Experimental studies on side columns of a RC frame with soft 1st story designed on the assumption of different failure modes

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SUMMARY:
In this paper, structural performances of side columns of RC frame with soft story designed on the assumption of different failure modes are described based on the result of substructure pseudo-dynamic tests. The characteristics of this method are that two RC column specimens can be loaded simultaneously. In the tests, two loading systems of RC specimens represent side columns of the first soft story floor. The integration method using the operator-splitting method was applied in the tests. To assume RC frames, which are a part of single frame of a building, two different failure modes, flexural yielding in the soft story columns ('Story collapse type') and flexure fracture mechanism in a whole frame by yielding the whole reinforcement of the tensioned side of the column in the soft story ('Flexural collapse type'), were applied. The pseudo-dynamic tests were executed successfully, and characteristic structural performances of side columns, which effect to seismic response to the whole frame, were elucidated.

Keywords: Online test method, Substructure pseudo-dynamic test, RC column, soft story building

1. INTRODUCTION

In this paper, structural performances of side columns of RC frame with soft 1st story designed on the assumption of different failure modes are described based on the result of substructure pseudo-dynamic tests.
It is recognized that especially for multistory RC frame buildings with soft story, the side columns or corner columns may encounter drastic varying axial load during strong motion. This type of building has been exposed to seismic damage in past earthquakes in Japan such as 1995 Hyogoken Nanbu Earthquake (Great Hanshin Earthquake), 1978 Miyagiken-Oki Earthquake and so on. As the most observed damage mechanism of the building is a collapse in the soft story, considerable structure design has been required. According to the Building's structural technical criterion in Japan (2007), a story-collapsed failure mechanism is allowed in so far as to ensure that the soft story has enough requisite strength and deformation capacity under earthquake ground motions.
To confirm these deformation, strength and cyclic deterioration capacities, it is important to understand seismic behavior of the building, especially the behavior of the soft story, in detail. To examine these behaviors, it is necessary to combine two methods, a tested part for corner column and an analytical part for the other frames, simultaneously. The authors have already developed a substructure pseudo-dynamic test method, which can add varying axial loads caused by random seismic motion to two RC column specimens (Teramoto et.al, 2008). The characteristics of this method are that two RC column specimens can be loaded simultaneously and also that the inflection point of the columns can be changed by loading moment to rotate the top of the column.
In this work, substructure pseudo-dynamic tests were performed for two kinds of RC frame with soft first stories designed on the assumption of different failure modes, and investigated the different behaviors of side columns such as axial force, structural damage and energy dissipation.

2. OUTLINE OF THE TEST

2.1. Outline of the Failure Modes of the Soft Story Buildings

According to the Description of building's structural technical criterion in Japan (2007:685-703), desirable examples of the failure modes of the soft story buildings are 'Story collapse type' and 'Flexural collapse type'. The outline of the failure modes are shown in **Figure 1**.
'Story collapse type' is a failure mode caused by flexural yielding in the soft story columns. As the damage of this type of building is limited to the soft story columns, the seismic resistance capacity of the building is required to be larger than the other types of frame buildings. The necessary ultimate horizontal resistant force of the 'Story collapse type' building should be added as a function related to story stiffness ratio or number of building stories.
On the other hand, 'Flexural collapse type' is a flexure fracture mechanism in a whole frame, the failure mode of which caused mainly by an overturning moment, by yielding the whole main reinforcement of the tensioned side of the column. As the axial displacement of the column could absorb seismic energy more stable than share displacement, the 'Flexural collapse type' would be good for ductile behaviour, the damage process of which is different from the 'Story collapse type'.

