Analytical Study on Seismic Performance of RC frames with Concrete Block Wall

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SUMMARY:
The reinforced concrete (RC) frame incorporated within hollow concrete block (CB) wall is often being used in the construction of building structures in countries where is lower occurrence of earthquake. Normal structural design in Japan about the CB wall has not been treated as a seismic element. In this study, we intended to clarify the seismic performance of CB wall when it is being used as a seismic member, analysed the frames infilled with CB wall by using 3-D nonlinear finite element method (FEM). Based on the analysis results of the research that frame within CB wall under constant axial force and lateral cyclic loads, hysteresis characteristics and failure modes are estimated using an analytical model.

Keywords: Reinforced Concrete, Frame, Concrete Block Wall, Cyclic Loading, 3-D Nonlinear FEM

1. GENERAL INSTRUCTIONS

The concrete block infill walls are often used as an interior or exterior partition in reinforced concrete structure. And it has been known that the CB infill walls in RC frame affect the strength and stiffness of the structure. However how infill wall affects the seismic performance of the RC frame structure is an intricate issue since their exact role in the seismic loading resistance is not yet clearly being understood due to the interaction with the frame. In seismic areas like Japan, structure engineers always ignore the calculation for the reinforcing action of the CB wall while processing their structure seismic design. This is unsafe since the interaction between the wall and the frame under lateral loads dramatically changes the dynamic characteristics of the composite structure and hence it is response to seismic loads. Actually it has been generally recognized that infill walls enhance the response of frame buildings in low to moderate seismic regions, yet they exhibit poor seismic performance under high seismic demand. This behavior is due to the degradation of stiffness, strength and energy dissipation capacity, which results from the progressive damage of the CB wall and the deterioration of the wall-frame interfaces.

Engineers in order to figure out the mechanics action roles of CB infill walls in RC frame in earthquake, as well as improve the existing design methods to make seismic performance of CB wall work well within the frame, variety of experimental studies are in progress. In 2005, Yamakawa et al from the University of the Ryukyus carried out the experimental study to clarify the seismic performance of the RC frames that have been reinforced by the CB wall which is considered as seismic element.

In this study, compared with the experiment, the 3-D FEM analysis study was carried out as a different approach. Through the analytical visualization results such as the structure internal stress, crack propagation etc. those cannot be checked in experiment, verified that the infill CB wall can strengthen shear force behavior under cyclic loads. The main purpose of this study is to gain a better understanding of the seismic behavior of frame with CB infill wall and then improve the accuracy of analytical study about modelling and to establish more valid analysis method.

2. OVERVIEW OF ANALYTICAL

2.1. Analytical specimens

Four specimens included in the experimental study were tested by the Yamakawa research group from University of the Ryukyus in 2005. In this analytical study, we chose three specimens for FEM analysis target including RC-Frame (the pure RC frame as base specimen), SW-Frame (base on the RC-Frame reinforced by shear wall) and CB-Frame (reinforced by concrete block wall). The details of specimens are given in Fig. 1, and Table 2.1.1, 2.1.2 lists the material properties about concrete, concrete block and reinforcement which are being used in the analytical study. The two reinforced specimens were based on the same reference specimen, so frames have same bar arrangement and material properties in columns, beams and bases. For comparing the reinforcing performance and verify reinforcing efficacy of the CB Wall, the study consider as the parameter about weather having reinforcing wall and different reinforce methods (the normal method of infill shear wall). The dimensions of the frame at column and beam are 175mm×175mm and 125mm×250mm, and all models were made in 1/3 scale of the actual size as experiment test. The Fig. 2 shows the details of CB-Frame specimen can be used as reference. The characteristics of materials used in this analysis are the same as those in the experiment.

