Dynamic Properties of Conventional Beam-Column Timber Structure Under Successive Damage

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Abstract

A full-scale, three-story conventional beam-column timber structure was tested in-situ to investigate the changes of natural frequencies due to progressing artificial damage. A total of 45 test steps were adopted in the execution of this experiment and analysis. Columns were cut by saw and/or totally removed at each testing step in order to simulate different levels of damage. A three-dimensional finite element (FE) model of the test structure was established and applied to predict its natural frequency in each of the 45 test steps. Both the FE simulation and the testing results show similar tendencies in most test cases, however they slightly deviate from each other in some particular test cases. Damage sensitivity, as well as the influence of temperature and humidity on the natural frequency was also examined. The results and conclusions from this study can benefit the emerging research field of structural health monitoring.

Keywords: conventional beam-column timber structure; natural frequency; numerical simulation; modal analysis; damage

1. Introduction

Wood is one of the oldest and most sustainable materials used in construction. Despite its complex chemical nature and excellent mechanical properties, wood is a renewable and biodegradable resource. Nowadays timber has become the most widely used residential construction material in North America (Lindt 2005) and Japan (Sakata *et al*. 2008). Unfortunately, timber structures in these regions may frequently be subjected to considerable vibration induced by earthquakes (Murakami *et al*. 1999) or hurricanes (Eamon *et al*. 2007), which may create severe damage or cause collapse. Most recently, a number of researchers have devoted their efforts to the experimental study and numerical simulation of the dynamic and static behavior of whole timber structures (Ayoub 2007, Lindt 2008, Oudjene and Khelifa 2009, Songlai *et al*. 2010). However, research concerned with variation of the structural dynamic properties is relatively scarce. Ellis and Bougard (2001) reported the changes in stiffness and natural frequency during construction of a six-storey timber frame building. Xiong *et al*. (2008) showed that the dimension of shear wall, torsion effect and amplitude of excitation would influence the natural frequency of the light-frame structure. Heiduschke *et al*. (2009) observed that natural frequencies changed with the amplitude of input excitation due to the increase in damage level. Filiatrault *et al*. (2010) investigated the dynamic characteristics of the light-frame wood building with and without interior and exterior wall finishes using the shaking table test. Their experimental results revealed that the stiffness of the light-frame structure (approximated by fundamental frequency) deteriorated under seismic loading, and could be improved with the interior and exterior wall finishes. To the authors' knowledge (Xue *et al*. 2006, Fukuda *et al*. 2007, Xue *et al*. 2008), little has been done about the influence to the whole timber structure system when part of its members or sub-assemblies have been damaged. On the other hand, damage of structural members always leads to changes of dynamic properties such as natural frequency, which is one of the important indexes adopted in the identification of damage and/or decay. For engineering structures, an accurate and complete understanding of dynamic property changes caused by damage is the key step in the proper execution of structural damage detection and health monitoring works, and timber structures are no exception to such requirements. Theoretically the natural frequency of structures decreases when damage occurs, but for real structures it might not always be true, as cited by the previous study (Xue, 2008). It is therefore desirable to further investigate the influence of damage on the variation of structural dynamic properties inside a structural system.

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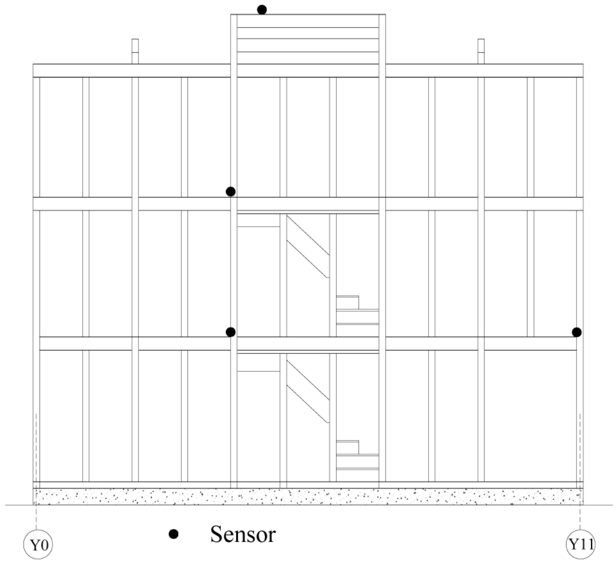
This study is the second of two companion studies on the influence of damage on the variation of dynamic properties in timber structures. In previous research (Xue, 2008), the changes in natural frequencies or fundamental frequencies had been studied when beams and braces of a three-storey skeleton structure were removed and reassembled. A shaking table test and numerical simulation were also conducted for comparison. Furthermore, the influence of temperature and humidity was also investigated by testing the structure over three years and compared with the shaking table test. However, while the braces and beams were removed to simulate damage effects, there was a combined influence of both stiffness and mass to the natural frequency. Moreover, these test cases could simulate either medium damage states (e.g., cracks of beams and columns), or failure of the joints. To further investigate the influence of damage on the variation of dynamic properties in timber structures, a three-storey beam-column residential building was built and its roof and wall sheathing were then dismantled for testing. Columns of the rest of the structure were cut by sawing and/or totally removed to simulate different levels of damage. The natural frequencies were obtained by a free vibration test at each step and compared with that obtained from the finite element analysis.