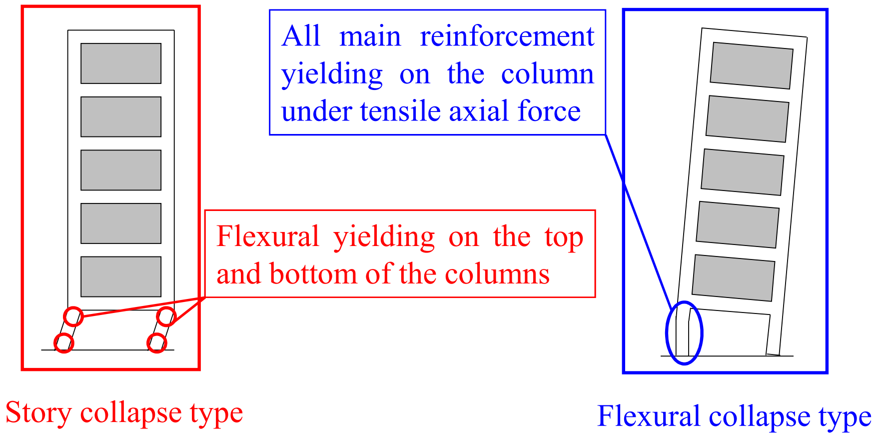


Figure 1. Outline of the failure modes of the soft story buildings

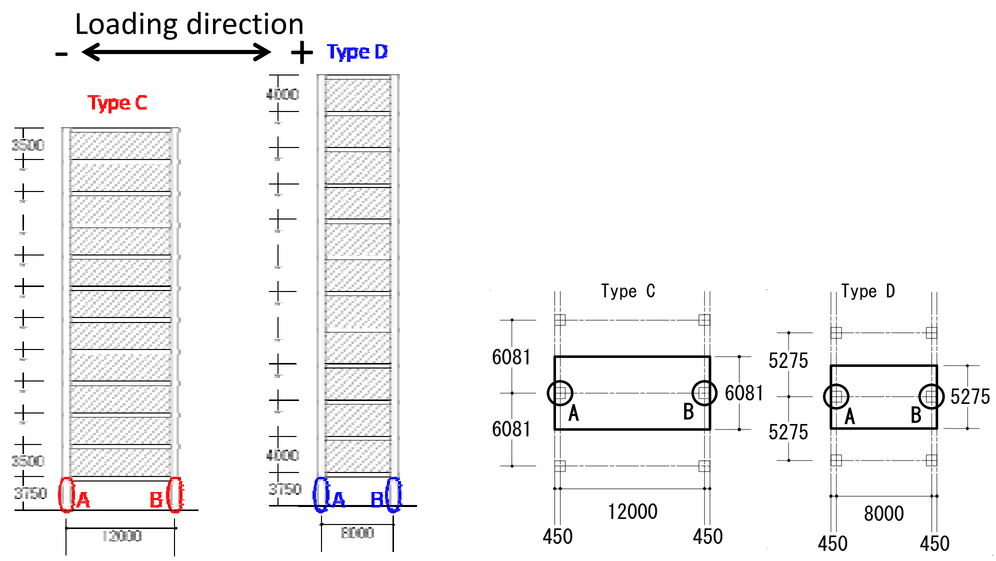
2.2. Building Models

The outlines of the frame models are shown in **Figure 2**. The two side columns of the soft first story (shown by A and B in **Figure 2**) are the tested parts, which are replaced with two specimens. These model frames are a part of single frame of a building. Each frame model has 12 stories and one spans. Shear walls of 200mm depth were added to second - twelfth floors. The length of each span is 12,000mm and 8,000mm, respectively. The height of each first floor is 3,750mm and the height of each second - twelfth floor is 3,500mm and 4,000mm, respectively. In this test, different failure types of soft story reinforced concrete building model, that is, 'Story collapse type' [**Figure 2(a)**] and 'Flexural collapse type' [**Figure 2(b)**], were applied. Hereafter, the 'Story collapse type' is referred to as Type C, and the 'Flexural collapse type' as Type D. The first story columns of Type C were designed so as to yield by bending at the top and the bottom of each column. For the Type D, the first story column on the tensile axial force side was designed so as to yield all main reinforcement however, column on the compression axial force side was designed not so as to yield by bending and shear failure at any part of the column. The respective base shear coefficients of Type C and Type D are 0.32 and 0.26, respectively. In the tests, the fixed base condition was adopted. Therefore, the first floor columns are connected directly to the base.

