A SHAKING TABLE TEST OF REINFORCED CONCRETE FRAMES DESIGNED UNDER OLD SEISMIC REGULATIONS IN JAPAN

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SUMMARY

In order to understand behaviours and failure mechanisms of existing reinforced concrete frames during a severe earthquake, a shaking table test of a frame was conducted. A prototype of the RC frame was designed based on a seismic regulations that had used before 1971 and assumed to have less shear reinforcement compared to the current regulations. The specimen completely lost its lateral load carrying capacity due to shear failure in the columns under the excitation almost equivalent in the building standard code. A static test of the frame was also conducted at the same time to compare the dynamic behaviour of the frame. The purpose of this paper is to grasp the failure mechanism of the reinforced concrete frame designed by the old regulation.

INTRODUCTION

In Japan, the building standard code and seismic design method have been frequently changed after experience of great earthquake disasters. The recent two major revision of the standard code have been made at year 1971, define the least limit of shear reinforcement for RC members, and year 1981, incorporate dynamic effect of seismic motion. These changes were quite necessary for life-safe but also made lots of buildings yet unqualified under the revised standard code at the same time. Such buildings are 25 million in Japan and about 14 million old buildings are assumed to have high possibility to suffer serious damage in case of big earthquakes.

Since the 1995 Hyogoken-Nanbu Earthquake, the importance of seismic retrofitting for buildings has been well recognized in Japan. After the earthquake, a three-year co-operative research project to develop and spread new rational retrofitting methods for existing buildings has been promoted by the Ministry of Construction since 1996. As part of this project, a retrofitting method using energy absorbers for reinforced concrete buildings was examined[Wada 1999]. In the first stage of the test program, to understand the behaviour and the collapse mechanism of existing reinforced concrete frames during a severe earthquake, both shaking table test and static test of a frame designed under the old seismic regulations that had used before 1971 were conducted.

DESIGN OF TEST SPECIMEN

Figure 1 shows an original reinforced concrete structure and dimensions of its members. This four-span and five-story structure was constructed before 1971 and it is selected as a typical old office building in Japan. On the year 1971, the building standard code was changed because there had been many damaged buildings after the 1968 Tokachi-Oki Earthquake. This original structure has a little amount of shear reinforcement bars compared with the current standard code.

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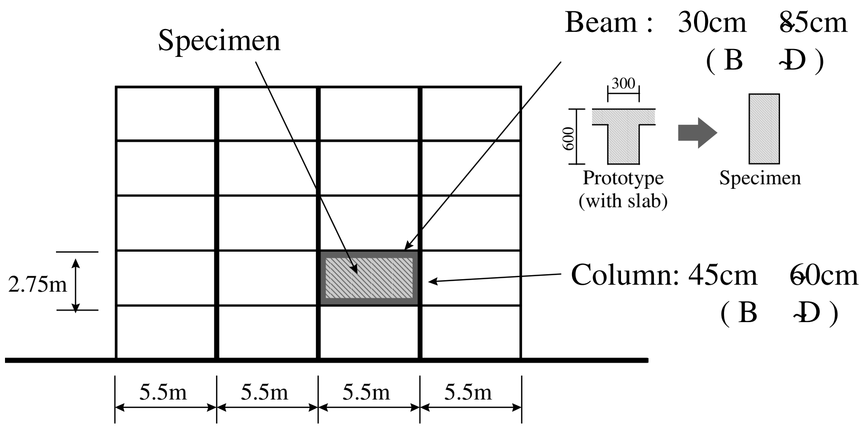