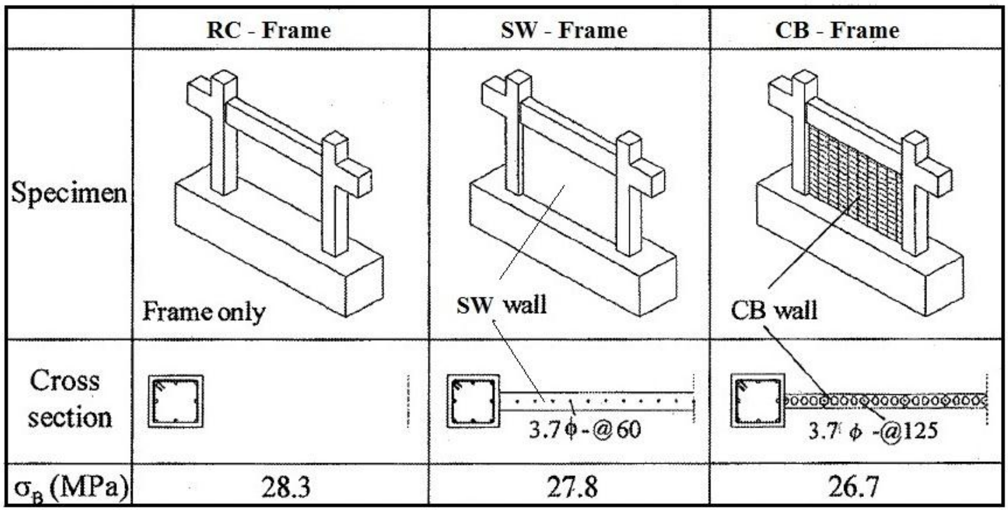


Figure 1. Details of specimens

Table 2.1.1. Characteristic of Concrete

Concrete				
Space Name	σ_B (MPa)	ε_{max} (μ)	σ_c (MPa)	E_c (GPa)
RC-Frame	28.3	2000	2.8	23.5
SW-Frame	27.8	2000	2.7	23.5
CB-Frame	26.7	2000	2.6	23.5
(CB)	13.6	-	1.3	18.1

Table 2.2.2. Characteristic of Reinforcement

Reinforcement					
Reinforcement		Dia. (mm^2)	σ_y (MPa)	E_c (GPa)	ε_y (μ)
Main Rebar	D10	71	349	202	0.17
	D13	127	342	202	0.17
Hoop, stirrup	D6	32	423	175	0.24
Foop	3.7φ	11	650	208	0.31

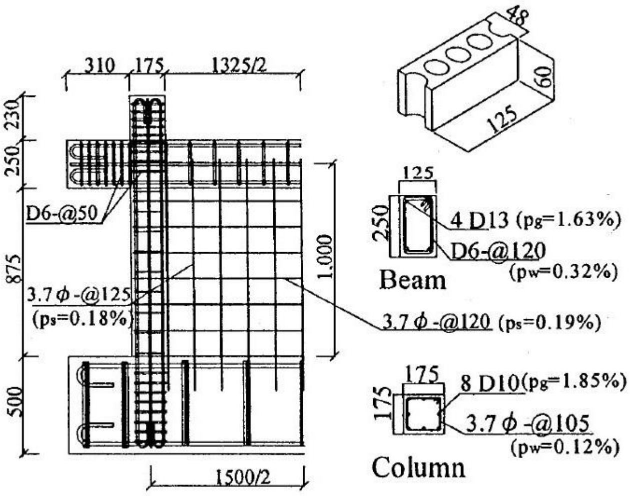


Figure 2. Details of CB-Frame specimen

2.2. Analytical models

In this study, the analysis was carried out by 3-Dimensional FEM analysis program incorporated with a cyclic load model, which are developed by Yu and Noguchi et al. (Yu 2004) and refined by Hong et al. (Hong 2006). Concrete was expressed by using 8-node solid elements, and reinforcements were expressed by using 2-node linear elements which only having axial direction stiffness.

The failure criterion of the concrete was expressed using the 5-parameter model by William-Warnke et al (William 1974). As shown in Fig. 3, the Saenz equation (Saenz 1964) was used for the concrete compression increase curve, and a straight line was used for the compressive softening region. While the Kent-Park equation (Kent 1971), which considers the restraining effect of the lateral reinforcements, was used for the descending section. The Nuguruma-Watanabe model (Nuguruma 2000) was used to calculate the convergence point.

The crack model was expressed by using the rotating crack model, the decrease in compression strength of cracked concrete was expressed by using the Noguchi-Iizuka equation (Noguchi 2002) and shear transmission characteristics in the direction of the crack was expressed using the Aoyagi-Yamada model (Aoyagi 1983). A corrected Menegotto-Pinto model (Menegotto 1973) was used to express the stress-strain relationship of the reinforcement. In this analysis, the characteristics of bond behavior between reinforcement and concrete were not considered.

