- Technical Paper -

A STUDY ON SOFT STORY RC FRAME STRENGTENED WITH BUCKLING RESTRAINED BRACE

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ABSTRACT

Cyclic tests of a soft story RC frame structure and their analyses were carried out. The test specimens were RC frame with infill wall, RC bare frame with steel jackets, and RC frame with buckling restrained braces (BRBs). The hysteretic loops of the specimen with BRBs were very stable with almost no pinching in the response. Though the results indicated that BRBs significantly increased the stiffness and lateral force capacity of the frame, where columns of the RC frame are slender, the lateral deformation capacity of the frame depends on the reinforcement slip at the lap splices.

Keywords: non-ductile RC frame, buckling restrained brace, steel jacket, slip rotation

1. INTRODUCTION

In several countries outside Japan, seismic design is not required for structural design because there may be low possibilities of earthquake occurrences. Therefore, dead loads are considered as the only main forces and no horizontal forces are considered in the design.

In those regions, almost all the structures have slender columns in comparison with those of the structures in Japan. The shear and flexural capacities of those columns are generally low. Nevertheless, it has been said that at least these structures must have some resistance against the possible earthquakes which are considered as an uncertain phenomena in those regions.

For example, it has long been believed that no earthquakes would hit Thailand. Therefore, seismic design such as considering horizontal forces due to earthquakes were not required until recently. The law about the seismic design was only recently established in 2007. The law now requires that all new structures must have enough strength against possible earthquakes, and therefore, new built structures should have enough seismic resistance.

On the other hand, it is necessary for the structures which were built before 2006 to be retrofitted because they were not designed based on the new seismic design code. In Thailand, bricks have been used as building infill walls and they greatly affects the variation of the maximum resisting force against horizontal forces of the frame structures. The presence of these infill walls make it difficult to assess whether a certain building is up to standard or not. The important point is that it is necessary to use adequate retrofitting techniques for the buildings which had been designed without seismic consideration, particularly, weak story structures. To resolve these problems, a method of replacing the brick walls with Buckling Restrained Braces (BRBs) is proposed in this study.

The use of BRBs has gained popularity as an alternative way to retrofit an existing structure [1][2]. This is due to the stable hysteretic behavior of these braces that results in large energy dissipation.

In this paper, experiments on an original

Fig.1 Prototype building and the proposed retrofitting scheme

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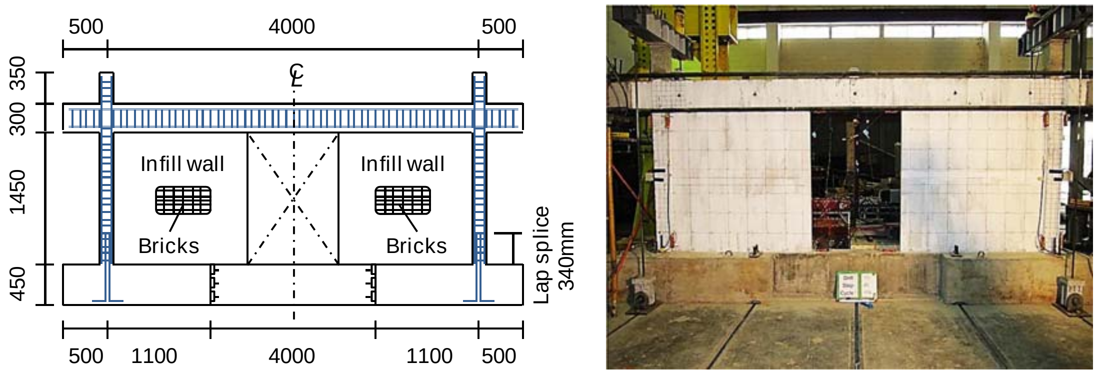