Figure 1: Original RC Structure and Modified Dimensions for the Test Specimen

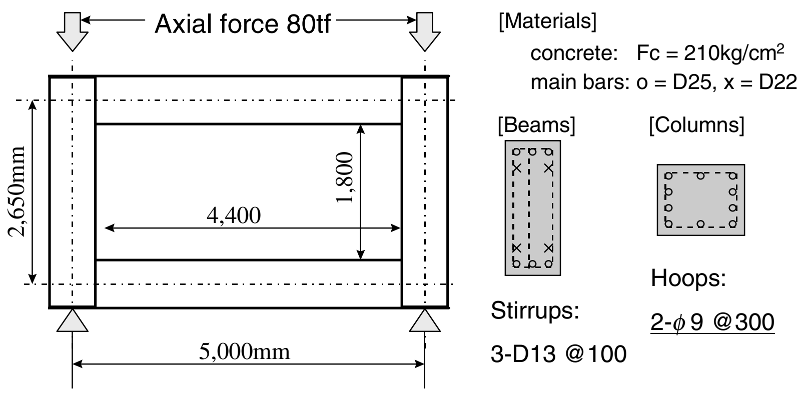

Figure 2: Dimensions of RC Specimen and Arrangement of Steel Bars

Table 1: Shear Capacity of the Specimen

Shear Capacity (tonf)				Shear Force at Failure Mechanism (tonf)
Equation 1 (mean)		Equation 2 (minimum)		
Tens. side	Comp.side	Tens. side	Comp.side	
43.4	47.7	36.9	41.2	51.8

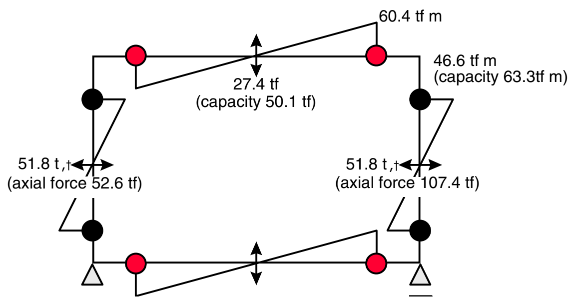

Figure 3: Failure Mechanism of the Specimen

Figure 2 shows a design principles and dimensions of members for test specimen. As a representative part of the building structure, a reinforced concrete flame with one span and one story at the second floor was selected. In the design of test specimen, dimensions of beam member was modified to have same geometrical moment of inertia as original T-shape beam with slabs. (See the upper right side of Figure 1.)

The specimen is designed to pay attention to occur a shear failure of columns prior to a bending failure. Distances between column hoops are 30cm (Pw=0.095%). Figure 3 shows the failure mechanism and table 1 shows predicted shear capacity of the specimen. Two major design formulae (mean and minimum estimation) used commonly in Japan ensure that both columns will be broken by the shear failure before the specimen reaches the mechanism point.

DYNAMIC TEST

Experimental Facilities

The experimental facilities on the shaking table are illustrated schematically in Figure 4 and shown in Photo 1. The RC specimen is settled on hinged supports at the bottom of columns. To adjust the natural period of the specimen to that of the prototype building with five-stories, 4 rubber bearings are installed between a load beam and an upper beam of the specimen. The resonant period of the specimen is 0.6 seconds under small excitation.

A 220tonf loading mass, which is supported by rubber bearings, is connected to the specimen. During the shaking test, the specimen was subjected to the lateral inertia force of the mass, which represents the inertia of total weight of the prototype building. This dynamic acting system was designed by Dr. Akiyama H. (Tokyo Univ.)[Akiyama 1998]

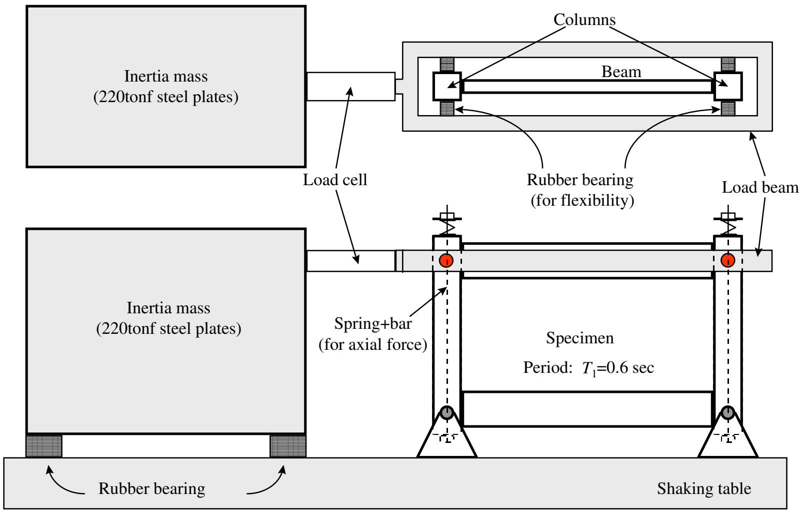

Figure 4: Schematic Experimental Facility System

Photo 1: Experimental Facility on Shaking Table (in Science and Technology Agency)