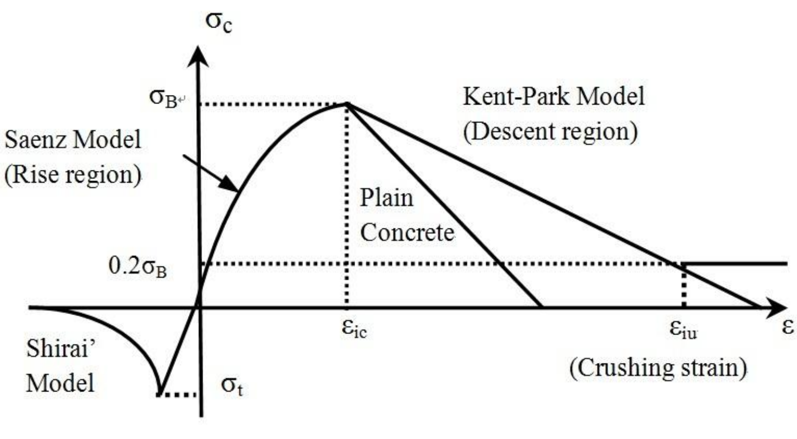


Figure 3. Concrete model

2.3. Analytical methods

Fig. 4 shows the loading apparatus in experiment. According to the experiment, all specimens in analysis were used the same boundary conditions that were showed in Fig.6. Since the element mesh according to the actual reinforcement, it should be taken much time on analysis calculation being caused by excessive number of nodes and elements. Therefore, the finite element discretization of the specimens were split in half in the Y-direction due to its symmetry, with the cutting surface being a Y-direction surface that is roller-supported. Besides, adjust the spacing of the reinforcement and enable the rebar arrangement being equal to the experimental ratio of reinforcement to reduce the number of rebar element.

The loading has two steps and each step with different boundary condition. First step for axial force is load control, constant force (0.2 ratio of concrete compression) is loading at the top of two columns and at the same time the bottom surface of the lower base is restrained in X-, Y-, and Z-directions. Second step for horizontal cyclic load is under displacement control, it was used inverse symmetry method to keep the upper beam and lower base in a horizontal direction. Both sides of the beam are bound in X-direction with roller and then the cyclic loading in X-direction was subjected to the side of the base. Loading information is shown in the Fig.5. Horizontal displacement δ=1.25mm,2.5mm were loaded for one time and from the δ=5mm to 30mm the displacement were loaded for two times for the cyclic loading (including 7.5mm) of a 5mm increments.

