Proceedings of the 8th U.S. National Conference on Earthquake Engineering
April 18-22, 2006, San Francisco, California, USA
Paper No. 1615

EARTHQUAKE COLLAPSE TESTS OF MINIATURE STEEL FRAME MODEL USING LARGE CENTRIFUGE MACHINE

A. Wada[1], S. Yamada[2], M. Takazawa[3],
M. Seki[4], H. Katsumata[4], S. Higuchi[4], and H. Okuda[4]

ABSTRACT

To achieve the safety of building structures under earthquake excitation, the clarification of collapse mechanism is essential. However there has been little experiment research on collapse behavior of structures subjected to earthquake excitation due to many difficulties of shaking-table tests of full-scale structures. When 1/N scale model is used as a specimen, the stress field on the model is inevitably underestimated by 1/N since area and weight become $1/N^2$ and $1/N^3$, respectively. In this study, in order to consider the realistic gravitational effects, shaking-table tests on the reduced-scale model are carried out using large centrifuge machine. Here, the realistic gravitational effects can be accomplished even using the reduced scale model since the gravitational field is inversely proportional to the scale in the centrifuge. By making use of this experimental system, complete collapse behavior of 3-story steel moment frame was simulated successfully. This paper summarizes the experimental data on collapse behavior of reduced scale model obtained through the dynamic centrifuge tests.

Introduction

The clarification of collapse mechanism of structures is important for achieve the safety of structures during an earthquake motion. The most accurate method to clarify the collapse mechanism would be to carry out shaking table tests using full-scale structural models. However, due to several problems including performance limitation of shaking table, costs of experiments, and the safety of experiments, it would be difficult to shake the structure to the level of complete collapse. Moreover, experiments using a reduced scale model under 1G gravitational field cannot simulate actual stress acting on original structure since 1/N scale model has an area of $1/N^2$ and the weight of $1/N^3$, which leads 1/N stress. Therefore, in this study, the experiments using large centrifuge machine are carried out for a miniature structural model. Although centrifuge machines have been used for soil mechanism, these have not been used for superstructures. The aim of this study is to establish the method of experiment for miniature-size structural models using large centrifuge machine. This paper describes the results of pilot experiments for 3-story

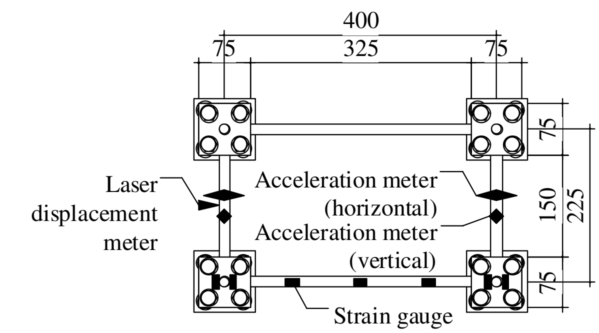
[1]Professor, Structural Engineering Research Center, Tokyo Institute of Technology, Tokyo, Japan
[2]Associate Professor, Structural Engineering Research Center, Tokyo Institute of Technology, Tokyo, Japan
[3]Graduate student, Tokyo Institute of Technology, Tokyo, Japan
[4]Research Engineer, Technical Research Institute , Obayashi Corporation, Tokyo, Japan

steel moment frame.

Experiment Description

Test Specimen

Figure 1 shows the test specimen and Figure 2 shows a general view of it. The specimen is 1/20-scale model of 3-story 1-span steel weak-column strong-beam moment-resisting frame. The model is designed so that yielding would occur at the top and bottom of the 1st story column. Also, Plane frame of the specimen is 400mm (shaking direction) x 225mm and floor height is 208mm. The cross section of all columns is 15.9(D) x 1.0(t) mm and the cross section of all beams is 16 x 16 mm. The base shear force ratio is 0.49 under a centrifugal acceleration of 20G and the axial force ratio is 0.12 of the yield axial force. Based on the free vibration test, it is found that the 1st natural period of the specimen is 0.041sec.