2. Test Setup and Test Details

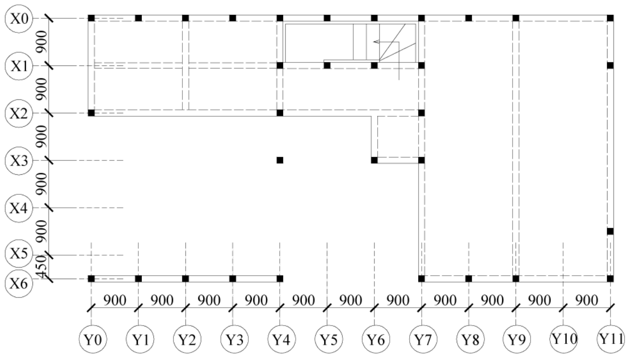
A full-scale conventional beam-column timber residential building was designed and built in accordance with the requirements as stipulated in the current edition of building codes/guidelines and common design practices in Japan. The height, length and width of the concerned building are 8.57m, 9.9m (in the North-South direction) and 4.95m (in the East-West direction), respectively. The whole building structure is supported on joists fixed in a cast-in-place concrete foundation. In this study, the roof system (including the rafters) and wall sheathings, as well as ceilings of every floor were dismantled beforehand and the remaining structural components for testing are shown in Fig.1. Fig.1. (a) shows the exterior view of the real beam-column residential building, while (b) illustrates the structure for testing. Fig.2. shows the typical arrangement of the structure for testing, in which (a) shows the elevation while (b) and (c) depict the plan views. The sectional dimensions of all beams and columns were standardized at 120x240mm and 120x120mm respectively and were made from spruce, and mortised together with a tenon. Some of the joints were strengthened with steel fasteners, particularly

(a) Real Building　　(b) Test Structure

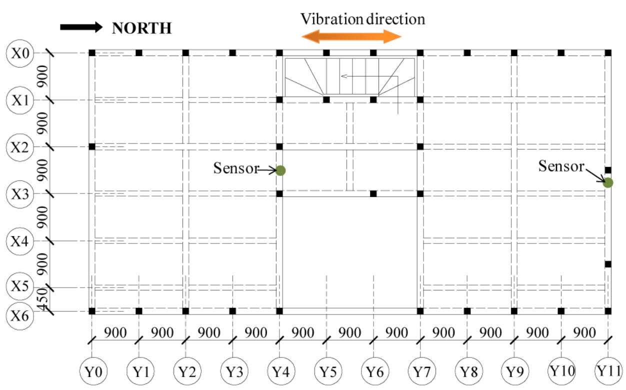
Fig.1. Test Structure On-site



(a) East Elevation



(b) 1F Plan View (units: mm)



(c) 2F/3F Plan View (units: mm)

Fig.2. Typical Arrangement of the Structure for Testing

(a) Half-cutting at column-base (HC)

(b) Full-cutting at column-base (FC)

(c) Removal of column (RM)

Fig.3. Three Damage Stages of the Column

those at corner-regions.

The test structure was monitored with 4 wireless digital sensors to measure acceleration. Three of them were installed on the top of the beams on each floor near the staircase, and the remaining one was installed on the north beam of the 2F, as shown in Fig.2.

