Dynamics of Real Structure in Fresh, Damaged and Reinforced States in Comparison with Shake Table and Simulation Models

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Abstract

The dynamics of a real three-story structure were studied based on changes of its natural frequency when beams and braces were removed, to simulate damage, and returned, to simulate reinforcement. Total 81 steps simulating different structural states were adopted for these testes. For comparison, laboratory shake table experiments were performed with 1/20-scale models, for the same 81 steps. In addition, numerical simulations of the real structure were also carried out over the same 81 steps for comparison. The change in natural frequency for the three methods, together with the influence of temperature and humidity, showed interesting tendencies, which prove important and meaningful for the development of structural health monitoring systems using dynamic data.

Keywords: natural frequency; real structure; damage; reinforcement; shake table; simulation

1. Introduction

Natural frequency is a typical parameter for studying the dynamics of a structure; it is often treated as a constant after the construction of the structure. In recent years, it has also been believed to be an important index in developing a structural health monitoring system. The reasoning is that when a structure receives an input, such as an earthquake, which causes damage to its beams, columns, or braces, the stiffness of the structure will change. Theoretically, this produces changes in its structural dynamics. If you can measure a dynamic parameter for the structure, the degree of damage and its location can then be determined through inverse analysis. In such cases, the natural frequency has generally been selected as an index of the dynamic parameters.

Based on the assumption that the change (often a decrease) of the natural frequency directly indicates a change of stiffness (structural damage), during the last decades, many inverse analysis methods have been presented (e.g., Cawley and Adams 1979, Ju and Mimovich 1987, Hjelmstad and Shin 1996, Salawu 1996, Law 1998, Lee and Shin 2002, and Pothisiri and Hjelmstad 2003). The authors have also presented an online method for identifying the damage (e.g., Xue *et al*. 2005, Xie and Xue 2006, and Tang and Xue 2007).

In general, according to the theoretical relation between natural frequency and stiffness, the natural frequency will decrease when damage occurs. Dynamic experiments such as shake table tests in the laboratory have also proved this assumption. But it might not always be true for real structures, especially indeterminate and complex structures. Aktan *et al*. (1994) concluded that significant frequency changes alone do not imply the existence of damage, since the frequency also shifts due to changes in ambient conditions. An investigation lasting three years was reported by Askegaard and Mossing (1988), who showed that the natural frequency of an undamaged structure is influenced by changes in temperature, humidity, etc., and a frequency change of about 10% was repeatedly observed for each year. Another study analyzing the effect of ambient conditions on the dynamic response of four pre-stressed concrete bridge decks, Purkiss *et al*. (1994), concluded that temperature influenced the natural frequency significantly, although the decks were fresh. The site's air temperature and humidity, mean air pressure, and the mean rainfall on the day preceding the test also influence natural frequency in their study. An investigation of the I-40 Bridge over the Rio Grande in New Mexico USA conducted by Farrar *et al*. (1994) showed that the natural frequency of the bridge did not always decrease with an increase in the degree of damage. Among the various factors influencing the natural frequency of the bridge, the ambient temperature played an important role. Based on two years of on-site measurements,

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Cornwell *et al*. (1999) reported that the modal frequency of the Alamosa Canyon Bridge in southern New Mexico varied by up to 6% over a 24-hour period. They also examined a linear adaptive model (Sohn *et al*. 1999) to discriminate changes of modal parameters due to temperature change from those caused by structural damage or other environmental effects, using the data from the Alamosa Canyon Bridge. The analysis of six different sets of earthquake records, as well as ambient vibration records, from a 40-story steel building in Los Angels have shown that although there was no damage, the natural frequencies of the building changed as much as 30% due to nonlinearities in the building's response and soil–structure interaction effects (Safak 2005). Similar conclusions were reached in other studies (Helmicki *et al*. 1999, Cioara and Alampalli 2000, Sohn *et al*. 2001, Kohler *et al*. 2005, Todorovska *et al*. 2004). The authors (2005, 2006, and 2007) have also presented research showing that the natural frequency does not always decrease when some beams are removed from a real structure.

