DYNAMIC COLLAPSE TEST ON 3-D STEEL FRAME MODEL

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ABSTRACT :

The collapse process of building under severe earthquake is not clarified yet. In order to make it clear, shaking table test of a full-scale building at E-Defense is conducted in 2007. This paper presents a pre-consideration of the full-scale collapse test. Main purposes of this study are follows; (1) to collapse three-dimensional steel frame model by three-dimensional input wave, and (2) to measure exactly dynamic collapse behavior of three-dimensional steel frame model. The specimen is 2-story and 1×1 span steel frame model designed as column yield-type. Input wave is three-dimensional acceleration record which is JMA Kobe record scaled in time domain corresponding to the scale of model. Finally the frame model lost restoring force because of local buckling at all columns of the first story. Dynamic behavior up to collapse was surely measured by couplings of potentiometer-type displacement transducers. Obtained results are effective to verify not only the instrumentation measurement methods but also numerical analytical methods for collapse simulation in steel structures.

KEYWORDS: Steel Moment Frame, Shaking Table Test, Collapse, Three-Dimension

1. INTRODUCTION

Behavior of steel building under severe earthquake and final collapse process are not clarified although those are important to verify earthquake resistant design. Reviewing previous studies on earthquake resistance of steel structures, evaluation on structural performance by numerical analysis, static loading test on partial frame of full-scale building, and dynamic loading test of reduced-scale model have been focused. It is difficult to directly estimate the overall behavior of full-scale frame on the basis of the experimental results of partial frames. Also, it is difficult to conduct full-scale experiment of three-dimension frame because three-dimensional full-scale testing facility has not existed. Moreover, reduced-scale model has some problem such as reproducibility of the detail and influence of gravity. Therefore, analytical results in previous studies are not evaluated correctly.
In order to clarify three-dimensional behavior up to collapse, a shaking table test on a full-scale steel building was conducted at E-Defense in 2007. In this project, full-scale steel building was expected to show large displacement; thus, it was necessary to verify measurement and examination in advance. This study is preliminary consideration for establishing experimental method of dynamic collapse test on shaking table. This result is a valuable data about collapse process of steel frame for full-scale test and is also administered to calibration of simulating collapse behavior by numerical analysis.

2. EXPERIMENT PROCEDURE

2.1. Specimen

As shown in Fig. 1, specimen is 2-story, 1×1 span three-dimensional steel flame. Specimen has the plan dimensions of 2.25 m in the longitudinal direction (X), and 1.25 m in the transverse dimension (Y). Each story height is 1.0 m. The frame members consist of steel square hollow section column; □-60x60x1.6 (STKR400), steel beam; BH-75x50x4.5x4.5 (SS400), and steel block; 70x70x95 (SS400) as beam-to-column connection. Column base is exposed type with enough stiffness. Counter weight on each floor is about 15.0kN, and total weight including steel frame is 31.0kN. Calculated value of the fundamental natural period is 0.302s, base shear from *Mp* (full-plastic moment of column) is 0.85, and yield axial force ratio of column in the first story is 0.05. Specimen was designed as column yield-type model. Cross-section of column was same between the first story and the second story; accordingly, it was expected to collapse in the first story. Also this model was not a scaled model of real building.