Fig.2 Details of the first phase test specimen

Table 1 Structural indices of the test specimen

Structure Element	Structure	Height / Length[m]	$\frac{a}{h}$	$\frac{M_n}{a \cdot V_n}$	$\rho = \frac{A_s}{b_w d}$	$\rho_s \sqrt{\frac{b"}{s}}$	$\frac{V_a}{b_w d \cdot \sqrt{f_c'}}$
Column	Prototype Bldg.	3.50	4.833	0.554	0.0357	0.0080	1.315
	Test Specimen	1.75	4.833	0.557	0.0415	0.0082	1.181
Beam	Prototype Bldg.	8.0	6.417	0.408	0.0244	0.0111	0.770
	Test Specimen	4.0	6.417	0.396	0.0266	0.0122	0.687

[Notations] M_n and V_n : the nominal moment capacity and the nominal shear capacity respectively, h : the depth of the member, b_w : the width of the member, a : shear span, d : the effective depth, f_y : the yield strength of reinforcing bar, f'_c : the compressive strength of the concrete, ρ_s : the volumetric confinement ratio, b'' : the center-to-center distance of the stirrups.

Table 2 Material properties of the test specimen (in MPa)

Concrete	Reinforcing steel						Brick wall	BRBs(Core)
Compressive Strength	Tensile Strength			Ultimate strength			Compressive strength	Tensile Strength
22.5	RB3	RB6	D16	RB3	RB6	D16	6.3(Bricks) 7.3(Grout Mortar)	315
	400	380	390	560	469	557		

structure model and retrofitted ones subjected to small horizontal displacement were carried out. In addition to this, numerical analyses for the retrofitted specimens were achieved and the effects of the BRBs for the weak story RC frames were discussed.

2. TEST PROGRAMS

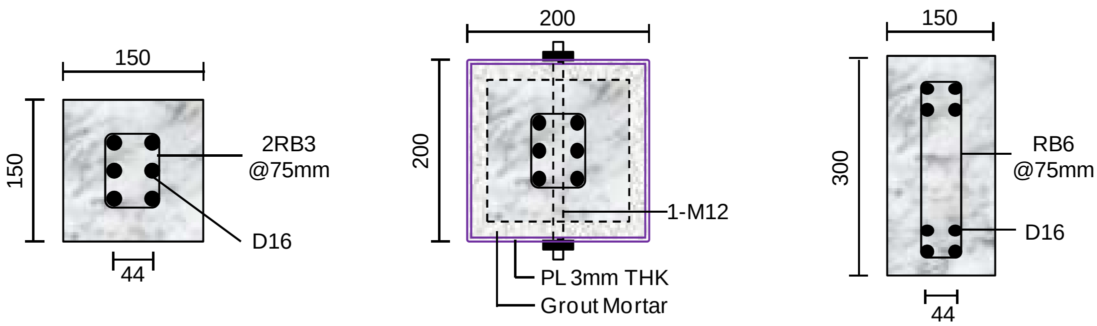
2.1 Prototype Building and Design of the Test

One of the typical elementary school buildings which were easily found in Thailand as shown in Fig.1 was the subject of this study. This building has slender columns with minimal amount of bricked infill walls in the first story. The shear and flexural capacities of the columns were very low. The columns have the capacity to support only dead loads. The building is composed mostly of strong-beams and weak columns. Besides, having the minimum lateral ties, the columns have low deformation and lateral load resisting capacities, especially against shear deformation.

School buildings in Thailand usually have open spaces in the first story for school activities while in the upper stories, infill walls are heavily used to divide the floor space for the class rooms. The presence of infill walls makes the upper stories significantly stiffer than the first story. This leads to a building with quite a severe soft first problem. Fig.1 represents only one of the possibilities to retrofit the building. As in any retrofitting project, the final size and the location of the BRBs must be confirmed by detailed nonlinear dynamic analysis using actual material properties and realistic ground motions.