2.3. Specimens of Tested Part

The outline of the specimen is shown in **Figure 3**(a) and **Table 1**. The dimension of the specimen was 300x300mm section and 1,000mm height, which was 1/3 scale of the frame model. As shown in

Table 1, two different patterns of tests were executed. The test parameters were the frame model (Type C and Type D). In each test, two specimens, specimen A and specimen B, were used as the side columns of the first floor. The yielding strengths of the longitudinal and transverse reinforcement were 370/mm^2 and 440N/mm^2, respectively. The compressive strength of the concrete was 32N/mm^2.
The test setup is shown in **Figure 3(b)**. One of the characteristics of this work is to use two specimens for two side columns of the first floor as described in 2.2. Therefore, two sets of test loading systems were prepared.
Here, each specimen must interact simultaneously with other beams, columns and wall as a part of the frame. Therefore, four static hydraulic jacks were installed to each specimen so that loading with three degrees of freedom (horizontal direction, vertical direction and rotational direction at the top of the specimen) could be performed. The middle jack in the vertical direction had a force capacity of 2MN and the force capacities of other two vertical jacks and one horizontal jack were 500kN. The controller of each jack can adopt either force- or displacement - control independently.
Digital displacement transducers were used to measure displacements and rotational angles. The digital displacement transducer can measure the displacement with a resolution of 1/1000 mm. The difference between the target displacement and the current displacement was set at ±3/1000mm, and the loadings in the three directions were performed simultaneously. Two more jacks were added to maintain the horizontal deformation in the direction perpendicular to the loading direction at 0.



(a)Story collapse type (Type C) (b)Flexural collapse type (Type D) (c)Plan of the frame

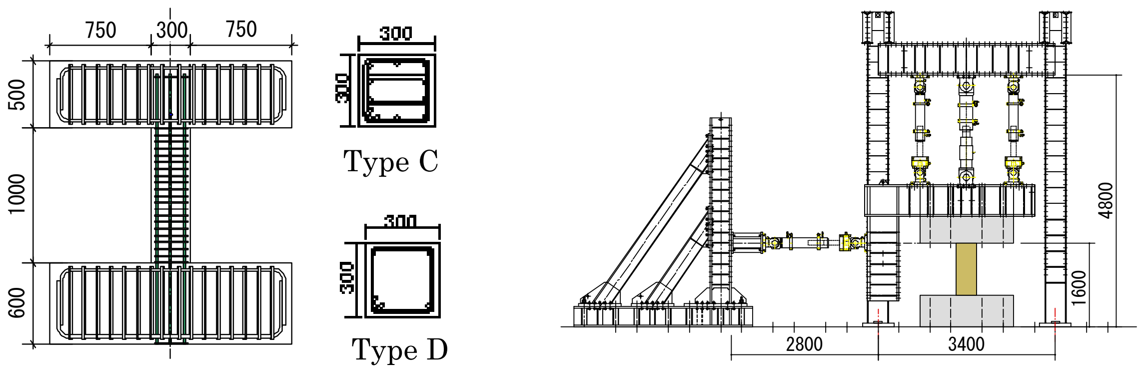
Figure 2. Outlines of model frames [mm]

Table 1. Outlines of the specimen (Columns of the soft first floor)

Frame No.	Falure type	Cross Section [mm]	Height [mm]	Main reinforcement (ratio)	Hoop (ratio)
Type C	Story collapse	300×300	1,000	10-D13 (1.41%)	4-D10@50 (1.89%)
Type D	Flexural collapse			4-D16 (0.88%)	2-D10@50 (0.95%)

2.4. System Setup of Substructure Pseudo-dynamic Test

The pseudo-dynamic test system used in this work is shown in **Figure 4.** The system consists of two sets of tested part, the analysis and main management part (PC for numerical analysis and main management), and the data acquisition part (PC for measurement). The main management part controls the total system during the tests. The main PC is connected to the computers for control (1) and (2), which control the tested parts, by LAN (TCP/IP) cables. The main PC is also connected to the PC for measurement via a RS232C serial cable, through which the main PC sends command signals to each part, such as the target displacement and forces assigned for the tested parts, and data acquisition part after each loading step is completed.



(a) Details of the column specimen (b) Loading system

Figure 3. Test setups

Each pump controller for Speciman was connected to the PC for control via RS232C serial cables, and each loading setup was controlled by the PC using programs developed in this study. In this setup, the jack in the horizontal direction was placed at the same height as the underside of the top stub of the specimen and used for horizontal seismic loading. The axial force, which includes varying axial force exerted by the vertical load, was controlled by the middle jack in the vertical direction. Two other jacks were used to control applied force in the rotational direction. Each degree of freedom is controlled by displacement in this test.