This paper presents our recent research on the dynamics of a real structure, together with models for shake table and finite element method simulation. The changes in natural frequencies due to damage of the beams or braces through repeated vibration experiments, the influence of temperature and humidity, and the effects of beam and brace reinforcement are discussed.

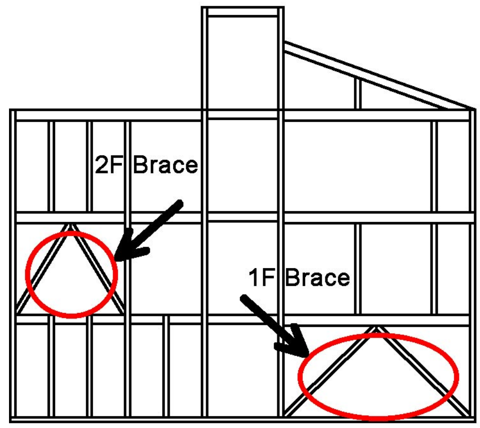
2. Real Structure Test

A real structure was built in 2002 on the campus of Kinki University, as shown in Fig.1. In 2005 the walls and floors were removed step by step and the changes in natural frequency were measured and discussed by the authors (2006). Unfortunately because removing of walls and floors is difficult work for students, only one set of test results were obtained at that time. However, the results clearly showed that the natural frequencies decrease with the degree of wall and floor removal.

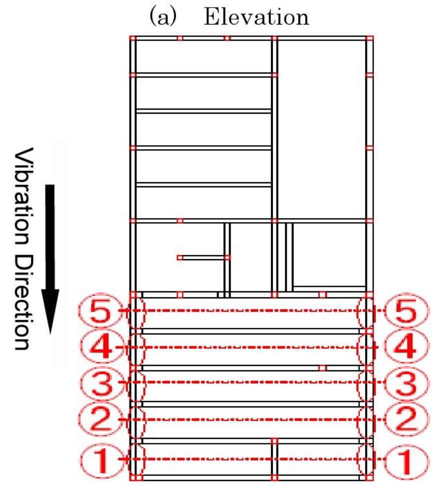
This paper reports the results on the skeleton structure shown in Fig.1. The frame was designed and constructed according to the design of a real residential building. All the beams, columns, and braces were made of red pine, and connected with metal pieces to form rigid joints. The height of each story is 2.73 m, and the building envelope dimensions are 10.92 × 10.92 × 5.55 m, as shown in Fig.2. The columns on the first floor are rigidly connected to the foundation. To create the effect of damage, typically the related beams and braces are removed. However, while this approach considers the change in building stiffness, it omits mass changes. The beams and the braces to be removed and returned repeatedly are shown in Fig.2., where two sets of braces and five sets of beams are repeatedly removed and returned during the tests.

Eighty one step experiments were performed in 2007 through various combinations of the beams and braces.

Fig.1. Real Wooden Structure



(a) Elevation



(b) 2F Plane view

Fig.2. Wooden Frame, and the Beams and Bbraces to be Moved and Returned

At each step, the natural frequency was obtained by free vibration tests in the direction shown in Fig.2.

The natural frequencies of the real structure for each of the 81 test steps, together with the date, temperature, and humidity recorded, are shown in Table 1. Because trends in the natural frequencies becomes important when comparing this data to shake table results and ANSYS simulation results, the measured natural frequencies are normalized to the first step (the first step is the fresh, or undamaged, state)—only the normalized data are shown in Fig.5. Section 5 discusses the tendency of natural frequency.