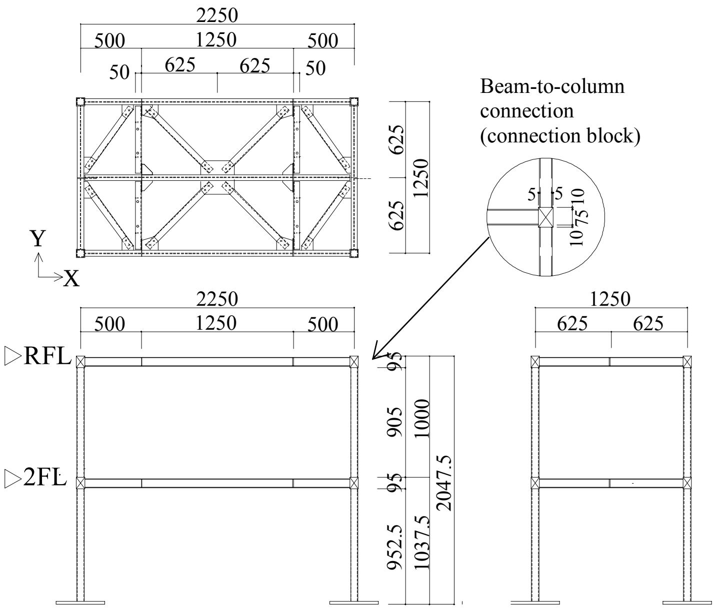


Figure 1 Specimen (unit:mm)

2.2. Measurement

In order to measure three-dimensional behavior of specimen from elastic range to collapse, following measurement instruments were settled. Eighteen strain-type acceleration transducers set on the surfaces of shaking table and faces of connection blocks in order to measure 6 DOF accelerations of each story. Twenty potentiometer-type displacement transducers set on safeguard frame as shown in Fig. 2, and their targets were put on the connection blocks. Displacement of each story in X, Y, and Z direction were calculated by the intersection of three spheres as shown in Fig. 3.

Elastic strain gauges were glued on two cross-sections of each column and beam. In column, the two cross-sections were located at a distance of about 0.3 m inward from the top and bottom. The locations were elastic, therefore, bending moment of each cross-section was estimated from corresponding curvature by strains. Shear force was calculated as dividing sum of bending moments by length between two cross-sections. Fig. 4 shows balance of forces around the first story. Q is story shear which is the sum of shear forces on column, W is vertical applied force including gravity, and Q_r is lateral force acting to the first story. Fig. 5 shows relationship of Q, W, and Q_r. Q is sum of $W\sin\theta$ as resistance to P-Δ effect and $Q_r\cos\theta$ as resistance to lateral applied force. $Q_r\cos\theta$ being zero means that specimen lose resistance to lateral applied force. It also means collapse. In the following consideration, Q_r is used as story shear.