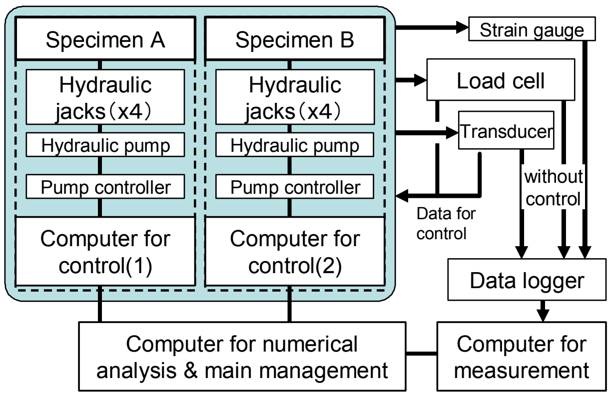


Figure 4. Outline of the substructure pseudo-dynamic test system

2.5. Algorithm of Substructure Pseudo-dynamic Test

The integration method using the operator-splitting (OS) method was applied in the tests. This method has been used in many substructure pseudo-dynamic experiments, and makes it possible to calculate earthquake response under the interaction between the specimen and the whole frame. The formulations of this method proposed by M. Nakashima et al.(1990:515-524) and P. Pan et al.(2005:869-888) are as follows:

$$Ma_{n+1} + Cv_{n+1} + K^I d_{n+1} + K^E_{n+1}\tilde{d}_{n+1} = P_{n+1} \tag{1}$$

$$\tilde{d}_{n+1} = d_n + \Delta t v_n + (\Delta t/2)^2 a_n \tag{2}$$

$$d_{n+1} = \tilde{d}_{n+1} + (\Delta t/2)^2 a_{n+1} \tag{3}$$

$$v_{n+1} = v_n + (\Delta t/2)(a_n + a_{n+1}) \tag{4}$$

Here, which K_I and K^E_{n+1} are the linear and non-linear stiffness matrices, M and C are the mass and viscous damping matrices, $\tilde{d}$ and d are the predictor and corrector displacement vectors, v and a are the velocity and acceleration vectors, and Δt is the integration time interval, respectively. The characteristic of this method is to divide the stiffness of the whole structure into a linear stiffness for the analysis part and a non-linear stiffness for the tested part (specimen). For the non-linear tested part, the explicit predictor-corrector method was used. By associating the non-linear stiffness with the linear stiffness integration method, the Newmark-β method could be applied to the whole part.
In the tests, the integration time was set at 0.01 s. The Rayleigh damping was applied and the viscosity damping property was set at 5%. El Centro (EW direction) was chosen as the input ground motion. The test was divided into 4 levels (Run 1 to Run 4), from the weak elastic response level to the strong plastic response level. The maximum acceleration of input ground motion for each level is shown in **Table 2**.

Table 2. Input levels of each frame

Input Levels	Maximum Velocity [cm/s]
RUN1	25
RUN2	50
RUN3	75
RUN4	100

2.6. Analytical Models of the Frame

The shear wall combined with the middle column and the columns on the both sides were modelled as a single line element, and five multi-springs (MS) were set on the both ends. The outlines of the respective models are shown in **Figure 5**. The tri-linear hysteretic model was used for the inelastic rotational springs.