To be sure to make shear failure of columns, PC steel bars are installed into both columns and post tensioned through weak springs. These bars and springs prevent the relaxation of the axial force due to deformations by temporary changes of axial force or occurrence of cracks of columns. The axial force for each column is 80 tonf and representing the mass of top three floors of the specimen (see Figure 1).

TABLE INPUT MOTION

An artificial earthquake motion was adopted as an input motion through the shaking table. The artificial motion was corresponding to an equivalent seismic force (Z*Co*Rt, Z=1) for second soil type(medium soil deposite) in the current building regulation in Japan. The amplitude of the motion is defined as a response acceleration spectrum with 5% damping and considered until 10 sec in period, shown in Figure 5. As a phase of the motion, the phase property of Taft EW component observed in 1952 is utilized.

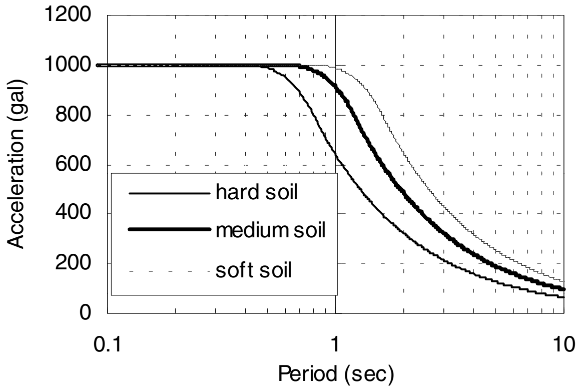

Figure 5: Acceleration Response Spectrum Corresponding to the Building Regulation in Japan

For the design limitation, the artificial motion must be modified according to the realised seismic performance of specimen. Since the specimen has only 72% of seismicity compared to the minimum required performance (in terms of the seismicity index I_s [MOC 1990]), the response spectra used for table input is factored by that value (=0.72). The maximum values of acceleration, velocity and displacement are originally 402.2gal, 83.5kine and 65.5cm and the maximum observed values of the table input motion are 478.3gal, 40.4kine and 14.5cm, respectively. With limitation of stroke of the shaking table, an analog filter is also applied to reduce the amplification of period regions higher than 2 sec. The time histories and the velocity response spectrum are drawn in Figures 6 and 7.