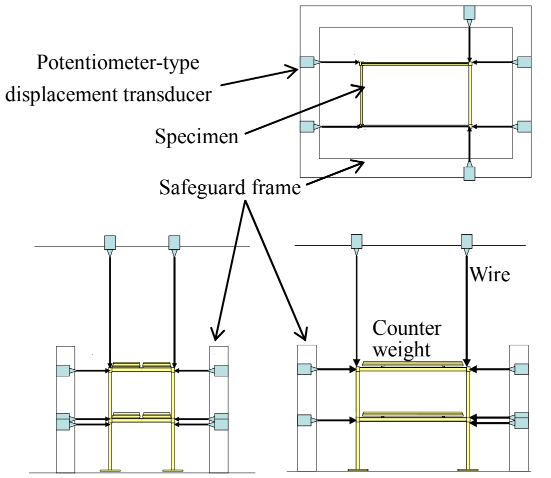


Figure 2 Set-up of displacement transducer

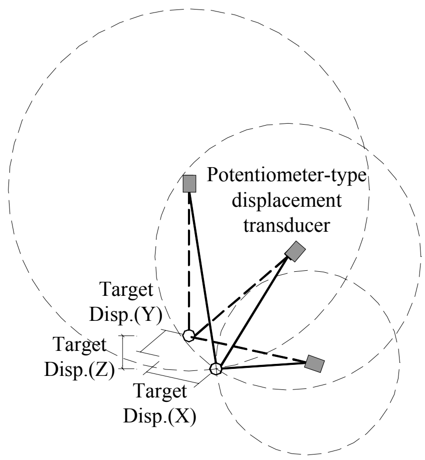


Figure 3 Intersection of three spheres

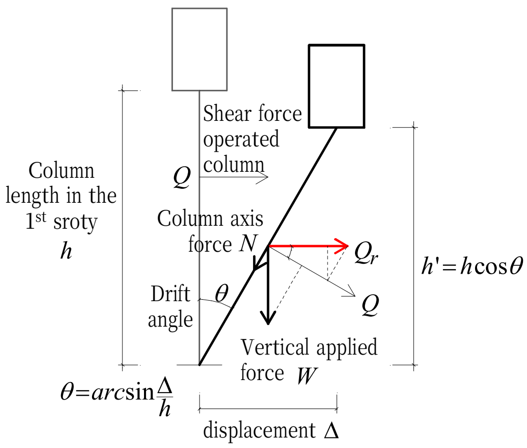


Figure 4 Balance of forces

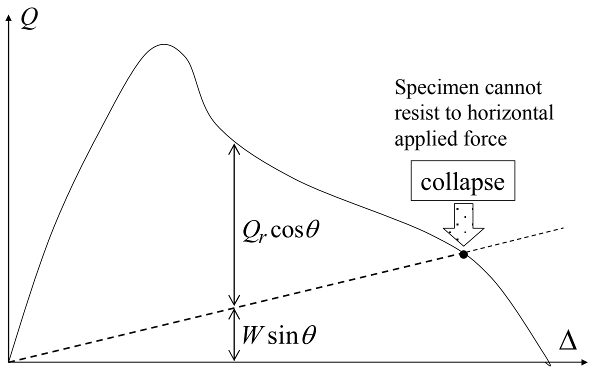


Figure 5 Relationship of Q, W, and Qr

2.3. Characteristic of member

Before shaking table test, in order to acquire characteristics of steel members, cyclic loading test of members were conducted. Table 1 shows results of coupon test. Fig. 6 shows set-up of cyclic loading test. Load was controlled by rotation angle, and bending moment corresponding to rotation angle was calculated as shown in Fig. 7.

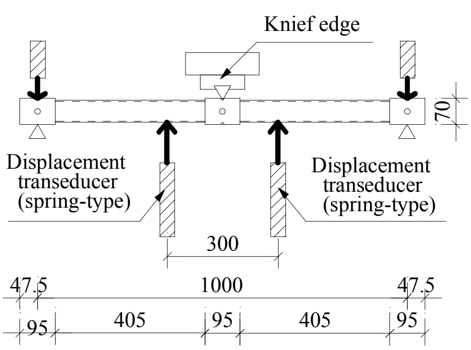


Figure 6 Set-up of cyclic loading test

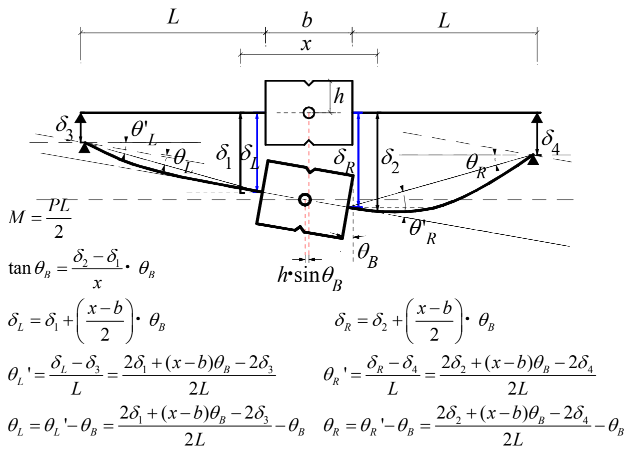


Figure 7 Calculation method of angle and moment

Column-to-beam strength ratio calculated by full-plastic moment estimated by test results is 2.5. The bending moment versus rotation angle relationship of column is shown in Fig. 8. Strength of column was remarkably deterioration just after local buckling was generated. Finally, strength of column decreased about 40% to the maximum strength.