Typical floor plan

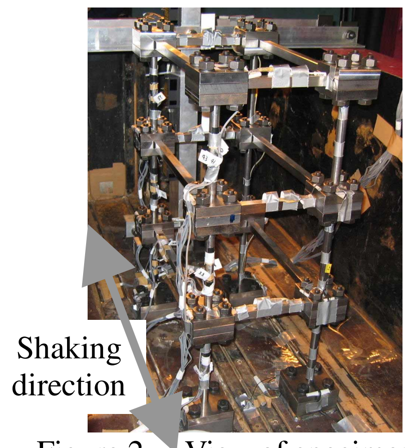
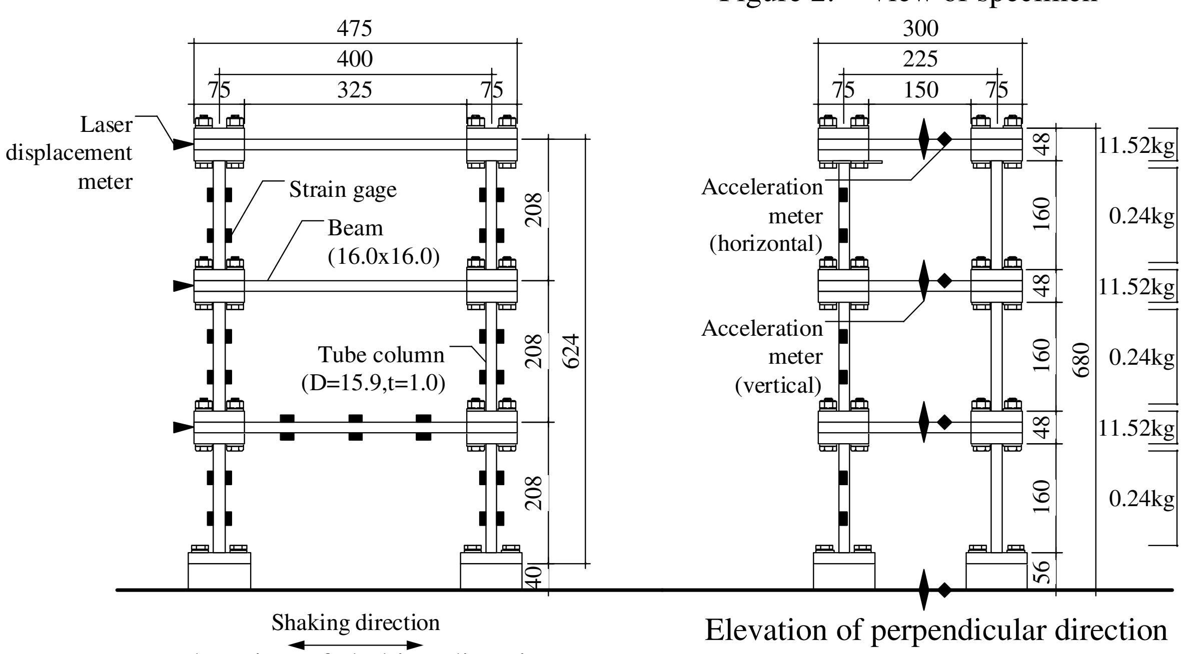


Figure 2. View of specimen



Elevation of shaking direction

Elevation of perpendicular direction for shaking direction

Figure 1. The specimen and measuring plan

Measurement Plan

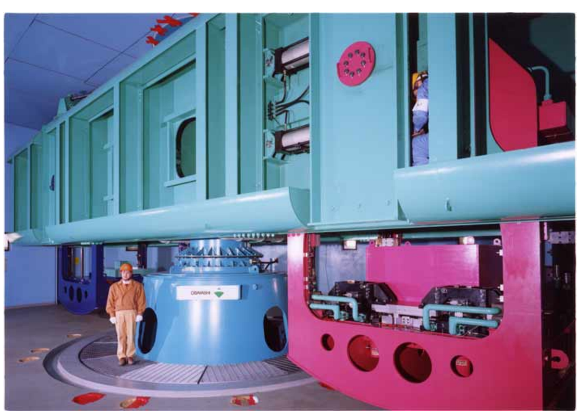
The absolute accelerations in horizontal and vertical directions are measured by acceleration meters installed on beams in each floor, floor displacements relative to the shaking-table are measured by laser displacement meters installed on frames for measurements placed on the shaking table, and axial and shear forces at each story are measured by strain gages set on both left and right sides and at both top and bottom of each story column. All measurements are carried out with sampling frequency of 1000Hz. Also, the high-speed and CCD cameras are used to capture collapse behavior of the miniature model graphically.