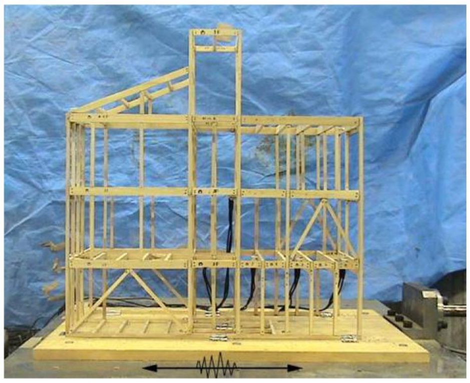


Fig.3. Model for Shake Table Tests

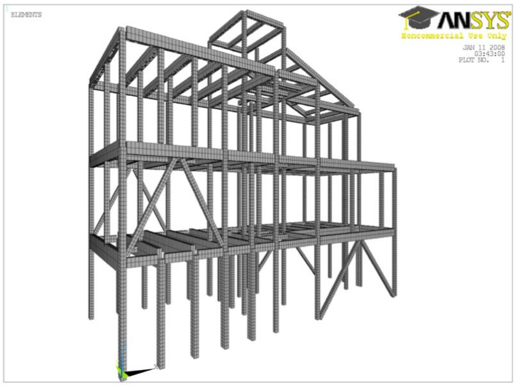


Fig.4. Finite Element Modeling in ANSYS

3. Shake Table Test

The shake table in our laboratory is a 1 × 1 m platform and can only simulate excitation in a single direction. To accommodate the size of this platform, three 1/20-scale models of the structure were made. All the elements of the model were made of cypress, and the joints were made of metal pieces, same as in the real structure. The model had an envelope measuring 54.6 (length) × 22.8 (width) × 54.6 cm (height) and was rigidly installed on the shake table, as shown in Fig.3. The arrow represents the same vibration direction as in the real structure. Sweep wave input was used to obtain the natural frequency. According the same 81 steps of various damaged states in the real structure, the natural frequencies of the model on the shake table were obtained. Table 1. shows the natural frequencies, and Fig.5. shows the normalized ones.

3.1 Numerical simulation by the finite element method

Numerical simulation was carried out using the finite element method (ANSYS). While building the model, three translation freedoms and three rotation freedoms at each node were considered for each element. The model for ANSYS simulation is shown in Fig.4. All rotations between parts (column, beam, and brace) at the connecting joint are considered as rotation springs, where the spring constant has been selected to be large enough to form a nearly rigid