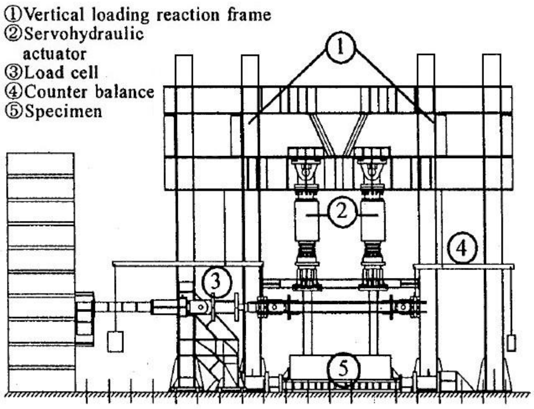


Figure 4. Experiment test setup

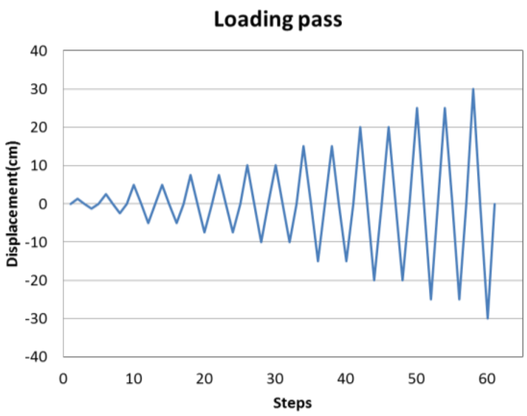
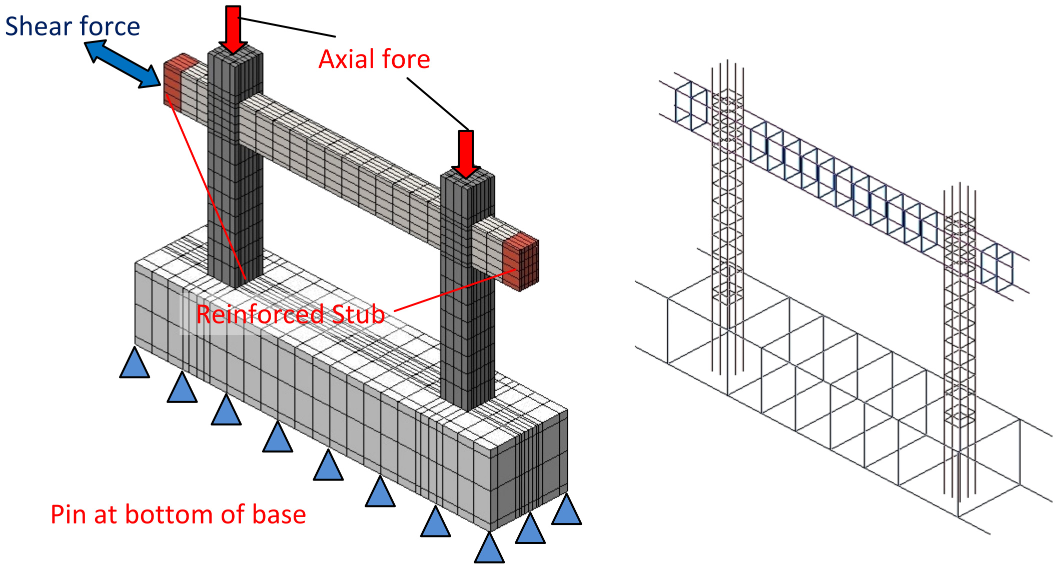


Figure 5. Loading information



a) Mesh and boundary condition

b) Rebar element (truss)

Figure 6. Analytical models

3. ANALYTICAL RESULTS

3.1. Relationships between story shear force and story displacement

The comparing of experimental and analytical results about the relationships between stories shear force and story displacement is shown in Fig. 7. First figure is the base specimen of the RC-Frame. The analysis result presented almost the same initial stiffness and similar hysteresis loop during the cyclic loading compared to the experiment. For the specimen of CB-Frame, it can be seen that the analysis presented a litter higher initial stiffness and the same maximum shear strength values about 270kN compared to experiment. Because of the mortar between the concrete block was ignored in modeling and made in an integration model when dividing the element, so the decline of the strength since the maximum value was not as large as that of the experiment. For the SW-Frame reinforced by shear wall, it also presented a well accordance about initial stiffness, but the maximum story shear was a litter higher and faster to reach the peak value than that of the experiment.

The figure of lower right showed the comparison of the analytical result among analysis companions. Through the comparison, it can be clearly seen that the infill CB wall reinforcing method has more than doubled times of shear strength than the pure frame without reinforcement, and it is also possess nearly 1/2 strength of SW-Frame reinforcing method. For the deformation capacity, the specimen of the pure frame demonstrated lower shear strength but better deformation capacity.