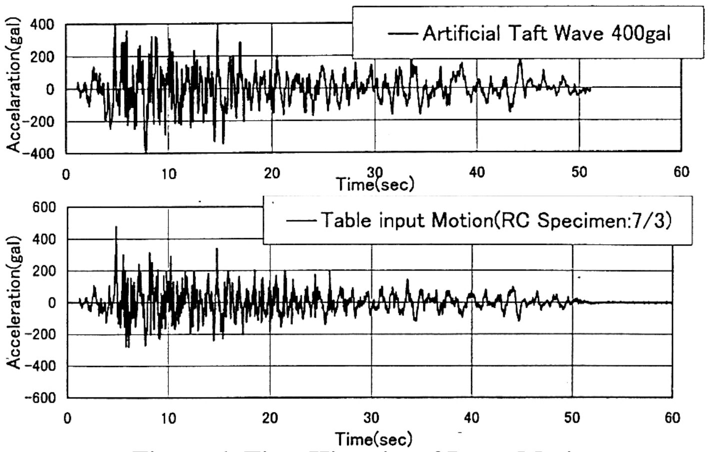

Figure 6: Time Histories of Input Motions

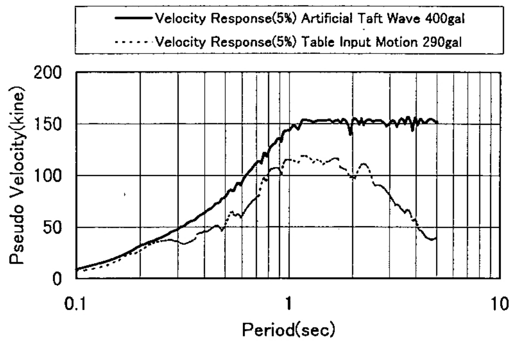

Figure 7: Velocity Response Spectrum

DYNAMIC RESPONSE OF TEST SPECIMEN

There were two specimens, A and C, used for dynamic test. The specimen C was also used for the performance evaluation of energy absorbing devices (details are shown in another paper for this conference). The relationship between horizontal load and displacement are shown in Figure 8. During excitation, after 8 seconds passed, shear failure of columns occurred after flexural yielding at the beam ends and the specimens completely lost its lateral load carrying capacity. The inter story drift and observed lateral restoring force at the failure points are about 25mm and 110tonf respectively. Figure 9 shows the damage situation (tensile yielding of steel bars) of the specimen C. The yielding of main bars in beams were started at displacement about 20mm prior to that of column reinforcement bars. Finally there were shear failures with bond split failure in columns after reduction of restoring force around 25mm displacement. See Photo 2.

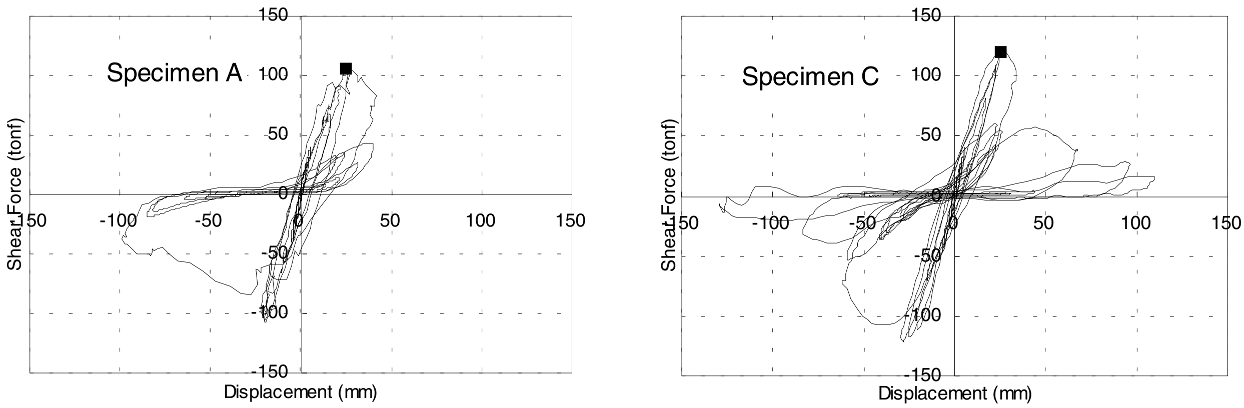

Figure 8: Shear Force-Displacement Hysteresis (■ indicates shear failure of columns)

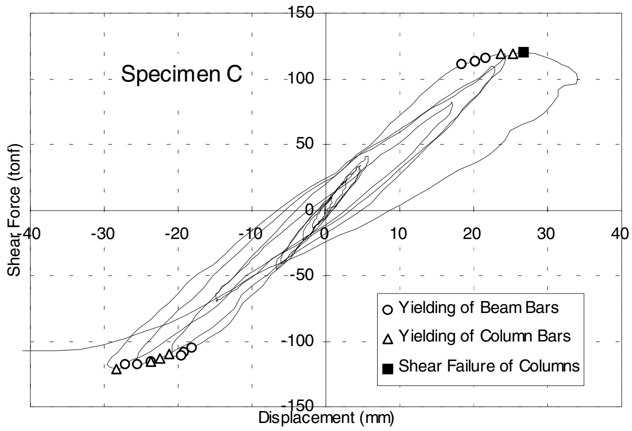

Figure 9: Yielding of Main Bars

Photo 2: Damage Situation (specimen C)

Photo 3: Damage Situation (static test)

STATIC TEST

In addition, a static test was also carried out using the same facilities except shaking table but reaction wall and oil jack (specimen B). To define the load schedule, time history of inter story drift obtained from shaking table test had used. From the time history we picked the appropriate displacement level and rearrange them in order. See Figures 10 and 11. In the static test, the shear failure of columns occurred at drift angle 1/117 (Photo 3).