Table 1 Results of coupon test

	σy [N/mm²]	σu [N/mm²]
Beam	306	432
Column	427	481

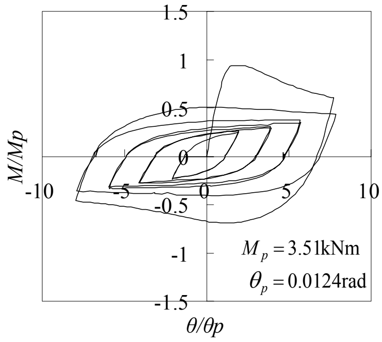


Figure 8 Bending moment versus Rotation angle Relationship

2.4. Excitation

Input wave was JMA Kobe record in 1995 Kobe earthquake. Input data was acceleration data that increased JMA Kobe by a factor of 0.5 corresponding to the scale of model. The factor was decided by spec of shaking table and characteristic of specimen. Table 2 shows excitation list. Excitation controlled by multiplied factor to acceleration data. When specimen touches safeguard frame, this experiment will finish.

Table 2 Excitation list

No.	Input	Maximum Acc.(X)
1	Free vibration (X dimention)	
2	Free vibration (Y dimention)	
3	JMA Kobe (Elastic:1 axis)	100 gal
4	JMA Kobe (Elastic:3 axis)	100 gal
5	JMA Kobe×1.00	813 gal
6	JMA Kobe×1.25	1016 gal

3. EXPERIMENT RESULTS

3.1. Examination of measurement

Displacement measurement system was set by couple of displacement transducers. Comparing both measurement results, they almost corresponded in all coupling cases as shown in Fig. 9. Therefore, error cause by slack of wire in potentiometer-type displacement transducer is negligible.

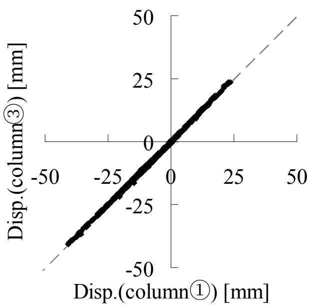


Figure 9 Examination of displacements (X direction)

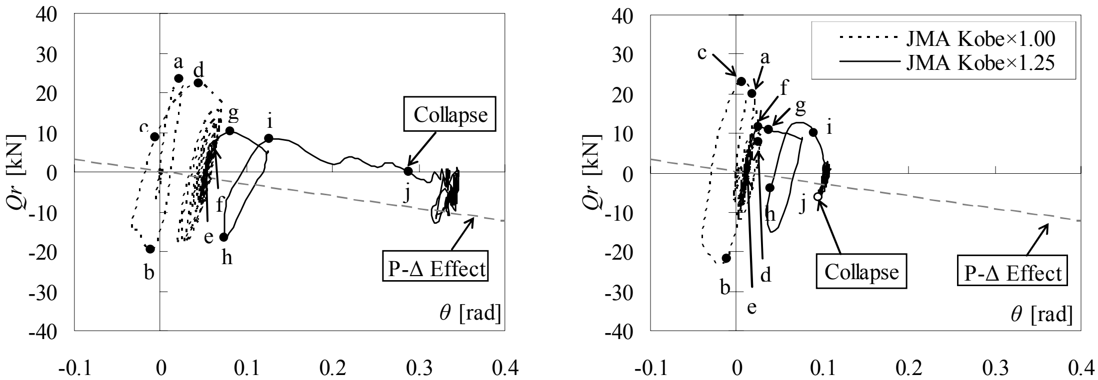
3.2. Natural period and damping factor

Natural period and damping factor of specimen was calculated by the results of free vibration (No.1 And No.2 Excitation). The fundamental natural periods were 0.33sec in the both directions, they were similar to the value in design. Damping factor is 0.9% in X direction and 0.11% in Y direction.

3.3. Collapse behavior of the first story

In this study, collapse is defined as specimen loses its restoring force. Specimen collapse in the first story by final excitation, while the second story is kept in elastic range. Therefore, only behavior of the first story is focused in the following consideration.