Summary of Centrifuge

The centrifuge shaking-table owned by the Obayashi Technical Research Institute in Japan is used in this experiment. A picture of the centrifuge is shown in Figure 3, and the specifications of the centrifuge are shown in Table 1, the specifications of the shaking table set on the centrifuge device is shown in Table 2. In the past many experiments using the centrifuge shaking-table have been performed for soils and underground structures. However, this study is the first to use the shaking-table for experiments on superstructures. Since the principal mechanically proportional lows as shown in Table 3 hold true in a centrifuge, it can be said that experiments using a centrifuge is the most truthful method to simulate realistic behavior of actual structures under 1G gravitational filed. Particularly, a centrifuge has the most valuable advantage that the same stress and strain field in actual structure under 1G field can be simulated in the experiment using 1/N scale miniature model subjected to Ng gravitational field created by the centrifuge.

Table 1. Specifications of Centrifuge

Outer diameter of arm	16.67m
Height of arm	3.00m
Driving system	Direct current motor with Reduction gear
Radius to the platform	7.01m
Maximum payload	700g t
Payload weight	7t
Platform space	2.2m × 2.2m
Test model height	2.5m
Number of platforms	2



Figer3. View of Centrifuge

Table 2. Specifications of shaking table

Payload mass	3t
Table area	2.2m(Length) × 1.07m(Wide)
Max. acceleration	$500m/s^2$
Max. velocity	90cm/s
Max. displacement	5mm
Max. drive force	1.176MN

Table 3. Similitude law at Ng

Quantity	Theoretical ratio (Model/Prototype)
Length	1/N
Density	1
Mass	$1/N^3$
Strain	1
Acceleration	N
Velocity	1
Displacement	1/N
Stress	1
Pressure	1
Young's modulus	1
Time	1/N
Frequency	N
Axial stiffness	$1/N^3$
Flexural rigidy	$1/N^4$

Experiment Results

Outline of Shaking Process

The shaking process is shown in Table 4. Here, although the white noise is input during the shaking, this is excluded in the table. The shaking was carried out using Kobe-NS wave under a centrifugal acceleration of 20G. When the specimen behaved elastically, the shaking level was increased at each step by approximately 0.5G, and after that, the level was increased at each step by 1G. Since the complete collapse, which was an aim of this study, did not occur for Kobe-NS wave, the centrifugal acceleration was increased to 30G using sinusoidal wave with 20Hz (close to the 1st natural frequency of the structure). Finally, when the sinusoidal wave with 9.8G is input, the structure collapsed.

Table 4. Shaking process

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Input wave	Kobe NS														
Max. acc.[G]	0.5	0.7	1.0	1.4	1.9	1.7	2.4	3.1	3.2	3.7	3.4	4.1	4.6	4.5	5.9
Run	16	17	18	19	20	21	22		23		24		25		
Input wave	Kobe NS						Sin wave(20Hz,50waves)								
Max. acc.[G]	6.6	7.8	8.6	9.4	10.4	11.5	1.8		3.6		6.9		9.8		

Comparison of Maximum Response on each Input

Let's evaluate the change of the model response under Kobe-NS wave input. Figure 4 shows the maximum story drift angle (SDA) under each shaking. The interstory drifts of the 2nd and 3rd stories increase almost proportionally to the maximum ground motion acceleration, $a_{g,max}$. However, after $a_{g,max}$ exceeds 20m/s^2, the change of the interstory drift decreases, and after 40m/s^2, the interstory drift becomes almost constant. In contrast, the SDA in the 1st story once decreases when $a_{g,max}$ is around 80m/s^2, and the SDA continues to increase.

Figure 5 shows the maximum acceleration response of each story for each shaking. The accelerations of all stories start to decrease when $a_{g,max}$ exceeds 20m/s^2. After $a_{g,max}$ is slightly greater than 40m/s^2, the acceleration response remains almost constant. Also, the maximum story shear force in each story for each shaking as shown in Figure 6 starts to decrease when $a_{g,max}$ exceeds 20m/s^2. After that, the story shear force in the 3rd story increases gradually. However the story shear forces in the 1st and 2nd stories do not increase significantly when $a_{g,max}$ is around 40m/s^2.

Figure 7 compares the relationships of the maximum story force and the maximum SDA for each shaking. Since the 1st story SDA does not increase after 2.6mm, it is found that the 1st story column yields. In contrast, the SDA and the story shear force in the 2nd and the 3rd stories are proportional, indicating that the observation of the change of the SDA, acceleration, and the story shear force in each story for each shaking result from the column yielding in the 1st story.