Table 2. summarizes the testing program and the corresponding damage stages in each of the 45 test steps. Columns were first grouped according to their Y axis location, and all the columns in the same group were then either cut or removed in three ways, namely, (i) half-cutting of the section at the column-base, (ii) full-cutting of the section at the column-base, and (iii) removal of the column. This preparation work of column cutting and removal was used to simulate the three damage states of the columns (i.e., from medium to severe damage), which are illustrated in Fig.3. The two columns along the Y-axis on the 2F, as shown in Fig.2. (b), are taken as an example to illustrate the testing setup and/or details in each testing step. In test step 11, the test was started by carrying out the sectional half-cutting of the afore-mentioned two columns at their respective bases, and the test ended upon the completion of the free vibration test. In test step 12, the test started by carrying out the sectional full-cutting of the two tested columns in test step 11 at the gap or cut made in test step 11, and the test ended upon the completion of the free vibration test. Similar procedures were conducted in subsequent test steps until the completion of the testing series. In order to prevent the collapse of the test structure, only sectional half-cutting of columns was conducted at the end of the test series. It was noticed that no damage occurred at the first step.

3. FEM Simulation

Despite the complexity of the timber structures, significant work has been conducted on numerical simulation of wood-frame buildings by FE analysis. A comprehensive review of these studies is given by Collins *et al*. (2005) and Lindt *et al*. (2010). Among these studies, Kasal *et al*. (1994) and Collins (2005) successfully modeled light wood-frame structures with ANSYS software. ANSYS was also utilized for simulating timber connections (Shanks and Walker 2009) and wood properties test specimens (Dahl and Malo 2009). A combined usage of experimental measurements and FEM simulation was adopted in previous research (Xue 2008). Based on experiences from the previous study, numerical simulation using ANSYS was employed in this paper for calculating the natural frequencies of the testing structures.

Wood is always described as an orthotropic material: the longitudinal axis L is parallel to the fiber (grain); the radial axis R is normal to the growth rings; and the tangential axis T is perpendicular to the grain, but tangent to the growth rings, as shown in Fig.4. Material models implemented to finite element models were all linear elastic for modal analysis. In the linear-elastic region, the orthotropic elasticity can be expressed as:

$$\{\varepsilon\} = [S]\{\sigma\} \qquad (1)$$

$\{\sigma\}$ and $\{\varepsilon\}$ are stress and strain tensor respectively. The tensor of elastic stiffness $[S]$ is expressed as:

$$[S] = \begin{bmatrix} E_T^{-1} & -\nu_{RT}E_R^{-1} & -\nu_{LT}E_L^{-1} & & & \\ & E_R^{-1} & -\nu_{LR}E_L^{-1} & & & \\ & & E_L^{-1} & & & \\ & sym & & G_{LR}^{-1} & & \\ & & & & G_{LT}^{-1} & \\ & & & & & G_{RT}^{-1} \end{bmatrix} \qquad (2)$$

Since only E_L was provided by the designer, the others were approximated according to the wood handbook (Forest Products Laboratory 1999) Part of these elastic constants are given in Table 1.

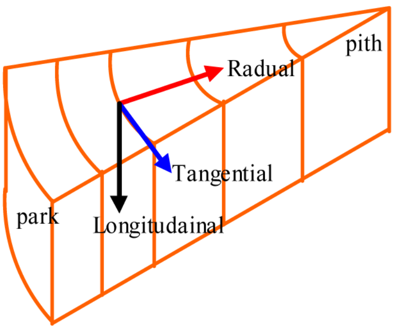


Fig.4. Difinition of Material Axis

Table 1. Elastic Constants used in FEM Simulation

ρ Kg/m^3	E_L Mpa	E_R Mpa	E_T Mpa	G_{LR} Mpa	G_{LT} Mpa	G_{RT} Mpa	ν_{RT}	ν_{LT}	ν_{LR}
430	11767	900	500	760	700	40	0.43	0.46	0.37

Note: Shear moduli and the Poisson's ratios are obtained from the wood handbook (1999).

It is necessary to simulate the semi-rigidity of the mortise and tenon joints properly because they have significant influence on the behavior of the whole test structure. Based on the beam-column connection model presented by Bulleit *et al*. (1999), an enhanced model composed of six spring elements (three translation and three rotation) was used to simulate the semi-rigidity of beam-column connection. All the spring constants were calculated according to the dimensions of the test structure based on the method of Kiyono and Furukawa (2004).