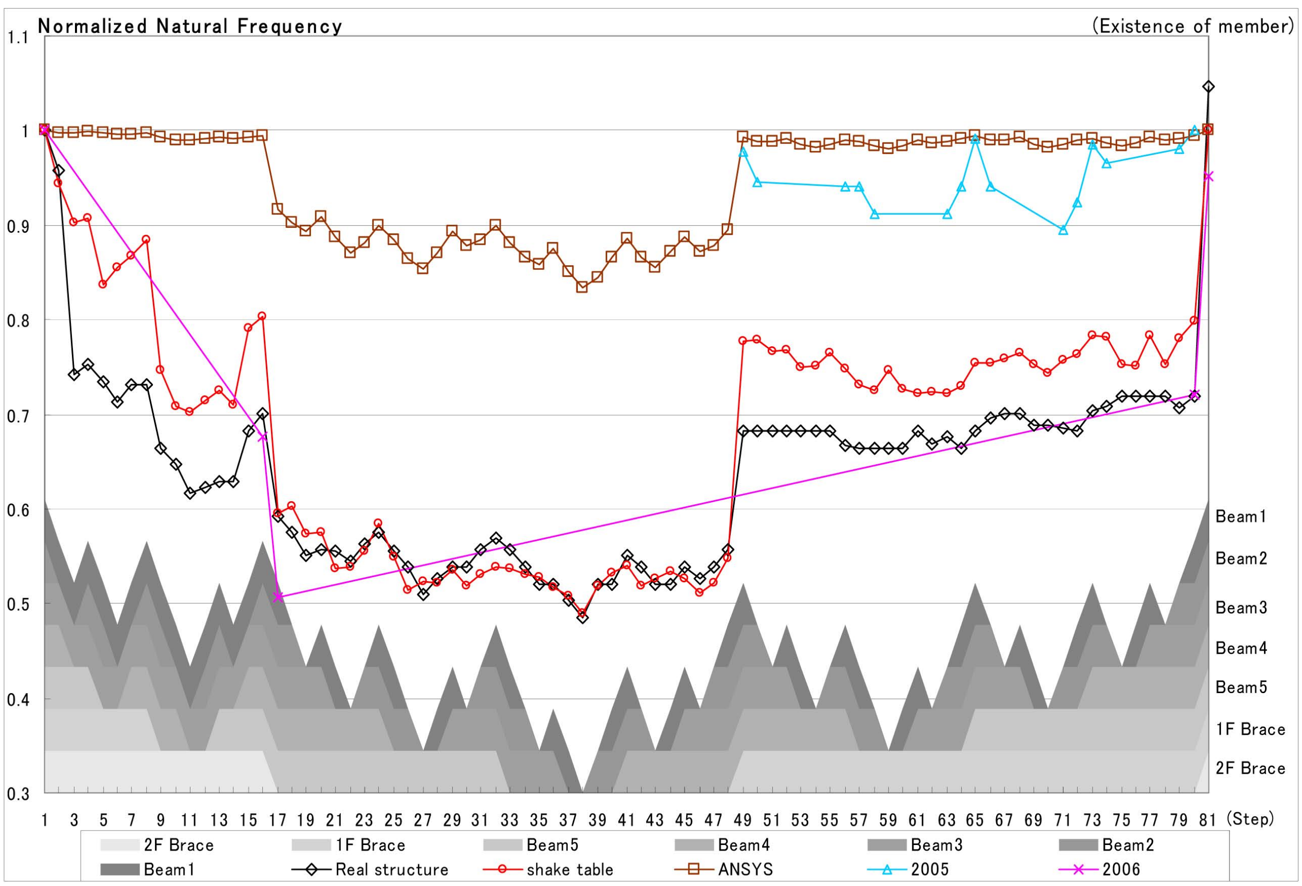


Fig.5. Natural Frequencies

connection. Elastic responses have been calculated and the parameters of the material, geometry, and boundary conditions were all determined according to the design of the real building. Following the experiments for the real structure in both damaged and reinforced states, a total of 81 steps are calculated. Normal mode analysis clearly gives the natural frequencies shown in Table 1., and Fig.5. shows the normalized data.

4. Explanation of Results

The natural frequencies from the tests with the real structure, shake table experiments, and ANSYS simulations are shown in Table 1., as well as in the graph of Fig.5. Some interesting and important facts of these results are discussed in the following sections.

Table 1. shows the natural frequencies for the 81 steps with the real structure, shake table experiments, and simulations. The symbol × in the table means the corresponding member (brace or beam) is removed, which implies that damage occurred on that member. The date, together with the temperature and humidity, represent the experimental days only for the real structure, not for shake table and simulation data. Three natural frequencies (average values) are measured from the real structure, recorded from shake table, and calculated from ANSYS simulation.

Fig.5. shows the normalized natural frequency for the real structure (including data from 2006 and 2005), shake table tests, and ANSYS simulations. The horizontal axis represents the test steps. The left vertical axis represents the normalized natural frequency, where the black full line represents the real structure, the red line represents the shake table, and the brown line represents the ANSYS simulation results. Two other lines in the figure represent the normalized natural frequencies obtained in 2006 (pink) and 2005 (blue). The data from 2005 represents the state of a column instead of a brace. The right axis represents the presence of the structural members (beams and braces) drawn in the background (the shadow). According to elastic mechanics, the rise and fall of the line should be identical with the rise and fall of the background.