Fig.10 shows Q_r versus θ relationship. Broken line shows P-Δ effect, and points named *a*～*j* corresponds to the behaviors of X direction and Y direction at same time. At JMA Kobe×1.00 Excitation, the maximum value of Q_r was observed in both X and Y dimensions. Both of the values were about 23kN, however, they were not observed at same time (X direction: point *a*, Y direction: point *c*). After this excitation, local buckling was slightly observed at all the top and the bottom end of columns in the first story. At JMA Kobe×1.25 Excitation, Q_r raised only up to 50% of maximum value (X direction: point *g*, Y direction: point *f*). After it reached the point *g*, Q_r decreased by P-Δ effect of X direction significantly increased (point *g*～point *i*). Finally specimen lost restoring force and touched safeguard frame at the time of point *j*. Therefore excitation finished.



(i) X direction (ii) Y direction

Figure 10 Q_r versus θ Relationship

3.4. Orbit and rotation in the second floor

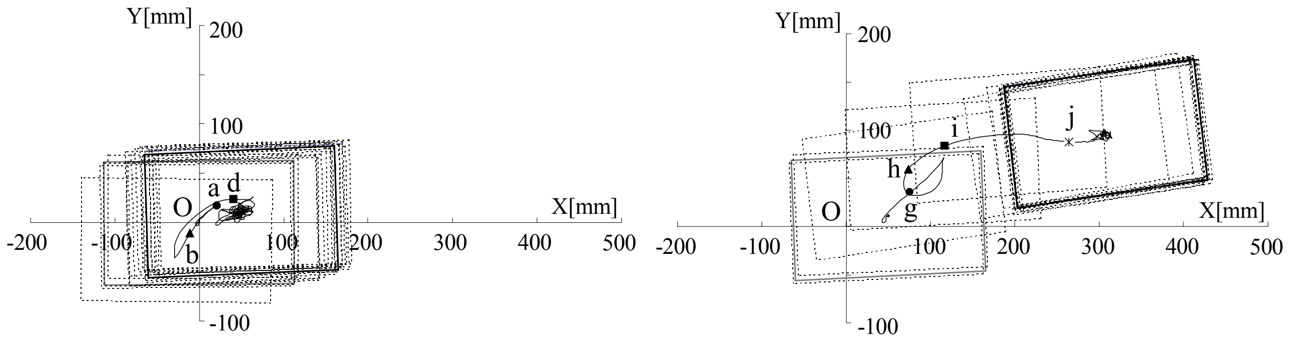
Fig. 11 shows orbit of the center of second floor (displacement is shown by ten times actual). This figure also shows orbit of the second floor frame rotates around Z axis. Points *a*～*j* are same as ***3.3***. The main timings of points in the each excitation are follows; point *a* and point *g* are 1.50 sec, point *b* is 1.66 sec, point *h* is 1.78 sec, and point *c* and point *i* are 1.96 sec. In orbit of the second floor frame plotted every 0.2 sec in 1.0 sec to 5.0 sec.

As shown in Fig. 11 (i), at the Kobe×1.00 Excitation when maximum strength was observed, the frame, each lines show the timings as follows; grey thick line is at 0.0 sec (start time of excitation), black thick line is 30.0 sec (finish time of excitation), and. break lines are locations of the second center of second floor from point *O* to point *a* moved in the direction of 45° against positive X axis and positive Y axis. The center kept moving on this 45° direction line until it reached point *b*. After it reached point *d*, the center moved in the direction of X axis.

Here, rotation of the second floor frame is focused. Before Q_r reached maximum value (point *a*), few rotation was observed. However after Q_r reached maximum value, rotation reached about 0.004 rad and it kept until the excitation finished.

As shown in Fig. 11 (ii), at JMA Kobe×1.25 Excitation when collapse behavior was observed, the center of the second floor also moved in the direction of 45° against positive X axis and positive Y axis at first. It continued to move in this direction after the center of the second floor reached point *g*. Thus, the timing that orbit changed to its direction don't agree with the point that Q_r reached peak strength of this excitation. After it reached point *i*, the center of second floor changed movement direction to parallel with X axis. And specimen continued to move to this direction until it touched safeguard frame.

