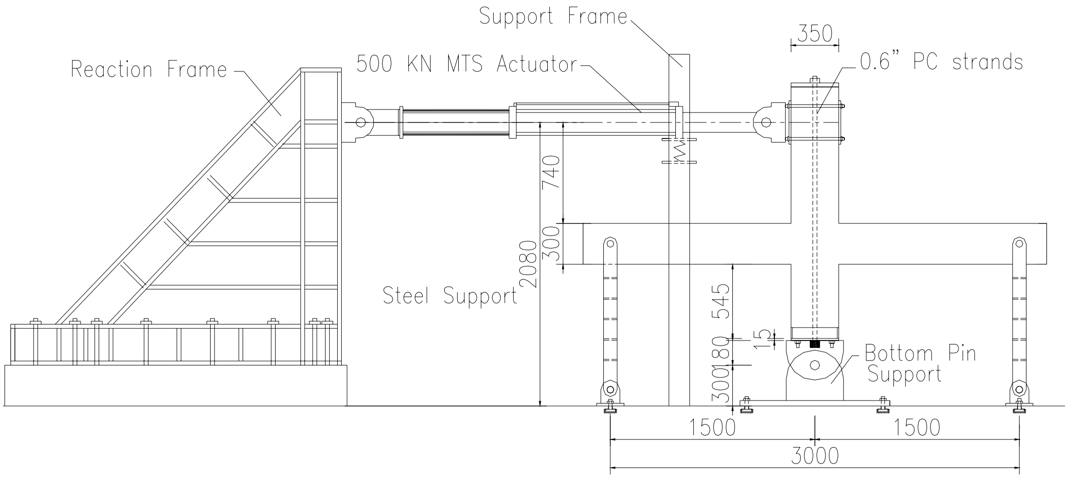


Fig. 7 Experimental setup

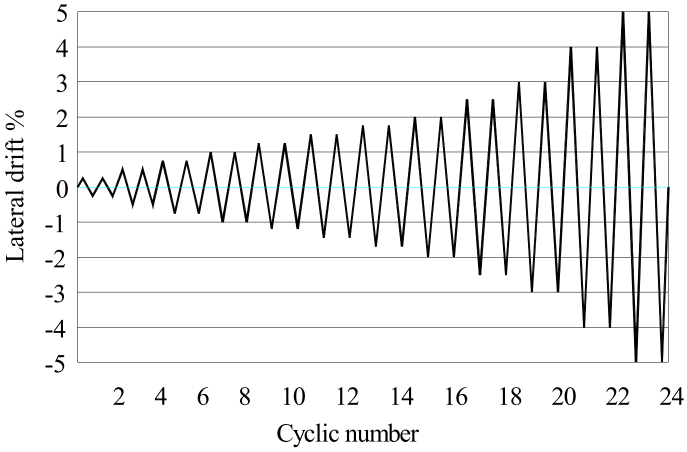


Fig. 8 Displacement history of specimen

The load applied to the specimen was lateral cyclic displacement controlled. The column was pushed forward and pulled backwards with increasing interstory drift of ±0.25%, ±0.5%, ±0.75%, ±1% and so on as shown in Fig. 8. At each drift level, the displacement was repeated twice to check the stability of the loop as well as to investigate the energy dissipation.

The force-story drift relationship is shown in Fig. 9. The beam started yielding at 1.5% drift ratio and reached peak load of 72 kN at 1.75% drift ratio. Beginning from 2.25% drift ratio, the concrete at the joint core spalled off and the load dropped continuously. As shown in Fig. 10, most damage is concentrated within the joint where the concrete spalling covered the entire joint area. The peak load of the specimen is less than the predicted load base on beam capacity because of premature failure in joint region of the specimen.

The failure could be classified as post-yield joint shear failure. It is noted that the experimental failure mode agrees with the predicted by the proposed flowcharts, thus verifying the application of the flowcharts.

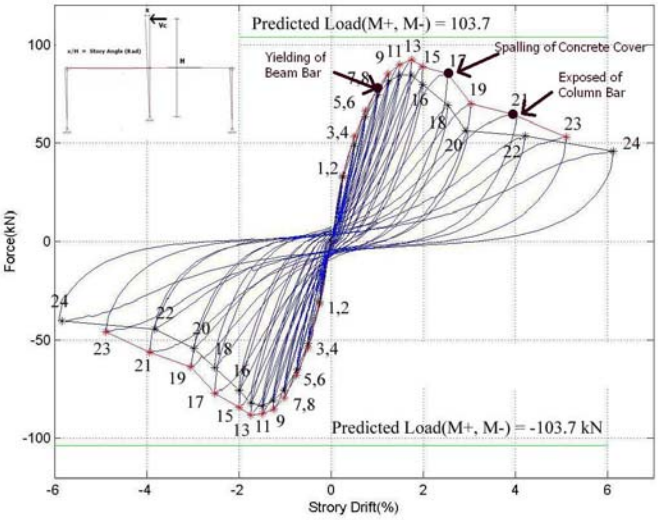


Fig. 9 Force-drift relationship of specimen

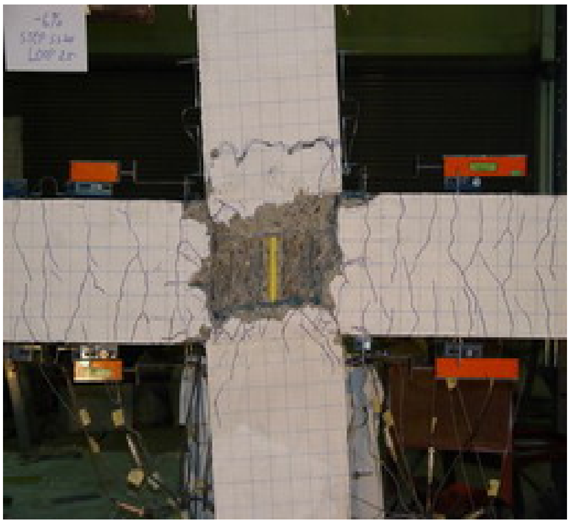


Fig. 10 Failure mode of experimental specimen

7. Conclusions and recommendations

A simple seismic evaluation method for reinforced concrete building constructed as beam-column rigid frame is proposed in this paper. The proposed method is simple to use and suitable for practical designer. The method consists of DCR determination, reinforcement detailing check and failure mode investigation. The DCR determination is intended to check the safety of building under code-specified lateral load. In the method, the linear static analysis of building structure is required. The reinforcement detailing check is required to check the toughness compliance with the seismic design codes. In order to retrofitting the structures, the failure mode must be identified. The investigation of failure mode consists of two flowcharts, namely, load flowchart and yielding flowchart. The input data to the flowchart are DCR and structural indices. The load flowchart is to check the failure of building under code-specified earthquake load. The yielding flowchart is to check the failure of building after some members yield. The use of these flowcharts enables the determination of staged failure sequence. The applicability of failure mode investigation is verified by recent experiment of beam-column joint conducted under reversed cyclic test.

However, it should be noted the structure which does not pass the criterion proposed in this paper may possess actual higher strength. Failure to comply with proposed criterion thus does not indicate that structure must actually fail in earthquake. It simply indicates that the structure fails to comply with No.49 Ministerial Law and ACI requirements only. For such structures, more advanced method such nonlinear push-over analysis is recommended.

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