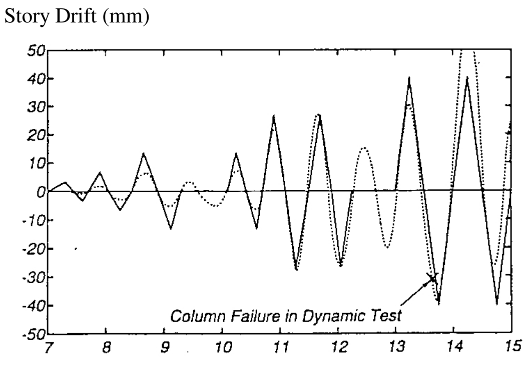

Figure 10: Inter Story Drift (dynamic test)

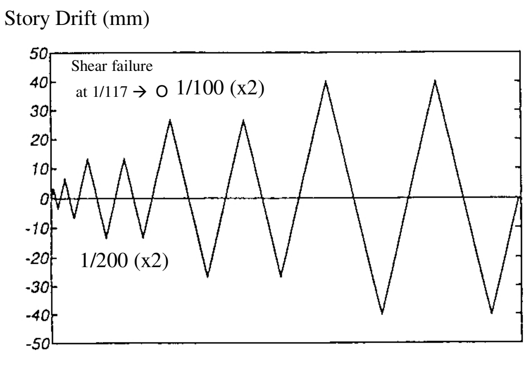

Figure 11: Load Schedule for Static Test

FAILURE MECHANISM AND MODELING OF THE SPECIMEN

Figure 12 presents the relationship between horizontal load and story drift of the specimens both in dynamic (specimen C) and static loading test (specimen B). Two results are almost the same but there are some little differences (i) failure displacement is smaller and (ii) there were no tensile yielding in main bars during the static test. The maximum lateral restoring force obtained from dynamic (121tonf) and static (113tonf) test are larger than predicted value 103.6tonf by the current design formula formerly shown in Table 1.

In the Figure 13 there is also a skeleton modelling curve for the numerical analysis. The hysteretic behaviour of the restoring force of RC frame specimen can be modelled by Takeda's hysteresis rule (in the stage of removing load, aiming cracking point before yielding and stiffness reduction factor 0.4 after yielding). The region of elastic behaviour was assumed from the data of dynamic test. An instantaneous stiffness proportional damping for the specimen was 1%. For the Takeda's rule, there were four characteristic points to describe the behaviour of the specimen. (1) cracking point [0.91mm, 20tonf], (2) a point between (1) and (3), (3) yielding point [20mm, 109tonf] and (4) shear failure point after reduction of restoring force.