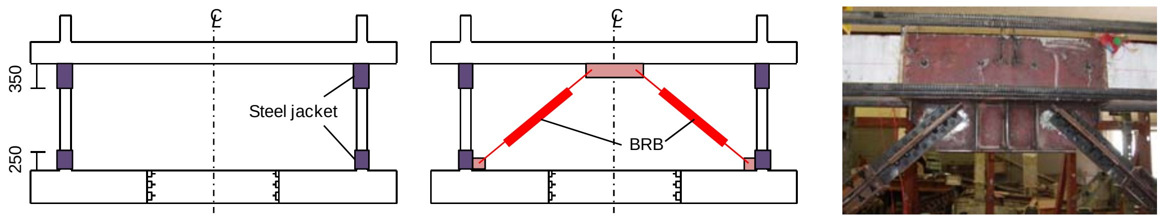
2.2 First Phase

The experiment was carried out in three phases. The first phase is the test of the frame with infill wall. The test was conducted by using a half-scale RC specimen of the first story. The member dimensions of the specimen were carried out from numerical indices, or indicators, that can be used to assess the seismic behavior of structural members [3]. The indices were calculated based on member dimensions, amount of



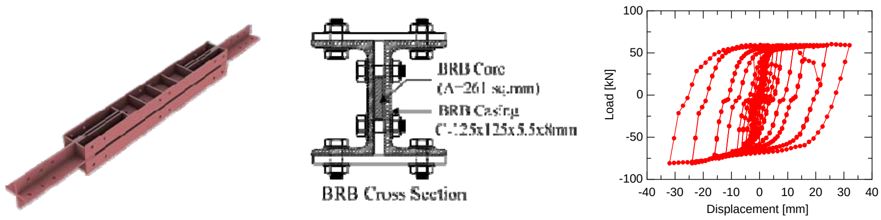
a) Column detail b) Steel jacket detail c) Beam detail

Fig.3 Details of members



a) The 2nd phase specimen b) The 3rd phase specimen c) BRBs-to-beam connection detail

Fig.4 Details of the test specimens



a) BRB overview b) BRB detail c) BRB testing result

Fig.5 Details of BRBs

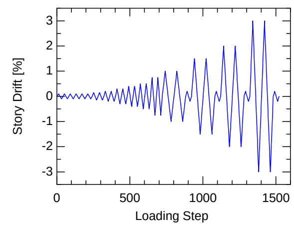


Fig.6 Loading history

longitudinal and transverse reinforcement and material properties. For this study, a standard elementary school structure was used as a prototype. At present, nearly one hundred of such structures exist. The specified concrete strength of these structures is generally 18 MPa. The specified steel strength is 250 MPa with the actual strength approximately between 350-400 MPa. The strengths of concrete and steel for the actual building and test specimens are similar.

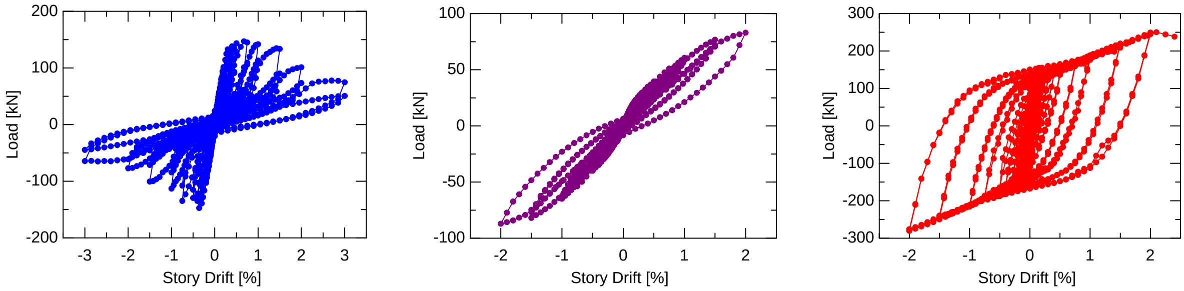
The main structural indices were shear span to member depth ratio, normalized shear stress, and normalized axial stress. The details of the test specimen are shown in Fig.2. The structural indices of the test specimen in comparison with the prototype buildings can be found in Table 1. Note that the indices for the test specimens were based on a conservative lower bound strength of f_c' =14.7MPa. The material properties are shown in Table 2. The column details are shown in Fig.3. The lap splice length was based on the old Thai code which was for primarily non-seismic design, As such, that version of the code required a slightly shorter lap splice length compared to other modern codes.