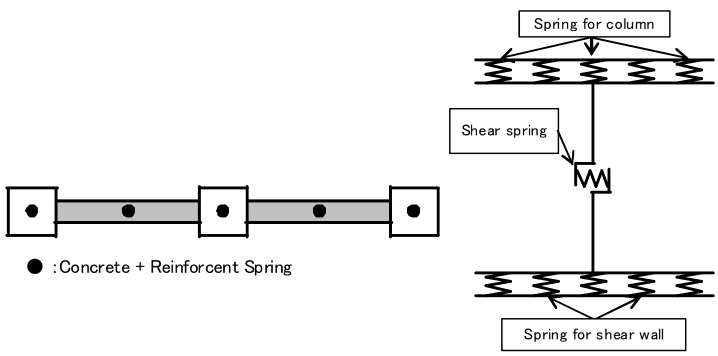


Figure 5. Applied analytical model

3. RESULTS OF THE TEST

The experiments could be successfully performed by the end of Run 4. **Figure 6.** shows the relationships between base shear coefficient and horizontal drift. In Type C test, the main reinforcement of the specimen on the first floor yielded by bending during Run 2. The maximum base shear coefficient of the test during Run1 to Run4 was 0.41 and the maximum horizontal drift of the test was 3.55 x 10^{-2} rad. In Type D test, the failure mode of which was 'flexural collapse mode', the main reinforcement of the specimen yielded when the axial force was on the tensioned side during Run 2. The maximum base shear coefficient of the test during Run1 to Run4 was 0.47 and the maximum horizontal drift of the test was 1.24 x 10^{-2} rad, the value of which is less than that of the Type C test. The hysteresis loop area of Type C was larger than that of Type D.