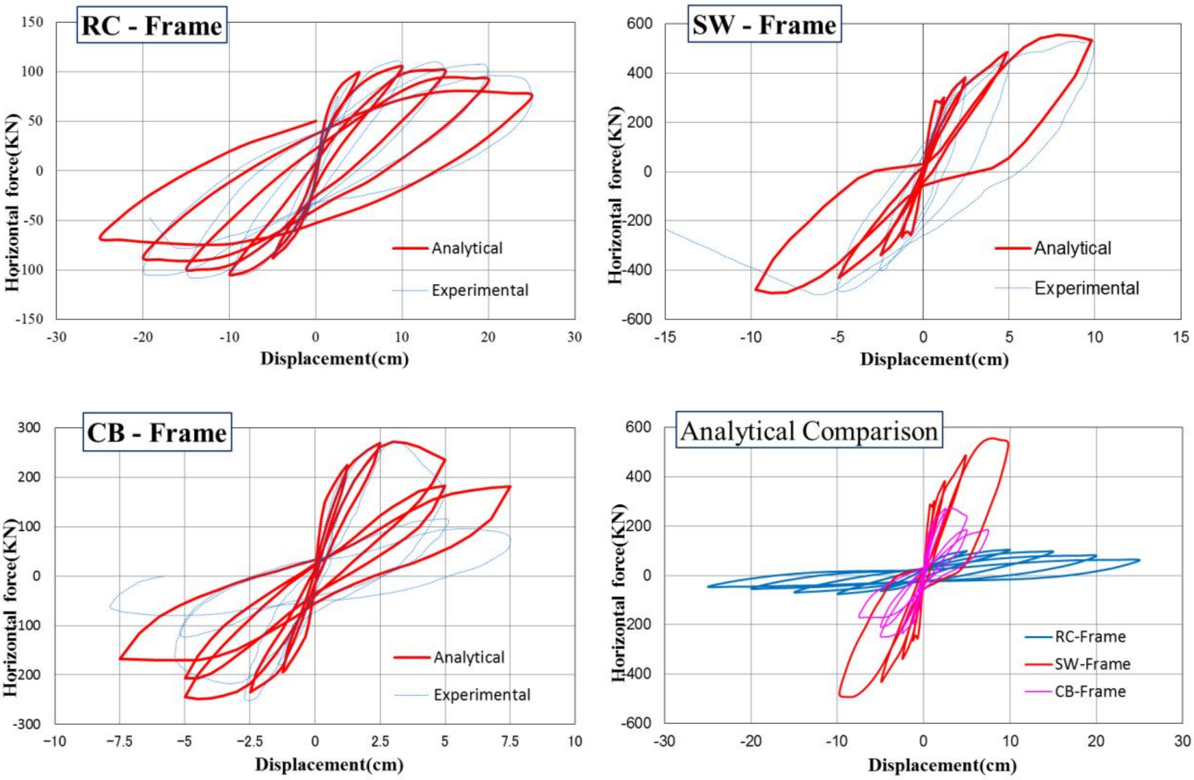


Figure 7. Relationship between story shear force and story displacement

3.2. Concrete compressive stress contour and crushing condition

The principal stress contour at maximum strength of concrete and the crushing condition (10-fold magnification deformation) of each specimen is indicated in Fig 8. The starting of crushing was defined as the strain exceeds the strain at compressive strength of concrete.

As it can be seen in Fig. 8, the compressive stress is mainly focus on capital and column base in compression side of column, and arch mechanism is formed on the diagonal direction of the column in

RC-Frame specimen. It is understood that crushing started from the compressive side at bottom of the column and the corner of Beam-Column Joint, and those results consistent with the experimental. In the SW-Frame specimen, it can be seen that the high compressive stress is spreading in the Shear Walls means shear walls share more stress from lateral shear force. The crushing of concrete first appeared in the shear wall especially boundary area where near the column. The CB-Frame specimen, the strain has spread in the entire wall from the upper left corner to the right side column of. Crushing situation is different to the experiment, it can be considered that ignoring the interface reaction of wall and frame caused the shear -slips action among the concrete block wall was not being expressed.