The FE model of the test structure using ANSYS is shown in Fig.5. Three-dimensional (3D) beam elements with six degrees-of-freedom (DOF) per node are used to simulate beams and columns, while shell elements with four nodes and six DOF per node are adopted for floors. A beam element, with a height of 1 cm and an equivalent section, is used to simulate the seam at the HC stage. The equivalent section is specified in such a way that the elastic mechanical properties and dynamic performance of a single column with a cutting modeled by beam elements is the same as that modeled by 3D solid elements. Following the same steps for the test structure, a total of 45 cases were calculated. Natural frequencies along the longitudinal direction were selected from the results of modal analysis, as shown in Table 2.

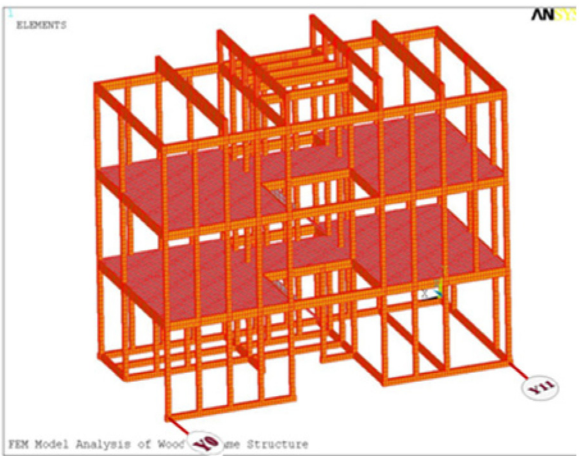


Fig.5. FE Model of the Testing Structure

4. Results Explanation and Analysis

For the purpose of further investigation, columns damaged during the test are classified into two groups based on their connection style with the beams. These are: (1) columns which were connected to beams with only tenons at both ends, referred to as 'posts'; and (2) the rest of the columns, which were connected to beams with mortise or with joints strengthened by steel fasteners, referred to as 'columns'. In this study, eleven groups of posts were first tested with 33 steps, as shown in Table 2. and Figs. 6 and 7.

The free vibration test along the longitudinal direction (shown in Fig.2.) of the test structure was repeated 5 times at each step. By using the Peak Peaking Method, natural frequency of each step was obtained from the Fourier amplitude spectrum of the low-pass filtered time series. All the natural frequencies from the tests, along with ANSYS simulations are tabulated in Table 2. On the whole, the simulations over-predict the natural frequencies by about 20%. Potential sources for this difference are the simplification of the connections between the floor and the beams or joists. For example, although six spring elements were used to simulate the beam-column connections, it is hard to define the properties of these elements for those connections strengthened with bolts. In addition, connections between floor plates and beams were simply simulated by a combination of two nodes at the same location.

Fig.7. shows the normalized natural frequencies, for both the test structure and the ANSYS simulations, versus the damage stages. The lower part of Fig.7. shows the damage stages of the test structure for each step. Every rectangular bar in this plot represents a group of columns along the Y-axis at one story on the current test step, with different colors/textures denoting different damage stages. In order to be distinguished clearly between neighbor columns, those bars, which represent undamaged columns, are filled with three kinds of wood textures. Take test step 11 as an example, which is marked with a pink box in Fig.7. In the same figure, the rectangles filled from yellow to red denote those columns along the axis of Y1 on the 2F (denoted as Y1@2F, as shown in Fig.2.b) which had been half cut. Furthermore, columns along the axes of Y1, Y3 and Y8 on the 1F (above the gradient filled rectangle, here the authors use blanks to denote those columns which were totally removed for simplicity) were removed while the rest of the columns (filled with wooden texture, below the gradient filled rectangle) were undamaged. The examination of these plots reveals that more and more columns are damaged as the test step number increases, which results in gradual, more severe damage to the whole structure.