Bricks for the infill wall were especially produced to fit with the scale of the test specimen using the same materials as commonly used in regular brick (60*140*30mm^3) unreinforced infill walls that may be found in the actual buildings. The size of each brick and the thickness of mortar layer were scaled down according to the size of overall the test frame (30*70*15mm^3). The bricks for the infill wall were laid following typical local practices. The wall was finally plastered with a thin layer (10mm) of mortar as is commonly done in Thailand.

2.3 Second Phase

In the second phase, a test for the bare frame with steel jackets at both ends of the columns was carried out. Fig.4a shows the dimensions of the frame specimen. It should be noted that the jackets only encased the column ends and were not fixed with the strong floor or the beam. The section of the column at the steel jacket can be also found in Fig.3.

2.4 Third Phase



a) First Phase b) Second Phase c) Third Phase

Fig.7 Test results

a) 1% drift b) 2% drift c) 3% drift

Fig.8 Crack pattern of the test specimen in the first phase

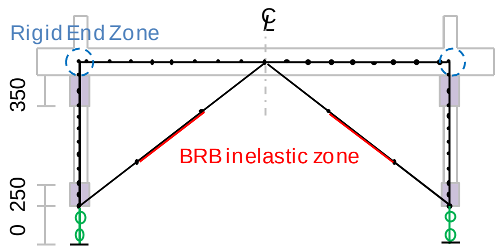
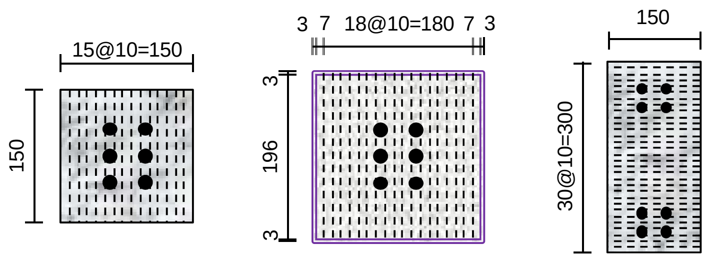


Fig.9 Analytical model



a) Column b) Steel jacketed column c) Beam

Fig.10 Fiber division of each element

The third phase is the test of the bare frame with steel jackets and BRBs (Fig.4b). The steel-only BRBs can be taken apart and assembled together easily at a construction site (Fig.5). The BRBs were attached to the beam through a gusset plate which is in turn attached to the steel beam jacket. The steel jacket was attached to the RC beam using four anchor bolts as also shown in Fig.4c. The anchor bolts were designed for the shear and the estimated unbalanced vertical force due to the BRBs in tension and compression.

Before the frame test, cyclic loading test of a BRB alone was carried out. The test result is shown in Fig.5c. This figure indicates that the steel-only BRB has good energy dissipation.

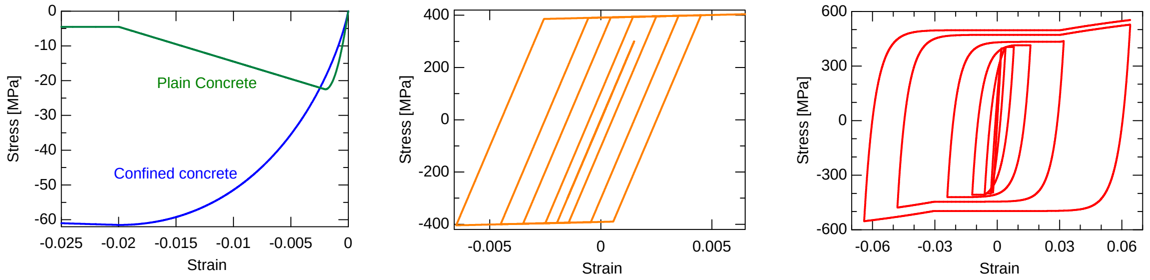
3. CYCLIC TESTS

3.1 First Phase

In the three tests mentioned above, the frame was subjected to quasi-static loading using a hydraulic actuator with a lateral loading history as shown in Fig.6, and constant vertical loads of P =150 kN at the top of the columns. The column loads were selected to represent the dead load acting on the columns. They were selected such that the structural index ($P/A/f_c'$, A : concrete column cross-sectional area) are similar (0.32 and 0.44 for the actual building and test specimen respectively). The infill walls are primarily non-structural. They are generally built after all the structural elements are in place. As such, any removals of the infill walls will vary slightly affect the axial dead load in the columns.