Rotation changed at a range between 0.004 rad to 0.016 rad while the center of the second floor moved from point *g* to point *j*



(i) JMA Kobe×1.00 excitation (ii) JMA Kobe×1.25 excitation

Figure 11 Orbit of center and floor frame in the second floor

3.5. Correspondence between frame and member

This section focuses on the correspondence between behavior of specimen in shaking table test and result of the cyclic loading test shown in ***2.3***.

First, comparison of skeleton curve in two tests is shown in Fig. 12. Skeleton curve of shaking table test (Frame) in X and Y directions are shown by thin lines with plots. And skeleton curve obtained in cyclic loading test (Member) was shown black thick line. In Fig. 12, initial stiffness of X and Y directions obtained in shaking table test are not corresponded to initial stiffness of cyclic loading test. The reason is that bending moment distribution in column of frame isn't ideal reverse symmetry.

Maximum strengths of Frame in X and Y dimensions are about 20% lower than maximum strength of Member. It is resulted that specimen in shaking table test moved three-dimensionally. And story shears in X direction and Y direction are each X component and Y component of overall story shear shown in Fig. 13. Specimen at elastic range moved in the direction of 45° against X axis and Y axis as shown in ***3.4***, thus, skeleton curve of cyclic loading test can be modified by multiplying a factor of $1/\sqrt{2}$. Modified skeleton curve corresponded to skeleton curve of shaking table test in the both directions.

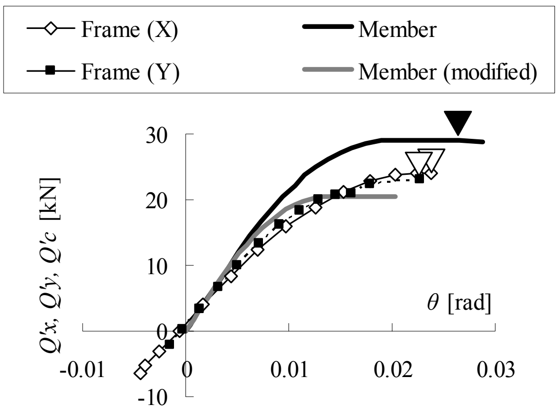


Figure 12 Comparison of skeleton curve

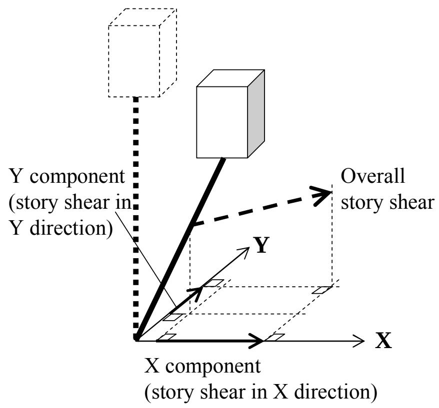


Figure 13 Component of shear force

Secondly, deterioration behavior after Q_r reached its maximum strength is evaluated. In this study, deterioration behavior in cyclic loading test is defined by story shear and cumulative displacement relationship. Fig. 14 shows approximation of this relationship by three straight lines named 'the member envelope'. Fig. 15 shows comparison between deterioration behavior of specimen in shaking table test and the approximate envelope. As mentioned to previously, deterioration behavior of specimen was mainly in X direction, thus, only behavior of X direction was used in comparison. The member envelope corresponded to deterioration behavior of specimen in both the 1st deterioration range and the 2nd deterioration range.