Three curves are shown in the upper part of Fig.7. Normalizing the natural frequencies of the test and ANSYS simulation, in Table 2., to the value of the first step, respectively, generates the green and blue

Table 2. Summary of the Test Program and Damage States

Step No.	Test Stages				Experiment Date YYYY-MM-DD	Humidity (%)	Temperature (°C)	Natural Frequency (Hz)	
	Columns' Location	Sum	Type	Damage States				Test	ANSYS
1				Undamaged	2008-12-10	63.10	15.65	2.04696	2.4647
2	Along Axis Y1 at 1F	3	p	HC	2008-12-10	62.55	15.80	2.02738	2.4576
3	Along Axis Y1 at 1F	3	p	FC	2008-12-10	68.00	14.75	2.02309	2.4417
4	Along Axis Y1 at 1F	3	p	RM	2008-12-10	63.40	13.20	2.01671	2.4431
					2008-12-11	62.00	13.50	2.04467	
5	Along Axis Y3 at 1F	2	p	HC	2008-12-11	62.10	13.45	2.04418	2.4383
6	Along Axis Y3 at 1F	2	p	FC	2008-12-11	59.95	14.05	2.01977	2.4298
7	Along Axis Y3 at 1F	2	p	RM	2008-12-11	61.60	13.70	2.02916	2.4306
8	Along Axis Y8 at 1F	2	p	HC	2008-12-11	67.20	13.80	2.01595	2.4253
9	Along Axis Y8 at 1F	2	p	FC	2008-12-11	62.05	14.20	1.98642	2.4162
10	Along Axis Y8 at 1F	2	p	RM	2008-12-11	62.80	14.15	1.98948	2.4170
11	Along Axis Y1 at 2F	2	p	HC	2008-12-11	55.95	16.45	1.98286	2.4149
12	Along Axis Y1 at 2F	2	p	FC	2008-12-11	55.10	16.85	1.97143	2.4016
13	Along Axis Y1 at 2F	2	p	RM	2008-12-11	51.15	18.15	1.96533	2.4065
14	Along Axis Y3 at 2F	2	p	HC	2008-12-11	55.65	17.20	1.97065	2.4042
15	Along Axis Y3 at 2F	2	p	FC	2008-12-11	61.90	16.40	1.95795	2.3815
16	Along Axis Y3 at 2F	2	p	RM	2008-12-11	64.80	16.00	1.97320	2.3873
17	Along Axis Y8 at 2F	2	p	HC	2008-12-11	68.80	16.10	1.95211	2.3852
18	Along Axis Y8 at 2F	2	p	FC	2008-12-11	66.80	16.35	1.95212	2.3698
19	Along Axis Y8 at 2F	2	p	RM	2008-12-11	69.55	15.45	1.95769	2.3748
					2008-12-12	51.00	14.90	1.97265	
20	Along Axis Y10 at 2F	2	p	HC	2008-12-12	51.00	14.90	1.96558	2.3726
21	Along Axis Y10 at 2F	2	p	FC	2008-12-12	44.90	15.00	1.94448	2.3583
22	Along Axis Y10 at 2F	2	p	RM	2008-12-12	43.00	15.60	1.94450	2.3633
23	Along Axis Y1 at 3F	2	p	HC	2008-12-12	42.00	15.40	1.95058	2.3621
24	Along Axis Y1 at 3F	2	p	FC	2008-12-12	42.50	15.90	1.93634	2.3512
25	Along Axis Y1 at 3F	2	p	RM	2008-12-12	42.40	15.30	1.94703	2.3601
26	Along Axis Y3 at 3F	2	p	HC	2008-12-12	38.20	16.80	1.94041	2.3571
27	Along Axis Y3 at 3F	2	p	FC	2008-12-12	39.30	16.30	1.92720	2.3301
28	Along Axis Y3 at 3F	2	p	RM	2008-12-12	42.00	16.10	1.93561	2.3420
29	Along Axis Y8 at 3F	2	p	HC	2008-12-12	43.50	15.90	1.93153	2.3402
30	Along Axis Y8 at 3F	2	p	FC	2008-12-12	43.80	15.80	1.92337	2.3212
31	Along Axis Y8 at 3F	2	p	RM	2008-12-12	43.20	15.90	1.94804	2.3330
32	Along Axis Y10 at 3F	2	p	HC	2008-12-12	44.30	15.60	1.95161	2.3313
33	Along Axis Y10 at 3F	2	p	FC	2008-12-12	46.20	15.50	1.93838	2.3059
34	Along Axis Y10 at 3F	2	p	RM	2008-12-12	47.70	15.40	1.95948	2.3256
					2008-12-13	30.55	18.30	1.96533	
35	Along Axis Y2 at 1F	2	c	HC	2008-12-13	30.55	18.30	1.97345	2.3192
36	Along Axis Y2 at 1F	2	c	FC	2008-12-13	30.60	20.05	1.95085	2.2981
37	Along Axis Y9 at 1F	2	c	HC	2008-12-13	36.85	16.30	1.94143	2.2936
38	Along Axis Y9 at 1F	2	c	FC	2008-12-13	40.70	16.40	1.89437	2.2856
39	Along Axis Y2 at 2F	2	c	HC	2008-12-13	39.55	17.15	1.89233	2.2803
40	Along Axis Y9 at 2F	2	c	HC	2008-12-13	42.10	15.40	1.88724	2.2746
41	Along Axis Y2 at 3F	2	c	HC	2008-12-13	41.20	16.00	1.88472	2.2707
42	Along Axis Y9 at 3F	2	c	HC	2008-12-13	39.90	15.75	1.87938	2.2673
43	Along Axis Y0 at 1F	3	c	HC	2008-12-13	39.10	16.60	1.87706	2.2623
44	Along Axis Y11 at 1F	4	c	HC	2008-12-13	39.00	16.15	1.86971	2.2552
45	Along Axis Y4 at 1F	5	c	HC	2008-12-13	36.43	17.50	1.85904	2.2438