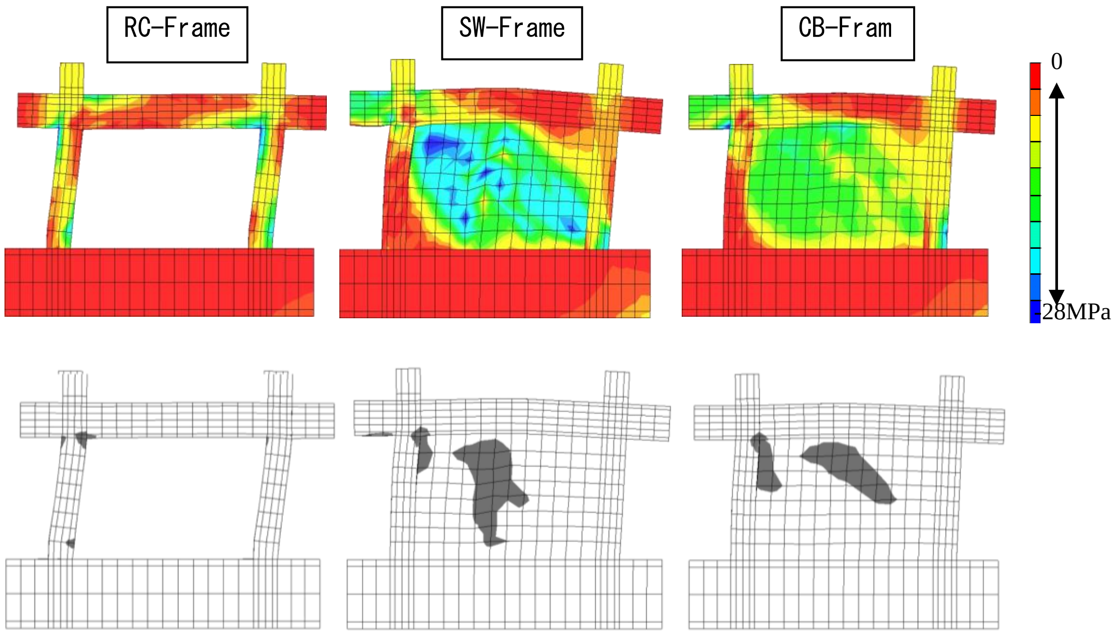


Figure 8. Concrete compressive stress contour and crushing condition

3.3. Crack propagation in concrete

Fig.9 shows the crack distribution in analytical models at the time of the maximum strength of structures and the upper one show the ultimate crushing stage of the frame in the experiment. In this study the cracking of concrete is assumed as the tensile principal strain is beyond the strain at maximum tensile strength. Cracking has been represented by the circle, and if the color of the circle appears much closer to blue, which means the wider cracking is. In addition, the slope of the circle indicates the direction of the crack.

For the RC-Frame, the cracking first occurs in the tensile side of structure, with the increased deformation, the cracking concentrated in bottom and tops of columns have become prominent. In specimen of SW-Frame, first the flexural crack can be confirmed in bottom column, and then the thin crack spread in shear wall and much larger cracks appeared in tensile side of the joint can be seen clearly. It can be confirmed that under the cyclic loading the X figure cracking was concentrated on the shear wall and the analysis results can be represented well to the experimental of cracking propagation.

In CB-Frame, the crack progress is approximately the same as that in SW-Frame specimen in analysis because the slip characteristic of the concrete blocks was ignored. The crack progress in the CB wall was not creating the same effect as that of the experiment, but acted well on the frame of columns and beams. It is difficult to simulate the shear force-slip characteristic in CB wall, so the shear slip crushing in CB wall cannot be observed in present analytical study.