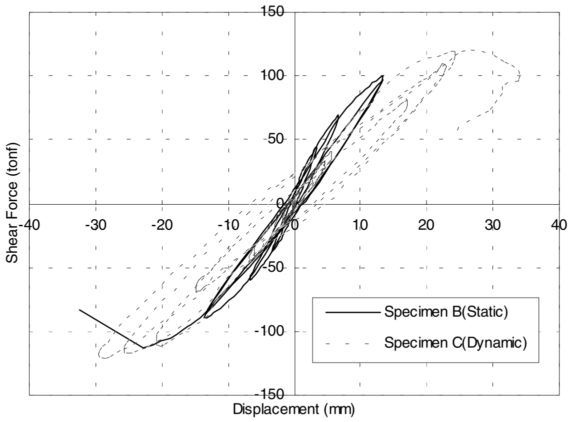

Figure 12: Comparison of Dynamic and Static Test

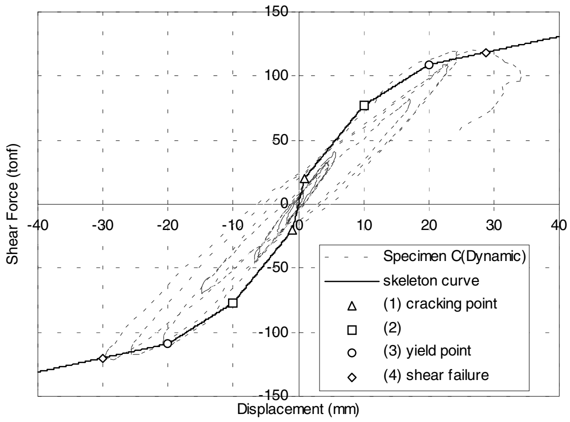

Figure 13: Analytical Model

NUMERICAL ANARYSIS

A numerical analysis was lastly carried out to confirm the possibility for the failure prediction of old reinforcement concrete structures. For the analysis, each part of experimental facilities were properly modelled and combined. From characteristic confirmation tests, initial stiffness of rubber bearings used to support the inertia mass and justify the natural period were defined to 2.0tonf/cm and 25tonf/cm respectively. See Figure 14. The natural period of whole numerical system was 0.6sec and equal to the value obtained from shaking table test using small level step excitation of 20gals. In the actual numerical analysis, stiffness was set to 20tonf/cm and viscous damping proportional to stiffness (=0.01146) was used for period adjusting rubber bearings.