Fig.6. shows an enlargement of Fig.5. from the 49^{th} to the 79^{th} step.

4.1 Changes of natural frequency in general steps

An overview of Fig.5. shows that, in general, the natural frequencies decrease with removal of members (decrease in the shadow area indicates that a member is removed), while they increase as structural members are returned. This is true, not only for the real structure, but also for shake table tests and ANSYS simulations. This clearly demonstrates that the change tendency of the natural frequency of the real structure is almost identical to both the theory and laboratory experiments. At the same time, the tendency for this general case also reveals that the natural frequency can represent the degree of damage. Thus, it can be used as an index in the research field of structural health monitoring system.

4.2 Damage Sensitivity

From Fig.5., it is clear the normalized natural frequencies of the real structure, together with the shake table model, are sensitive to changes between 0.48 to 1 of either increased damage or reinforcement, while those of the ANSYS simulation are insensitive to changes between 0.83 and 1. The real structure and shake table tests are performed on actual existing objects, and the changes are similar, while the results of imaging simulation differ, even though the simulation model is built using real design parameters. Generally a structural health monitoring system often uses inverse analysis to identify the degree and location of damage. These results suggest that a computer program may be insensitive to stiffness changes compared to the real structure. This should be taken into account.

4.3 Damage and reinforcement of brace

8^{th} and 9^{th} steps involve removing the 1F brace. A sudden decrease of the natural frequency can clearly be seen in Fig.5. for the real structure, the shake table, and ANSYS simulation. The same decrease occurs from the 16^{th} to the 17^{th} step, where the 2F brace has been removed. The 48^{th} to 49^{th} step shows a large increase when the 2F brace has been restored, and the same increase is observed from the 80^{th} to the 81^{st} step, when the 1F brace is restored. This indicates that the braces play a more important role than the beams in resisting horizontal vibration.

4.4 Damage and reinforcement of beams

The change of natural frequency for damaged or reinforced beams showed an irregular tendency for the real structure and shake table tests, compared with ANSYS simulations. Beam 2 is removed at step 67, and for the real structure and shake table tests the natural frequencies increase compared to the 66^{th} step. For the ANSYS simulations, however, the natural frequency decreases. Beam 1 is restored at step 68, but the natural frequency of the real structure is unchanged, whereas it increases for the shake table and ANSYS simulation. Such inconsistencies can also be seen at the 35^{th}, 50^{th}, and 59^{th} steps. This inconsistency occurs only for beams, not for braces. Theoretically, if a beam has been removed, the natural frequency will decrease. But for a real complex structure, the results are incorrect, such as happens when removing beams. The building's beams turn out not to be very effective in resisting horizontal vibration force. Thus, an important fact about real structures has been revealed for the development of structural health monitoring systems—the change of natural frequency may not accurately represent the state of the structure. For some structural members, a decrease in natural frequency may imply an increase in stiffness and no change may imply slight damage. It is important to identify such irregular members when conducting identification research.