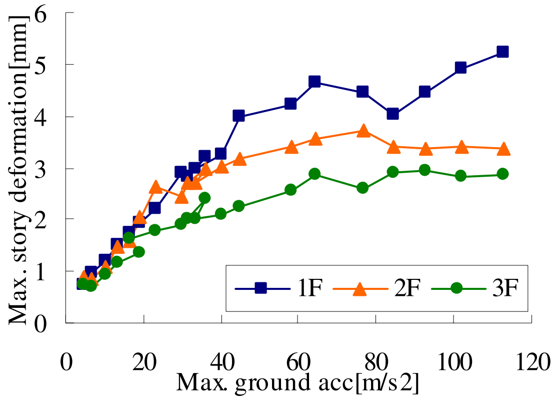


Figure 4. Response of story deformation and max. ground acc. in each run

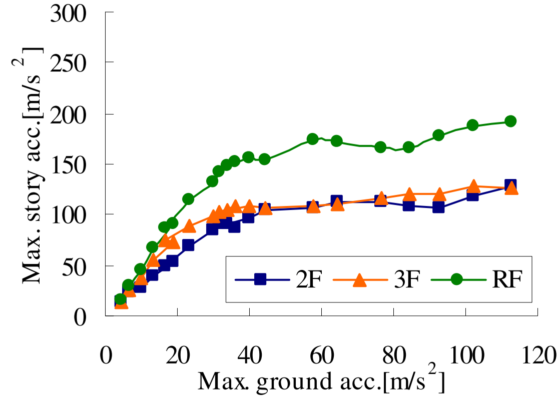


Figure 5. Response of story acc. and max. ground acc. in each run

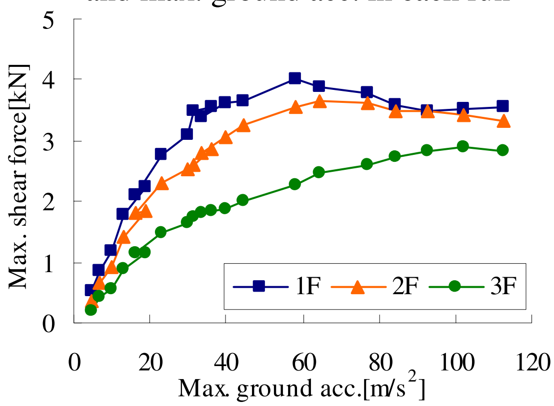


Figure 6. Response of shear force and max. ground acc. in each run

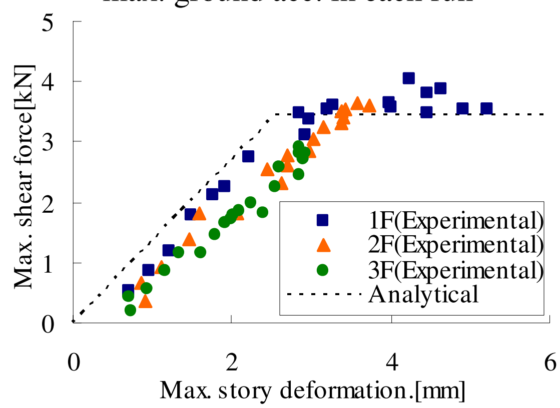


Figure 7. Response of shear force and story deformation in each run

Collapse Behavior

The structure does not collapse using Kobe-NS wave under a centrifugal acceleration of 20G. Therefore, the centrifugal acceleration is increased to 30G and the sinusoidal wave with the natural fundamental frequency of 20Hz is input. As the result, the base shear coefficient becomes 0.33 and the ratio of axial force to yield axial force becomes 0.18. As a result, under the sinusoidal wave with $a_{g,max}$ of 9.8G, the plastic hinges form at the top and the bottom of the 1st story, and the story-mechanism failure occurs. Figure 8 shows the time-history of ground motion acceleration at this time. Figure 9 shows the absolute displacement time-history in each story. The absolute displacements which the model has when it has the maximum 2nd story absolute displacement are indicated by ●. The absolute displacements in all stories are in the same phase and reach the maximum values at the same time. Moreover, the absolute displacements in all stories increase after 1.5s. Therefore, the absolute displacement distribution along the height at the time indicated by ● is shown in Figure 10. After 1.5s, the 2nd story absolute displacement increases significantly, indicating that the 1st story collapses. After that, the structure collapses completely at 1.9s. Figure 11 shows the acceleration time-history response of each story after the story failure occurs at 1.5s. Figure 12 shows the time-history of each story shear force. The ground motion acceleration has almost constant amplitude after 1.7s. However, the acceleration amplitude of each story starts to decrease significantly, and this value becomes 0 at 1.9s. As a result, the story shear force starts to decrease significantly after 1.7s and this value becomes 0 at 1.9s.