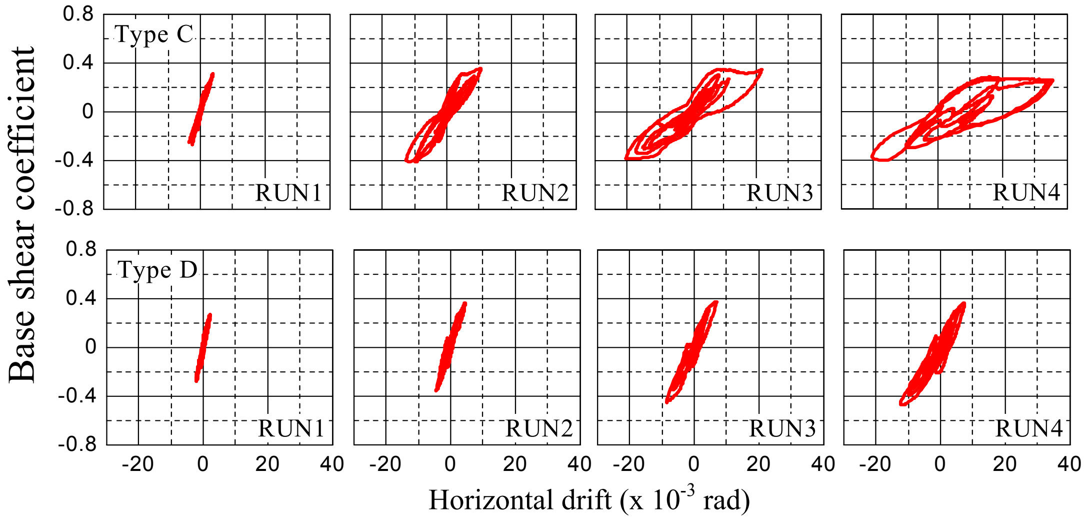


Figure 6. Relationships between base shear coefficient and horizontal drift

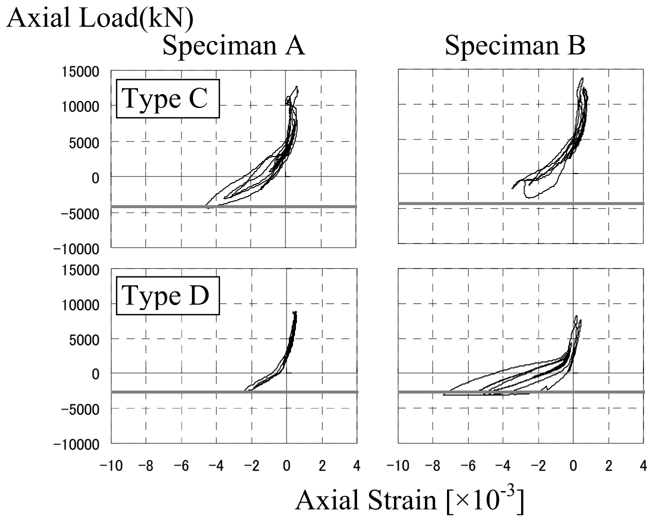


Figure 7. Relationships of axial load and axial strain

Figure 7. shows the relationship between the axial load and axial strain of the each specimen. The specimens A and B represent the left and right columns of the frame, respectively. The gray lines in the figure show the expected maximum axial tensile load, which is calculated from yielding strength and section area of the whole main reinforcement of the specimen. Because of the difference of failure mode, it can be obviously seen that in the axial tensile side of the column, maximum axial strain of Type D is larger than that of Type C. The maximum tensile axial load and tensile strain of the column in Type C test was 4,400kN and 4.6 x 10^{-3}, and that of Type D was 3,100kN and 7.4 x 10^{-3}, respectively. The maximum axial load ratio (ratio of the maximum axial load to the expected axial load) of Type C and Type D were 1.05 and 1.18, respectively. The maximum axial load ratio of Type C was more than 1.0 however, not of all main reinforcement of column were yielded. Unlike in the comparison result of hysteresis loop area in **Figure 6.**, the hysteresis loop area in the case of axial load - axial strain relationship of the column of Type C was smaller than that of Type D. This result

indicates that the Type C frame and the Type D frame have different energy consumption mechanisms.

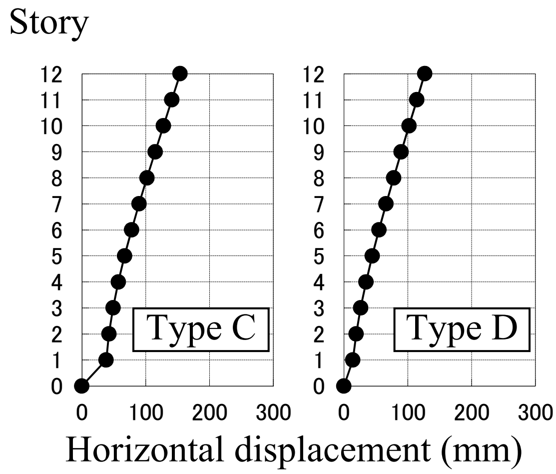


Figure 8. Maximum horizontal displacement of each story (RUN2)

Figure 8. shows the maximum horizontal displacement of each story in Run2. Here, the maximum horizontal displacement is an absolute displacement of each story. In general in the case of soft story building, relative displacement of first story was larger than other story. The same tendency can be shown in the results of Type C frame however, in case of Type D, most of all relative displacements of second story to twelfth story were similar to the relative displacements of first story. This is in agreement with the failure mode of each frame.
Damage patterns observed after the tests of Run2 and Run4 are shown in **Figure 9**. In Type C test, bending cracks were observed in the specimen during Run 2, and finally, the cracks observed in Run 2 developed and when the axial force was larger, peeling of cover concrete was observed both on the top and bottom of the specimen during Run3 and Run4. On the other hand, in Type D test, horizontal crack due to large tensile axial force of the column was observed evenly along the column in axial direction. Eventually, the crack and peeling damage in Type D test was less than that in Type C.