Table 1. Natural Frequencies in 2004

Step	2F brace	1F brace	beam 5	beam 4	beam 3	beam 2	beam 1	Experiment Date	Temperature (℃)	Humidity (%)	Natural Frequency, Real Building	Natural Frequency, Shake Table	Natural Frequency, ANSYS
1								2008/9/27	25.8	54	2.78320	17.4988	1.9755
2						×		2008/9/27	25.8	54	2.66113	16.4728	1.9041
3				×		×		2008/9/27	25.8	54	2.09961	15.5638	1.6555
4				×				2008/9/27	25.8	54	2.09147	15.6123	1.6660
5			×	×				2008/9/27	25.8	54	2.04264	14.1601	1.6589
6			×	×		×		2008/9/27	25.8	54	1.99382	14.6118	1.6481
7			×			×		2008/9/27	25.8	54	2.05078	15.0818	1.6720
8			×					2008/9/27	25.8	54	2.05078	15.3076	1.6815
9		×	×					2008/9/27	25.8	54	1.85540	12.9272	1.6195
10		×	×			×		2008/9/27	25.8	54	1.80660	12.1582	1.6070
11		×	×	×		×		2008/9/27	25.8	54	1.75780	11.8652	1.5745
12		×	×	×		×		2008/9/27	25.8	54	1.75780	12.1094	1.5889
13		×		×				2008/9/27	25.8	54	1.80660	12.4756	1.5954
14		×		×		×		2008/9/27	25.8	54	1.79033	12.1094	1.5814
15		×				×		2008/9/27	25.8	54	1.90420	13.5254	1.6673
16		×						2008/9/27	25.8	54	1.95310	13.6719	1.6900
17	×	×						2008/10/2	23.3	47	1.66016	11.6757	1.3996
18	×	×					×	2008/10/2	23.3	47	1.64388	11.5722	1.3862
19	×	×				×	×	2008/10/2	23.3	47	1.56250	11.1327	1.3793
20	×	×				×		2008/10/2	23.3	47	1.56250	11.1694	1.3931
21	×	×			×	×		2008/10/2	23.3	47	1.56250	8.1543	1.3746
22	×	×			×	×	×	2008/10/2	23.3	47	1.51367	8.1543	1.3602
23	×	×			×		×	2008/10/2	23.3	47	1.59505	10.7056	1.3694
24	×	×			×			2008/10/2	23.3	47	1.61133	11.1999	1.3883
25	×	×		×	×			2008/10/2	23.3	47	1.56250	10.5713	1.3793
26	×	×		×	×		×	2008/10/2	23.3	47	1.51367	9.9365	1.3599
27	×	×		×	×	×	×	2008/10/2	23.3	47	1.44857	7.9915	1.3505
28	×	×		×	×	×		2008/10/2	23.3	47	1.48112	7.9346	1.3653
29	×	×		×		×		2008/10/2	23.3	47	1.51367	10.2050	1.3839
30	×	×		×		×	×	2008/10/2	23.3	47	1.51367	9.9243	1.3699
31	×	×		×			×	2008/10/2	23.3	47	1.56250	10.1013	1.3747
32	×	×		×				2008/10/2	23.3	47	1.59505	10.1684	1.3901
33	×	×	×	×				2008/10/2	23.3	47	1.56250	8.6426	1.3780
34	×	×	×	×			×	2008/10/2	23.3	47	1.51367	8.5327	1.3622
35	×	×	×	×		×	×	2008/10/3	22.9	63	1.46484	8.4391	1.3571
36	×	×	×	×		×		2008/10/3	22.9	63	1.46484	8.2031	1.3717
37	×	×	×	×	×	×		2008/10/3	22.9	63	1.41602	8.0078	1.3524
38	×	×	×	×	×	×	×	2008/10/3	22.9	63	1.36719	7.6660	1.3371
39	×	×	×	×	×		×	2008/10/2	23.3	47	1.46484	8.4351	1.3467
40	×	×	×	×	×			2008/10/2	23.3	47	1.46484	8.5938	1.3668
41	×	×	×		×			2008/10/2	23.3	47	1.54622	10.1806	1.3793
42	×	×	×		×		×	2008/10/2	23.3	47	1.51367	9.7900	1.3600
43	×	×	×		×	×	×	2008/10/3	22.9	63	1.46484	7.9346	1.3506
44	×	×	×		×	×		2008/10/3	22.9	63	1.46484	8.0078	1.3653
45	×	×	×			×		2008/10/3	22.9	63	1.51367	9.9243	1.3801
46	×	×	×			×	×	2008/10/3	22.9	63	1.48926	9.6435	1.3659
47	×	×	×				×	2008/10/2	23.3	47	1.51367	9.8083	1.3707
48	×	×	×					2008/10/2	23.3	47	1.56250	10.1379	1.3870
49	×		×					2008/10/4	23.9	49	1.90430	14.1113	1.5055
50	×		×				×	2008/10/3	22.9	63	1.90430	14.1113	1.4934