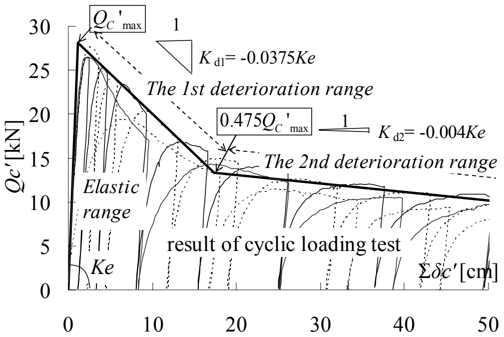


Figure 14 The member envelope

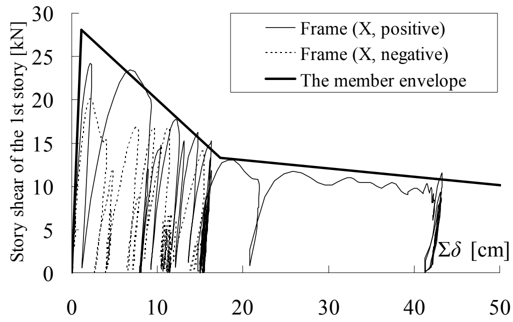


Figure 15 Comparison of deterioration behavior

3.6. Collapse energy

Equation of energy under earthquake is given by Eq. 3.1 below:

$$E = W_{ek} + W_{es} + W_p + W_h \tag{3.1}$$

Here, E is Total energy input, W_{ek} is Kinetic energy, W_{es} is Elastic strain energy, W_p is Plastic strain energy, and W_h is Damping energy. Generally damping force is contained in measured restoring force in shaking table test. W_{es}+W_p+W_h is acquired by integration of story shear and drift angle relationship. W_{ek} is acquired by differentiated velocity. W_{pd} is given by Eq. 3.2 below:

$$W_{pd} = \int \frac{W\Delta_1}{h_1'} \cdot d\Delta \tag{3.2}$$

Fig. 16 shows time history of observed energy around collapse time. According to behavior of specimen, this energy is calculated as the energy of the direction of collapse. W_{pd} was so small before specimen began to deteriorate. At JMA Kobe×1.25 Excitation, however, W_{pd} showed remarkable increase corresponding with increase of displacement in X direction. Increment of E during 1.9～2.4 sec after excitation was almost same as increment of W_{pd}. At collapse time, W_{pd} was about 19% for E.

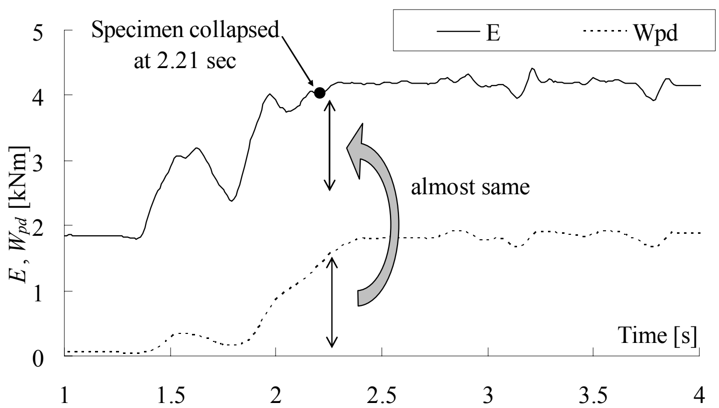


Figure 16 Time history of energy

4. CONCLUSIONS

Dynamic behavior of 3-D steel frame model from elastic range to collapse with column collapse mechanism in the first story could be generally identified by shaking table test.

The important findings are follows;

1) At the elasto-plastic excitation by input data, local buckling generated at the top and the bottom end of all

columns in the 1st story. Subsequently the input level increased, resistance against lateral applied force decreased and finally the 3-D steel frame model lost restoring force.
2) The potentiometer-type displacement transducers are effective to measure large displacements up to collapse.
3) Before it reaches maximum strength, 3-D steel frame model moves toward 45 ° direction against X axis and Y axis. Since column receives biaxial bending forces, skeleton curve multiplied $1/\sqrt{2}$ by the result of cyclic loading test corresponded to skeleton curve of model in X and Y directions
4) During the deterioration range of restoring force, 3-D steel frame model behaves mainly in the X direction up to collapse. thus, the behavior of column in frame corresponds to the envelope acquired by results of cyclic loading test.

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