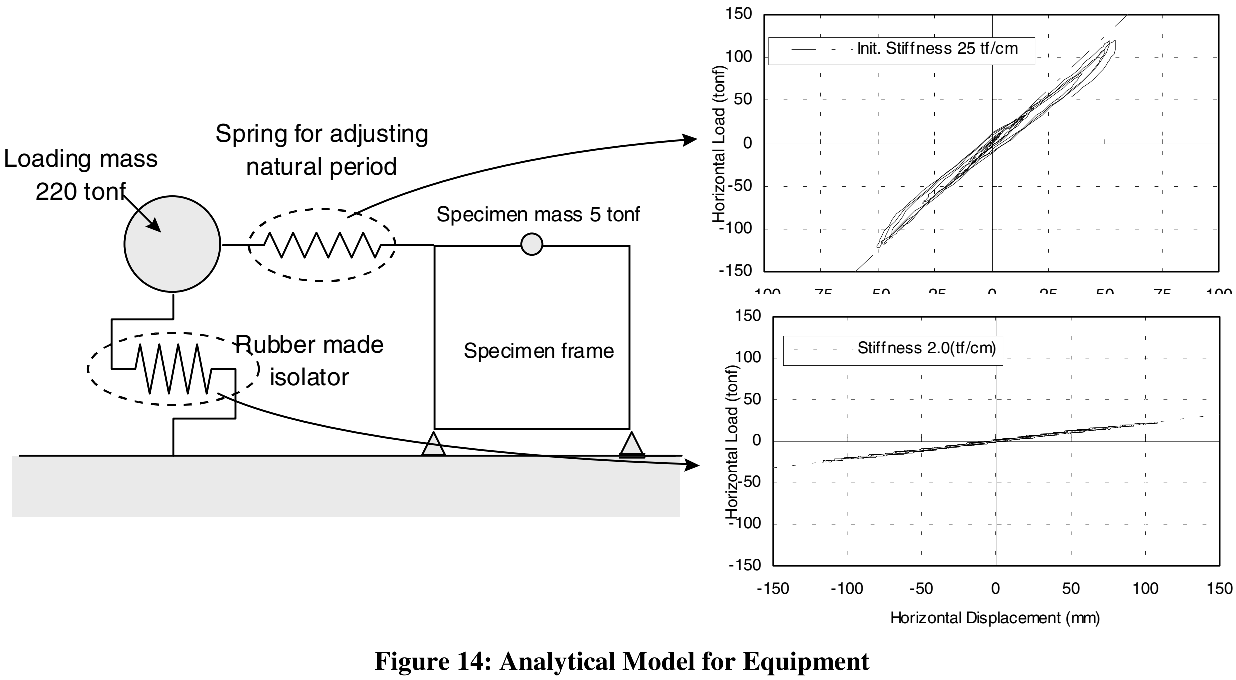

Figure 14: Analytical Model for Equipment

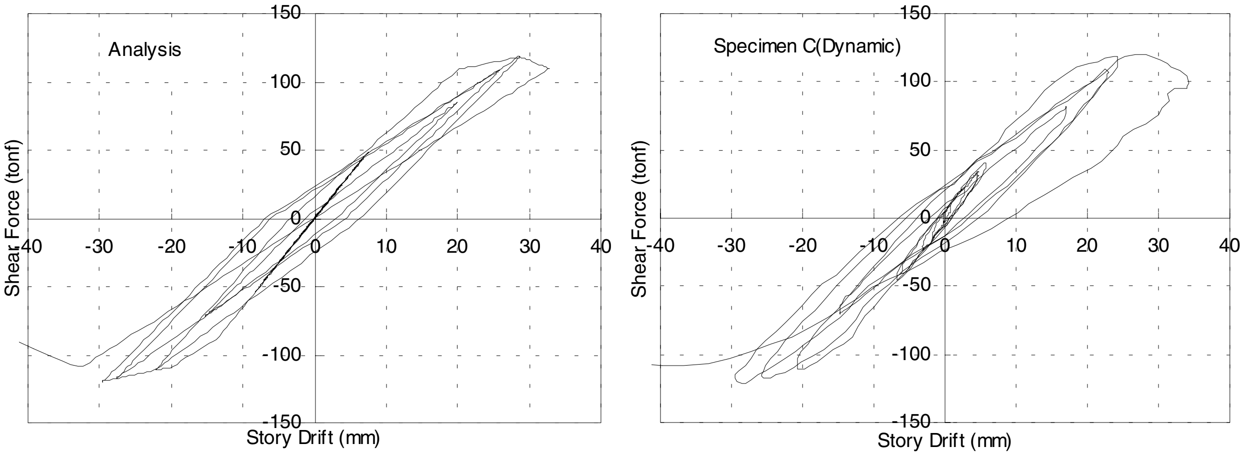

Figure 15: Comparison of Load-Displacement Hysteresis

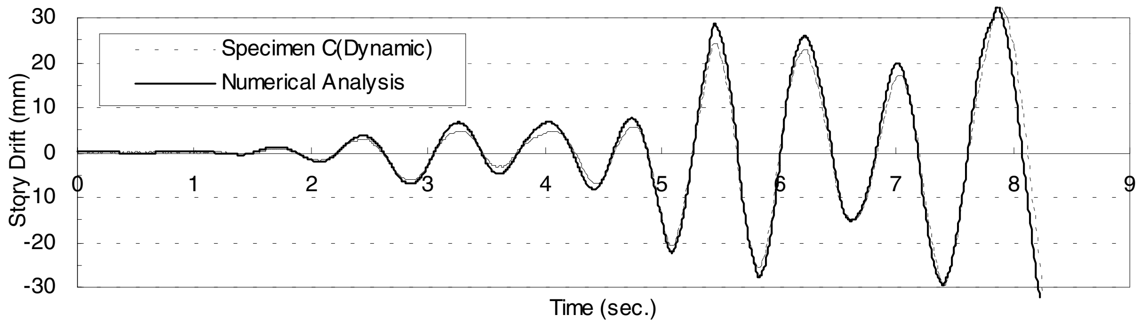

Figure 16: Comparison of Story Drift

Figures 15 and 16 show the comparison of dynamic test and numerical analysis. The input motion has been shown in Figure 6. The response obtained from the analysis is almost identical to the observed response until there had been shear failure in columns.

CONCLUSIONS

Reinforced concrete frames designed under the old seismic regulations have a high possibility of story collapsing because of shear failure in the columns during a severe earthquake. The behaviour of the frame under strong earthquakes can be predicted by numerical analysis. The current design formula used in Japan for the shear strength of the members is adequate, and has some safety margin to the experimental results.

ACKNOWLEDGEMENT

This experimental research was conducted under the project entitled "Improving seismic ability of existing buildings using new technology" sponsored by Ministry of Construction, private companies and etc. The authors express our sincere thanks to members of the project.

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