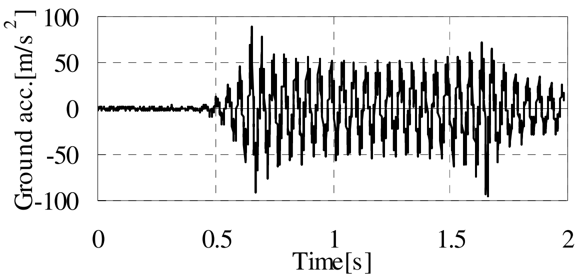


Figure 8. Ground acceleration time history in 9.8G sin wave input

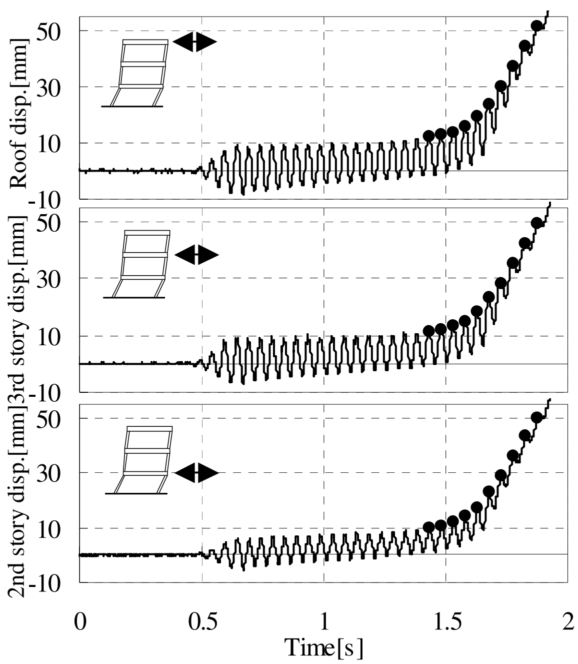


Figure 9. Displacement in each story

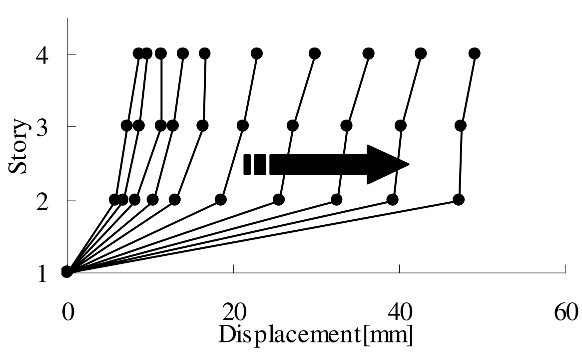


Figure 10. Displacement distribution along the height

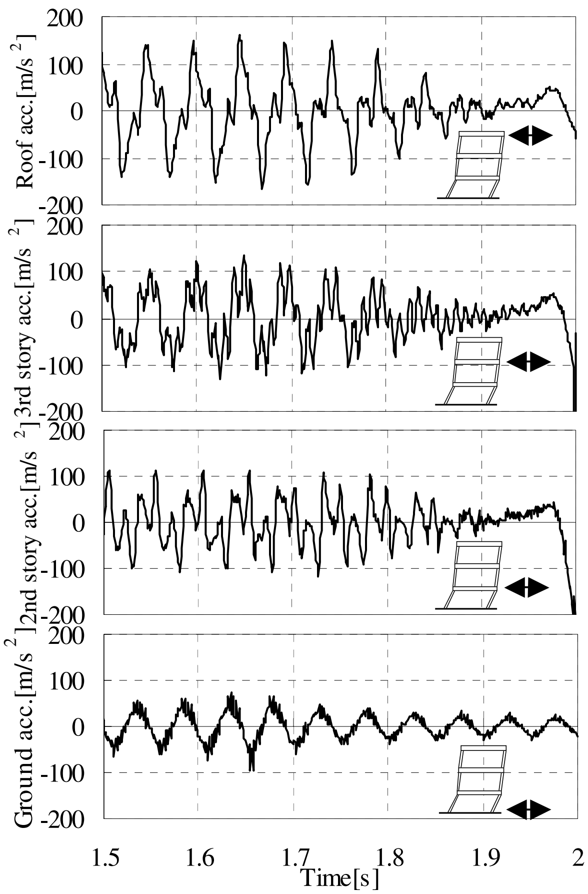


Figure 11. Acceleration in each story

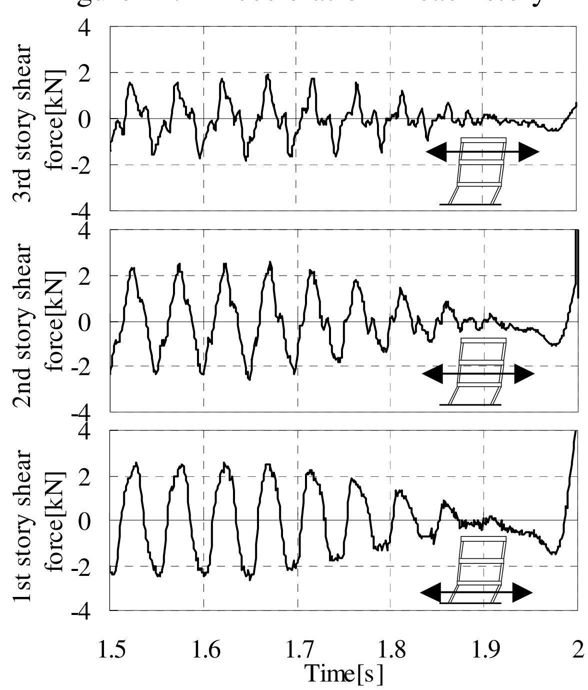
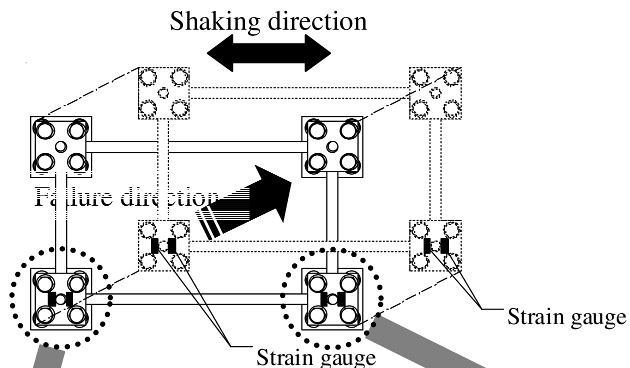


Figure 12. Shear force in each story

The transitions of the axial force since the story failure occurs and until the complete failure occurs are compared. The direction of the collapse and the location of the strain gauges are shown in Figure 13. Also, the time-history of the axial force in each member of the specimen obtained by strain gauges is shown in Figure 14. At approximately 1.5s, when the specimen increases the displacement, the axial forces in all left columns decrease. Also the direction of the axial forces changes from compression to tension. In contrast, the axial forces of the right columns in the 2nd and 3rd stories increase, and converge to the value greater than the initial axial force. However, the axial force of the right column in the 1st story converges to the initial axial force. This is because the specimen collapses in story mechanism not in the direction of shaking but in diagonal direction. This indicates that, when the 1st story collapses in story mechanism, the columns in the failure direction support the weight of the specimen.