(Continued on next page)

Step	2F brace	1F brace	beam 5	beam 4	beam 3	beam 2	beam 1	Experiment Date	Temperature (℃)	Humidity (%)	Natural Frequency, Real Building	Natural Frequency, Shake Table	Natural Frequency, ANSYS
51	×		×			×	×	2008/10/3	22.9	63	1.90430	13.8672	1.4899
52	×		×			×		2008/10/3	22.9	63	1.90430	13.8672	1.5001
53	×		×		×	×		2008/10/3	22.9	63	1.90430	12.1094	1.4934
54	×		×		×	×	×	2008/10/3	22.9	63	1.90430	12.1094	1.4788
55	×		×		×		×	2008/10/3	22.9	63	1.90430	13.8122	1.4862
56	×		×		×			2008/10/4	23.9	49	1.85547	13.6108	1.5001
57	×		×	×	×			2008/10/4	23.9	49	1.85547	12.1582	1.4919
58	×		×	×	×		×	2008/10/3	22.9	63	1.85547	12.1582	1.4777
59	×		×	×	×	×	×	2008/10/3	22.9	63	1.85547	12.1093	1.4702
60	×		×	×	×	×		2008/10/3	22.9	63	1.85547	11.8408	1.4809
61	×		×	×		×		2008/10/3	22.9	63	1.90430	12.0686	1.4945
62	×		×	×		×	×	2008/10/3	22.9	63	1.87174	12.1093	1.4841
63	×		×	×			×	2008/10/3	22.9	63	1.88802	12.2802	1.4878
64	×		×	×				2008/10/4	23.9	49	1.85547	12.1582	1.4995
65	×			×				2008/10/4	23.9	49	1.90430	13.6596	1.5114
66	×			×			×	2008/10/3	22.9	63	1.95313	13.6352	1.5001
67	×			×		×	×	2008/10/3	22.9	63	1.95313	13.5986	1.4965
68	×			×		×		2008/10/3	22.9	63	1.95313	13.7329	1.5065
69	×			×	×	×		2008/10/3	22.9	63	1.92871	12.0686	1.4934
70	×			×	×	×	×	2008/10/3	22.9	63	1.92057	11.9303	1.4830
71	×			×	×		×	2008/10/4	23.9	49	1.92057	13.5803	1.4903
72	×			×	×			2008/10/4	23.9	49	1.90430	13.6535	1.5041
73	×				×			2008/10/4	23.9	49	1.96126	13.9526	1.5252
74	×				×		×	2008/10/4	23.9	49	1.98568	13.8915	1.5125
75	×				×	×	×	2008/10/3	22.9	63	2.00195	12.2802	1.5056
76	×				×	×		2008/10/3	22.9	63	2.00195	12.2395	1.5152
77	×					×		2008/10/3	22.9	63	2.00195	13.8122	1.5206
78	×					×	×	2008/10/3	22.9	63	2.00195	13.4155	1.5111
79	×						×	2008/10/4	23.9	49	1.96940	13.7573	1.5195
80	×							2008/10/4	23.9	49	2.00195	14.0197	1.5440
81								2008/10/4	23.9	49	2.88086	16.1132	1.9755