In the first testing phase, the infilled frame described in 2.2 was tested. The objectives of the test are to estimate the failure mode and shear capacity of the infilled frame. The hysteretic loops from the test are shown in Fig.7a. The figure shows that the peak strength was 147 kN. Crack patterns of the test specimen in the first phase are shown in Fig.8. The first diagonal crack was observed at the drift of 0.4%. The load increased until peak strength at 0.5% drift and the specimen was able to deform upto 0.75%. The load resistance began to quickly decline at the drift of 1.2%.

Beyond this drift, crushing failure in the wall and out of plane deformation of the wall was observed, and eventually resulted in the failure of the wall at the drift



a) Concrete b) Reinforcing Bar c) BRB

Fig.11 Stress-strain relationships

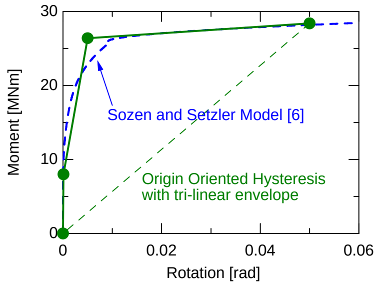
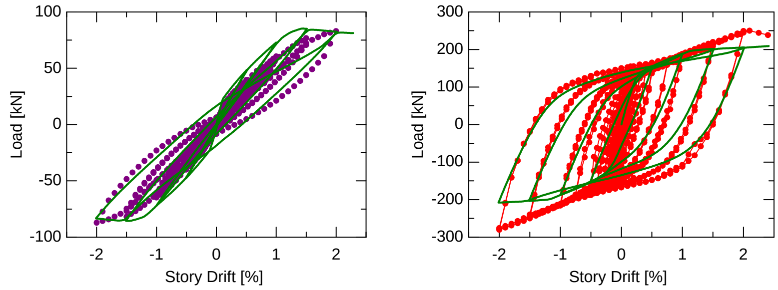


Fig.12 Reinforcement slip model



a) Bare frame b) BRBs frame

Fig.13 Analytical results

of 2%. However, the contribution of the infill wall to the overall strength was very significant in comparison with the bare frame which can be seen in the second testing phase.

3.2 Second Phase

In the second testing phase, the specimen with steel jackets at the top and bottom ends of the columns (Fig.4a) was tested to the drift of 2%.

The main objective of the test was to observe the behavior of the frame without the contribution from the infill wall. The testing result can be found in Fig.7b. The result shows that the peak strength was 87 kN which was significantly smaller than that of the infilled frame. In addition to this, the highly pinched hysteretic loops were observed. This indicated that the bare frame had a limited energy dissipation capability.

For this test structure, the beam was significantly stronger than the columns in bending. From the test, it was found that the beam suffered very little damage.

3.3 Third Phase

In the third phase, the specimen with BRBs installed (Fig. 4b) was tested to the drift of 2%. It was expected that BRBs could be used to mitigate the soft story problem and improve the energy dissipation of the structure. The testing result is shown in Fig.7c. The result shows that the BRBs significantly increased the strength and stiffness of the frame.

The hysteretic loops of the specimen were very stable without pinching. The loops were similar to that of the system with elastic-plastic bilinear hysteretic response. This shows that the BRBs would be able to dissipate the required energy in a small deformation range.

4. NUMERICAL SIMULATIONS

4.1 Analytical Model

The cyclic performance of the bare frame and the frame with BRBs were evaluated by numerical analyses. The test specimens were modeled by using beam elements, bar elements and rotation springs as shown in Fig.9. The details of these elements are given below.

(1) The resisting sectional forces of the beams and columns were calculated by the fiber model. Fig.10 shows the mesh of the sections.