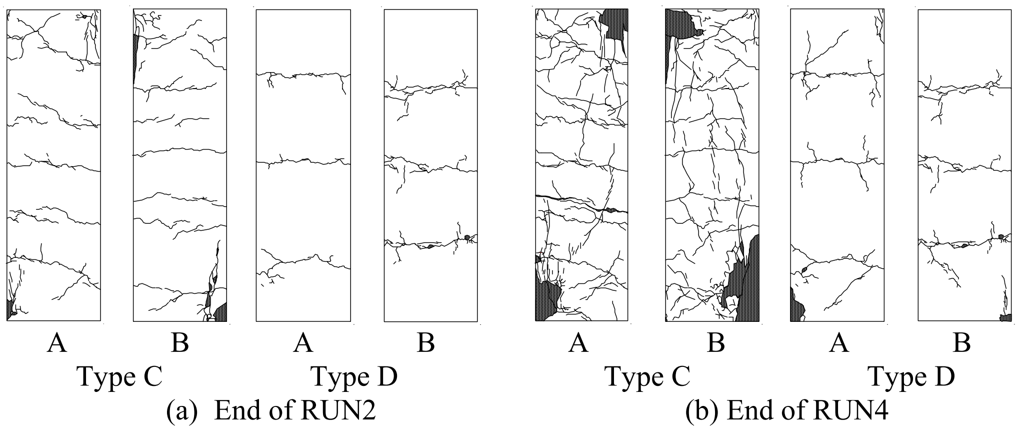


Figure 9. Crack patterns of specimen after test

4. STUDY IN TERMS OF ENERGY CONSUMPTION OF THE EACH FRAME

The soft story building suffered almost all damages of the frame in the first story. These damages can be divided mainly to two types of damages, the damage due to flexural failure at the top and bottom of the columns mainly caused by shear displacement, and the damage due to main reinforcement yielding caused by axial displacement. In general, damage due to flexural failure of the columns was the only damage in which would make consideration. However, the test results show obviously that the damage due to axial displacement should be also taking into account. Therefore, study in terms of energy consumption of the Type C and Type D tests was executed.

Time history of energy consumption in each Run in Type C and Type D tests were shown in **Figure 10.** Here, the energy consumption was calculated from the integration of a hysteresis area obtained from the envelope curves of the test. The energy consumption due to flexural failure, shown 'horizontal direction' in **figure 10.,** was obtained from hysteresis area of relationships between base shear coefficient and horizontal drift, some examples of which is shown in **Figure 6.** The energy consumption due to axial direction, shown 'axial direction' in **figure 10.,** was obtained from hysteresis area of relationships of axial load and axial strain shown in **Figure 7.**
In the Type C test, energy consumption due to 'horizontal direction' shares about 60 to 70% of total energy consumption. On the other hand, energy consumption due to 'axial direction' shares 65 to 80% in the Type D test.

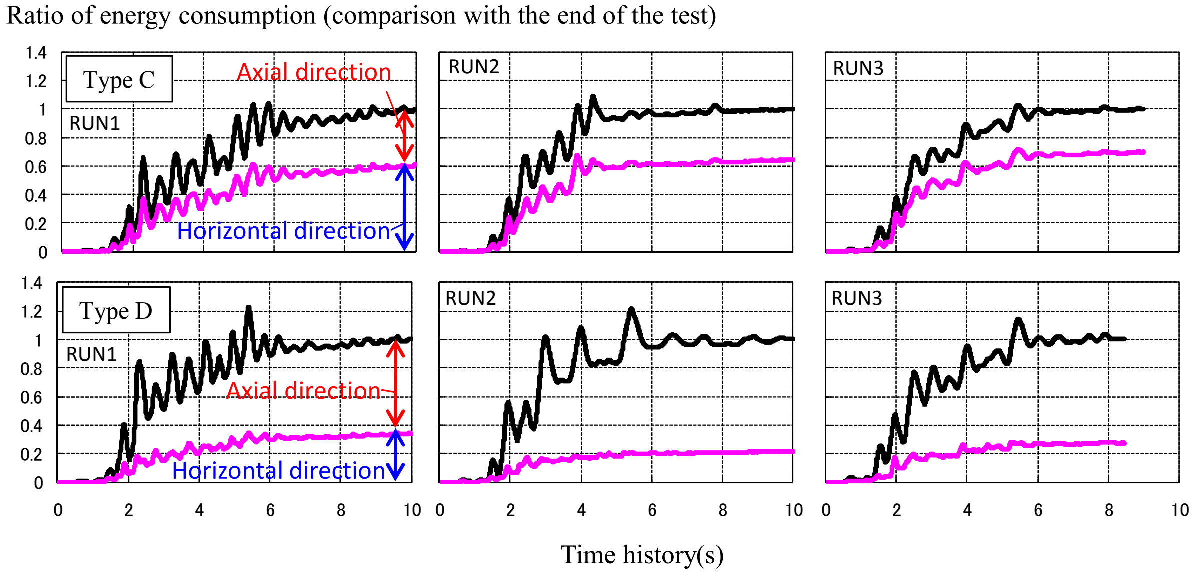


Figure 10. Time history of energy consumption

5. CONCLUSIONS

A series of substructure pseudo-dynamic tests was successfully performed to investigate the dynamic behavior of the side columns in the first floor of soft story RC frames, which has different failure modes, the shear collapse type and the flexural collapse type. From the test results, it was found that the damages of the first story column of each frame were different depend on the failure mode. As a result, soft story frame with flexural collapse type is less damaged than those with story collapse type. It was mainly due to the different types of damages which suffered to columns, the horizontal displacement and the axial displacement.

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