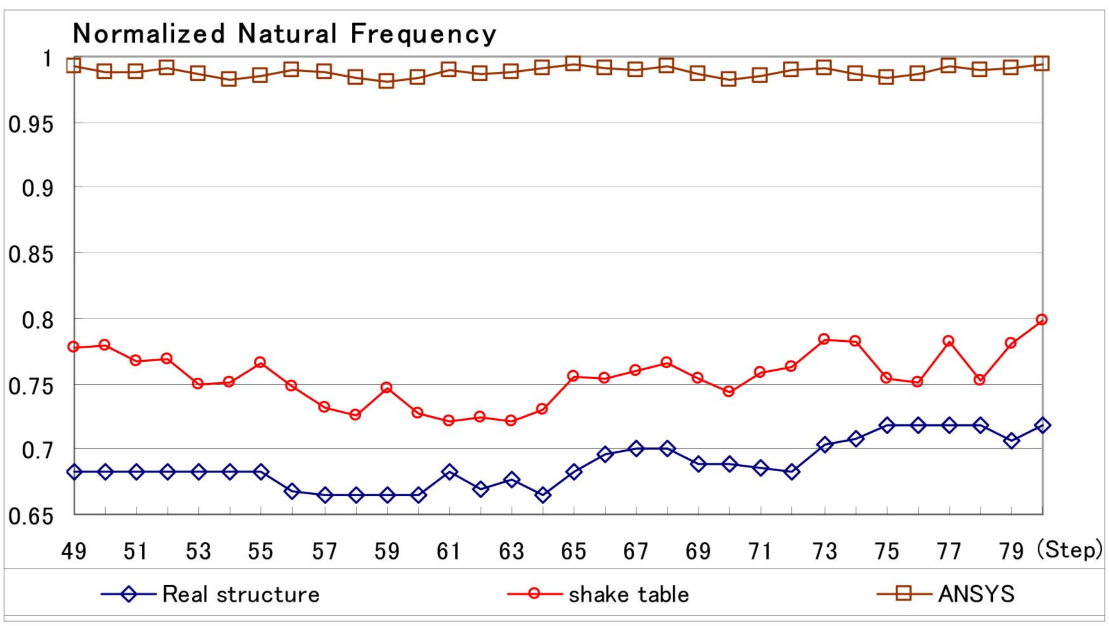


Fig.6. Natural Frequency from the 49th to the 79th Step

4.5 Natural frequency influenced by temperature and humidity

The dynamics of a real structure are often referred to as its natural frequency. Usually the natural frequency has been thought to be constant after design, and determined by the strength of the materials and the connections of the beam columns and braces, unless the structure is damaged. Unfortunately, recent research has shown that surrounding factors may influence the natural frequency. In this research, the influence of temperature and humidity was obtained using actual data collected over three years. During this three-year period, we obtained different natural frequencies for the same stage structures. For example, the 14th step in 2006 and the 17th step in 2007 are exactly the same, but the natural frequencies are different. This appears to be caused by differences in temperature and humidity. Assuming the difference in natural frequencies is caused only by temperature or humidity, the degree of influence is uniformly calculated as follows. The relation between the change in natural frequency (Δf) and the change in temperature (ΔT) is

$$\frac{\Delta f}{\Delta T} = 0.01358571 \tag{1}$$

The relation between the change in natural frequency and the change in humidity (ΔH) is

$$\frac{\Delta f}{\Delta H} = 0.004521429 \tag{2}$$

These influences are more obvious than expected. A rise of 20 degrees in temperature causes an increase of 0.26 Hz in the natural frequency. Such an obvious change will produce mistakes if someone wishes to calculate structural damage using only the recorded natural frequencies. The influence of temperature and humidity on the natural frequency is clear, but the degree of influence remains a subject requiring more experimental data.

5. Conclusions

The dynamics of a real structure were studied based on changes of its natural frequency in different damaged or reinforced stages. This data was compared with the results from reduction models for shake table tests and ANSYS simulations. It is clear that for a general case, the tendencies of the changes in natural frequency are the same, but the real structure and the shake table model show different (inconsistent) results at some steps. This clearly reveals that in some cases, it is difficult to simulate a real structure with a computer, especially for complex structures. Dynamic structural health monitoring systems have been developed, based primarily on the change in natural frequencies before and after the occurrence of damage; however, it is important to determine which structural members are sensitive beforehand, and fully use such information in the inverse analysis system.

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