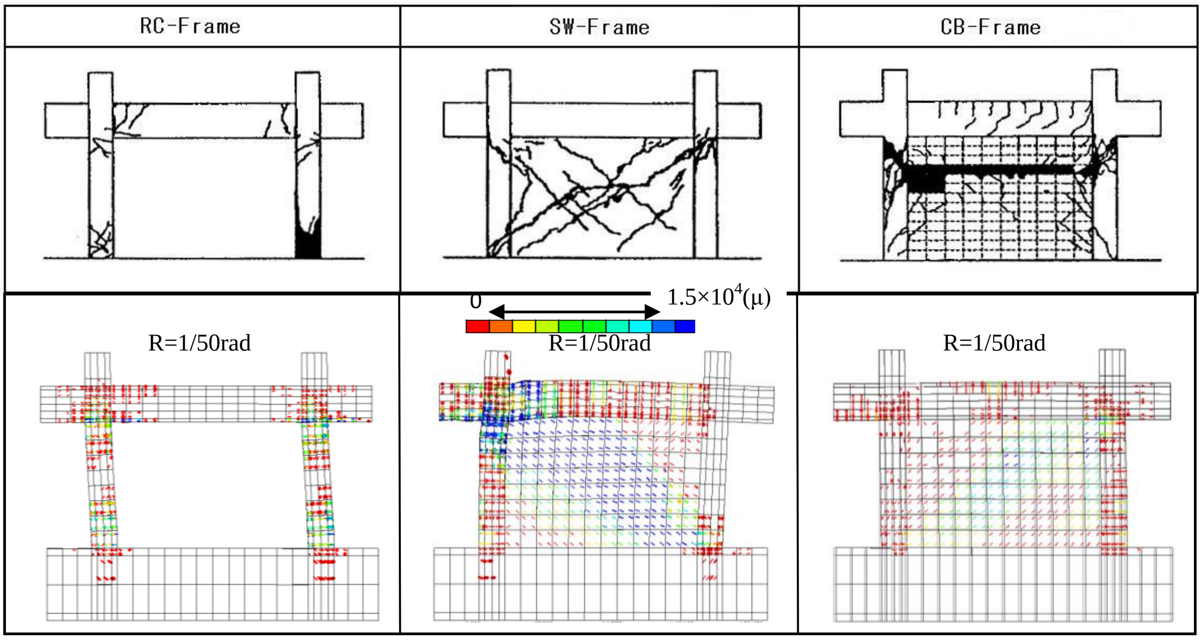


Figure 9. Comparing of Crack patterns

3.4. The cumulative strain energy consumption

The percentage of the cumulative burden of strain energy consumption at the maximum strength of frame which is reinforced by CB wall and Shear wall specimens is being showed in Fig 10.The definition of the cumulative strain energy consumption is according to the following expressions:

$$\Delta U = \int_V \int_{\varepsilon_i}^{\varepsilon_j} \sigma_{ij} \cdot d\, \varepsilon_{ij} \cdot dV \tag{3.4.1}$$

$$U = \sum \Delta U \tag{3.4.2}$$

Each symbol in the equation (3.4.1, 3.4.2) is discussed below.
U: Cumulative strain energy, V: Volume of element, ε_{ij}: Strain increment, σ_{ij}: Average stress.
The columns, beams and wall in the CB-Frame specimen have amounted to 18%, 3.2%, and 25% of the energy consumption. For SW-Frame, each has reached to bear 41.5%, 15% and 62% of the total cumulative energy consumption.

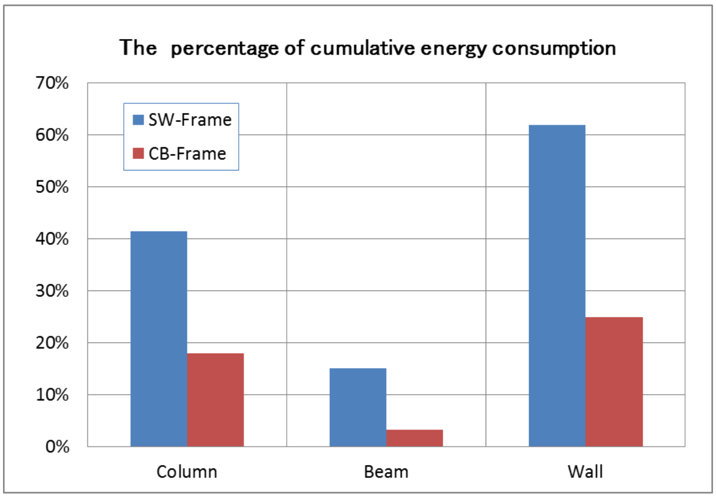


Figure 10. The percentage of cumulative energy consumption

4. CONCLUSIONS

(1) All specimens for the maximum shear strength and stiffness from the FEM analysis results are well consistent with the experiment. The shear strength of the CB-Frame can be expected to increase about 150KN degree compared to the pure frame. In addition, compare to the SW-Frame which reinforced by shear wall, CB-Frame can also reach a 1/2 yield strength of the SW-Frame.
(2) The failure type and cracking can be successfully estimated from the FEM analysis results. But the interaction properties between the mortar and concrete block, CB wall and frame were not being expressed completely, in order to grasp the exact details of mechanical behavior in FEM analysis; it is necessary to modelling faithfully and considering the interaction of dissimilar materials for specimens in future study.
(3) Respect to the relationships of story shear force and displacement, the analytical result show better agreement with the previous experiment study. However, about the hysteresis loops especially for the SW-Frame, the analysis presented a little different shape to the experiment. The material models and the boundary conditions on the analysis should be re-examined.
(4) The result of energy consumption shows that the SW-Frame has a higher energy absorption capacity compared to other specimens. The stress transfer in frame was changed by infill CB wall and its share part of the seismic energy has heightened the overall seismic intensity.

AKCNOWLEDGEMENT
The authors wish to express gratitude to Mr Bayarsaikhan, an undergraduate of Chiba University. A part of this study was performed by Bayarsaikhan as partial requirement for the Bachelor's degree.

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