Figure 13. Failure direction of specimen and the location of strain gauges



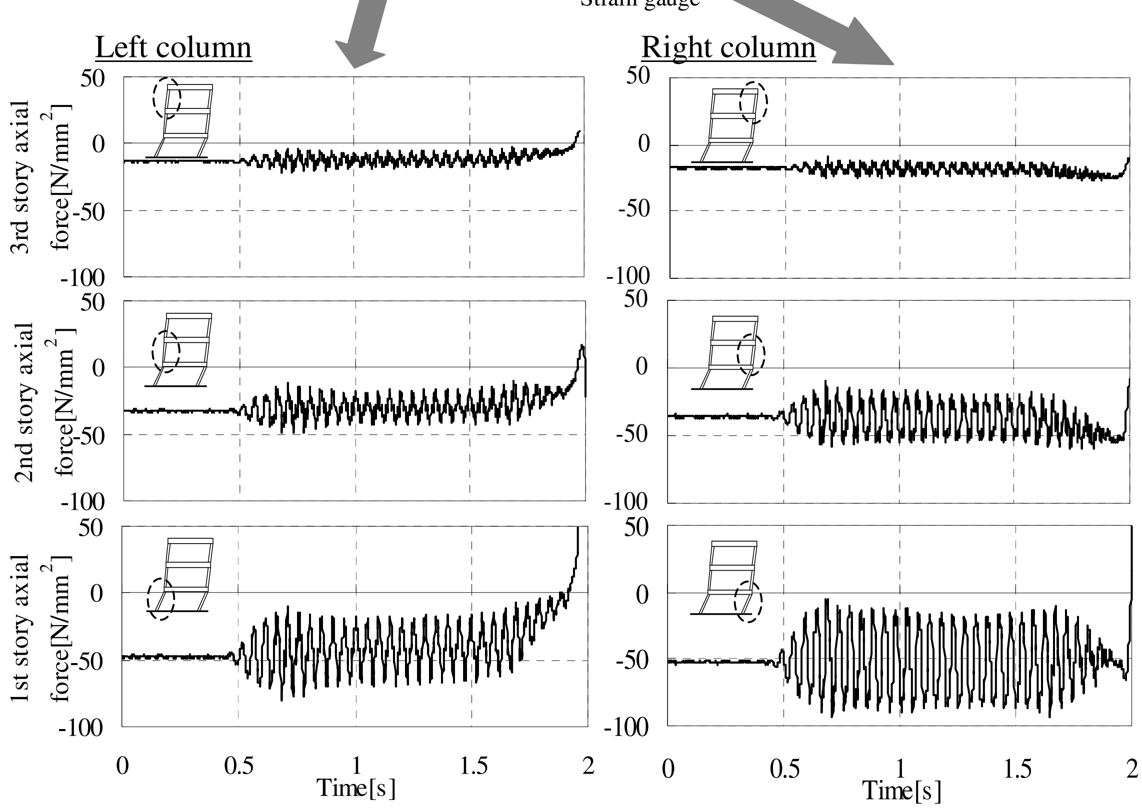


Figure 14. Axial force in each member of the specimen

Let's consider the relationship of the story shear force and the SDA. Figure 15 shows the relationship of the shear force and the SDA in the 1st story between 0.3s and 1.5s. The solid line represents the shear force obtained from the acceleration meter and the dotted line represents that obtained from the strain gauge. Both values obtained by the acceleration meter and the strain gauge are similar. The restoring force characteristics draw the oscillating hysteretic loop around the origin point between 0.3s and 0.7. However, the restoring characteristics after 0.7s, when the deformation progresses, have the center of the hysteretic loop swaying in the direction of deformation.

Figure 16 shows the relationship of story shear force and the SDA in each story since the story failure occurs at 1.5s until the complete failure occurs at 1.9s, indicating the hysteretic loop in the 2nd story has clearly elastic response. In the 3rd story, when the deformation increases, the hysteretic loop is disturbed. However, based on the shear force value, the 3rd story remains elastic. In contrast, the story shear force obtained from the 1st story acceleration has a negative slope in the horizontal restoring force and decreases as the deformation increases, indicating that the 1st story collapses due to *P*-Delta effect from specimen weight. Also, the story shear force measured by strain gauge remains at approximately 4kN after the deformation increases. This is because the *P*-Delta effect cannot be taken into account in the measurement using the strain gauges attached along the column axial direction.