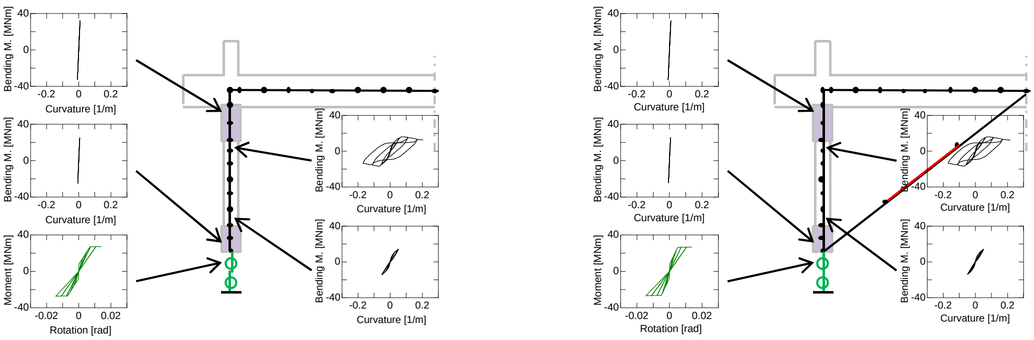
(2) The constitutive relation of plain concrete followed Darwin-Pecknold model [4] and that of jacketed concrete was calculated by the theory of Mander's confinement [5] as shown in Fig.11a. Both behavior of reinforcing steel and steel jackets were assumed to be the Bi-linear (Fig.11b).

(3) M-θ relationship of the rotation springs was used at the bottom of columns in this model. Firstly, the M-θ relationship by the theory of Sezen and Setzler [6] was obtained. Secondly, the trilinear envelope curve was assumed for the relationship. Lastly, an origin oriented hysteresis was applied to the rotation springs (Fig.12). It should be observed that the bar slip can take place not only from the lap splice but also at the RC base. Hence, two rotational springs were used at the bottom of the each column as shown in Fig.9.

(4) The stress-strain relationship for the BRB was modeled by the CEB model [7] as shown in Fig.11c.

4.2 Analytical Results

Fig.13a shows the analytical result of the bare



a) Bare Frame b) BRBs Frame

Fig.14 Moment-Curvature/Rotation relationships in the left column

frame and Fig.13b that of the BRB frame. Both results indicate a good agreement analysis and experimental results with respect to the peak strength, stiffness and loops shape.

Fig.14 shows the M-φ relationship of various sections of the left column including that of the bottom section. The springs at the bottom generated large rotation. In other word, the rotation caused by pullout is quite influential to the total deformation of the soft story frame. In addition to this, Fig.14a indicates that lap-splice yielding occurred at the base prior to reinforcing bars' yielding at the bottom of the columns. The pinched hysteretic response generally associated with a lap-splice failure thus dominated the response and eventually made the overall energy dissipation very limited.

Fig.15 shows the load-displacement hysteresis loops of the BRBs. This figure indicates that the BRBs increased the lateral force capacity and energy dissipation due to its stable hysteresis loops. Consequently, the soft story failure would be less likely to occur in the frame with BRBs than in the frame with infill wall.

5. CONCLUSIONS

(1) Although considered as nonstructural, the infill wall contributed significantly to the lateral strength. However, the load resistance began to suddenly decline in the post-peak range indicating that the infilled frame with nonstructural wall has limited ductility.

(2) BRBs increased the lateral force capacity significantly. In addition to this, the hysteresis loops of the frame were very stable and were able to dissipate large input energy. This would limit the damage to the overall structure under earthquake loading.

(3) The analytical model considering the confined effect of concrete and slip rotation indicated a good agreement. It showed that the rotation caused by the pullout is significant to the total deformation of soft story frame.

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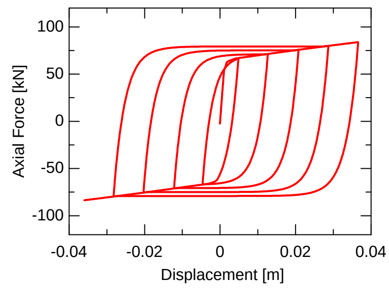

Fig.15 Hysteretic loops of BRB

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