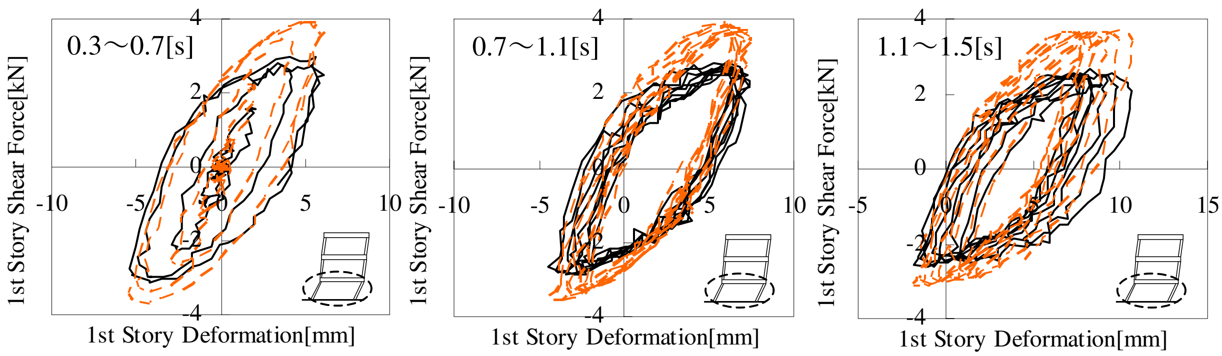


Figure 15. Response of 1st story shear force and deformation in each period

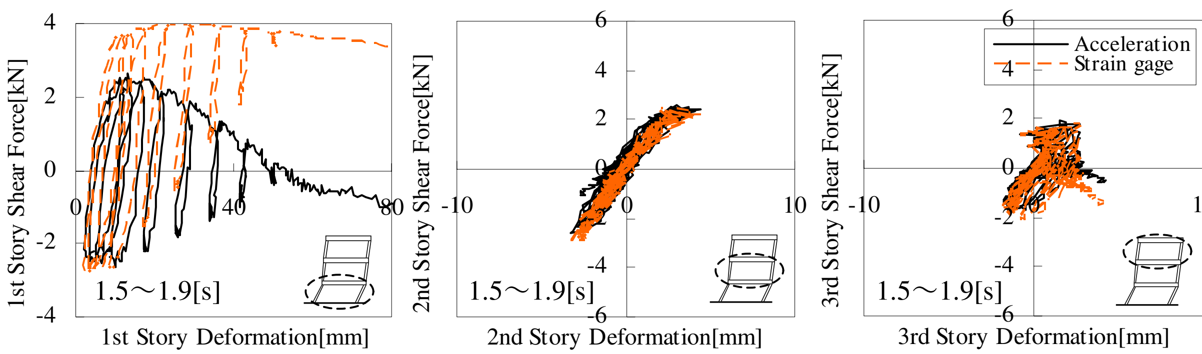


Figure 16. Response of each story shear force and deformation in final stage

Figure 17 shows the pictures obtained from the CCD camera. It is observed visually that only the 1st story column inclines and the story failure occurs. Figure 18 shows the pictures obtained from the high-speed camera installed at the top of the specimen. It is observed that after the 1st story collapses, the 2nd and 3rd stories collapse in this order.

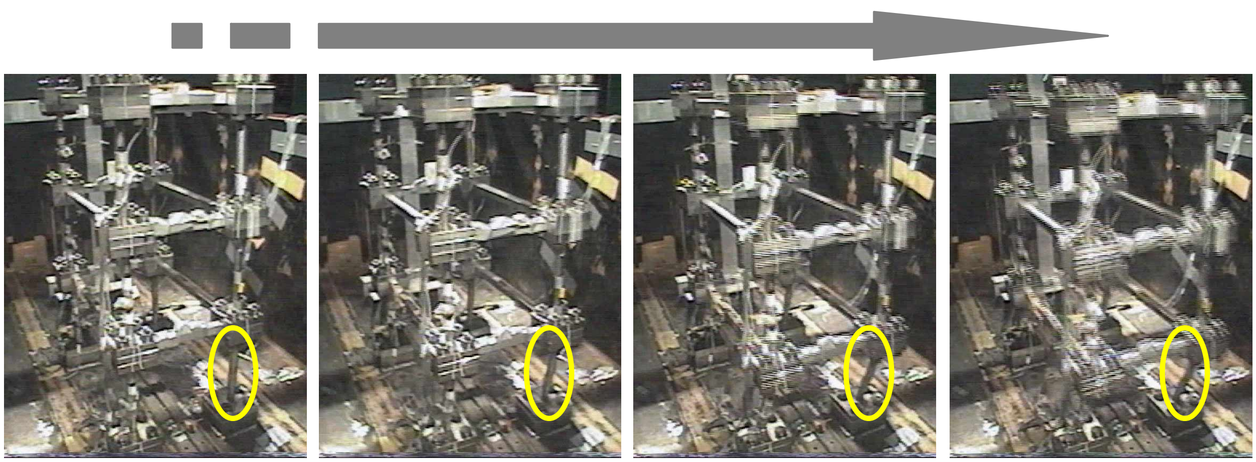


Figure 17. Pictures obtained from the CCD camera

Figure 18. Pictures obtained from the high-speed camera

Conclusions

Based on the experiments using the centrifuge shaking-table in this study, it was found that:

1) The phenomena of the displacement, acceleration, and the shear force at the story failure are clarified.
2) The specimen, designed with column yielding and no beam yielding, completely collapsed due to *P*-Delta effects.
3) Story mechanism due to column yielding is visually captured.
4) The complete failure of the upper miniature structure can be realized using the centrifuge machine.
5) The global behavior, from elastic to inelastic, of the 3rd story weak-column strong-beam model is presented.

Acknowledgments

We would like to express appreciation to Dr. Tagawa, COE researcher in Tokyo Institute of Technology, Japan, for his kind assistance, and to Hajime Ishii etc., technical assistants in Tokyo Institute of Technology, for production of the specimen, and Isamu Akama and Kenichi Ikeda, technical assistants in Obayashi Corporation, Japan, for helping us with experiment preparations.

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