Note: HC = Half-Cutting at Column-base; FC = Full-Cutting at Column-base RM = Columns Removed; p = post; c = column
The number of 'sum' means the amount of columns damaged during the current step.

lines. Because two values of the same step such as step 4 were obtained in different conditions, the latter is adjusted to be equal to the former and the same adjustment was continued until the last test step. The adjusted values were also normalized to the first ones, and are depicted by a red line in Fig.7. considering that environmental factors such as temperature and relative humidity will influence the natural frequency of the timber structure (Xue, 2008). From a comparison of these curves, the following can be concluded,

a) Natural frequencies in both experimental tests and numerical simulations change when damage occurs, and they decrease as the damage accumulates in the whole structure.

b) When the same damage was applied to different columns, changes of the natural frequencies varied from each other.

c) The experimental results, especially from the 31st to 35th step, showed irregular changes while the numerical results showed a relatively steady decrease. At some steps, such as the 14th and 35th, the natural frequencies from the tests increase regardless of damage.

d) Environmental factors, such as temperature and relative humidity, have a noticeable influence on the natural frequencies of the test structure.

Theoretically, when a post has been removed, the natural frequency of the test structure would decrease due to reduction in stiffness. In order to provide additional insight into the influence of damage created by removal of structural members on natural frequencies, eleven test steps designated by RM in Table 2. were selected. It is logical to assume that natural frequencies obtained by this means can be approximated to those values obtained by direct removal of the columns. Fig.6. shows the plot of the normalized selected data along with the damaged states. From the test results, a sharp decrease can be observed when the columns at the 1F were removed, and the reduction of natural frequency becomes relatively low for columns on the 2F. However, when the posts at the 3F were removed step by step (from the 25th to 34th step), the natural frequencies increased in general. This tendency causes a majority of the fluctuation in Fig.7. It is encouraging to see from Fig.6. that for most of the test steps, the natural frequencies obtained from the test results were very close to those of the simulation, even though the FE simulation failed to predict the tendency of a few steps.

The comparison of natural frequency changes, induced by successive half-cutting of the column-bases, could be observed from the last 8 test steps, as shown in Fig.7. Good agreement between the numerical and experimental results can be observed.

5. Conclusions

A series of successive damage tests have been performed on a conventional beam-column timber structure in order to estimate the influence and sensitivity of damage on its global dynamic characteristics. In order to simulate different phases of damage, columns were cut by saw or totally removed. A total of 45 test steps were adopted and free vibration tests were also conducted at each test step in order to obtain the current natural frequencies. Numerical simulation of the test structure with ANSYS was used for comparison. Comparison between experimental and numerical results generally reveals that, first, both of them show a similar decreasing tendency when damage accumulates (despite the fact that the numerical simulation overestimates the natural frequencies), and second, the degree of sensitivity varies when different members are under the same damage. However, the natural frequencies of the tests obviously deviate from those of the numerical results in some steps, which validate the conclusion that it is difficult to simulate complex structures at present. Finally, the temperature and relative humidity have a noteworthy influence on the natural frequency.

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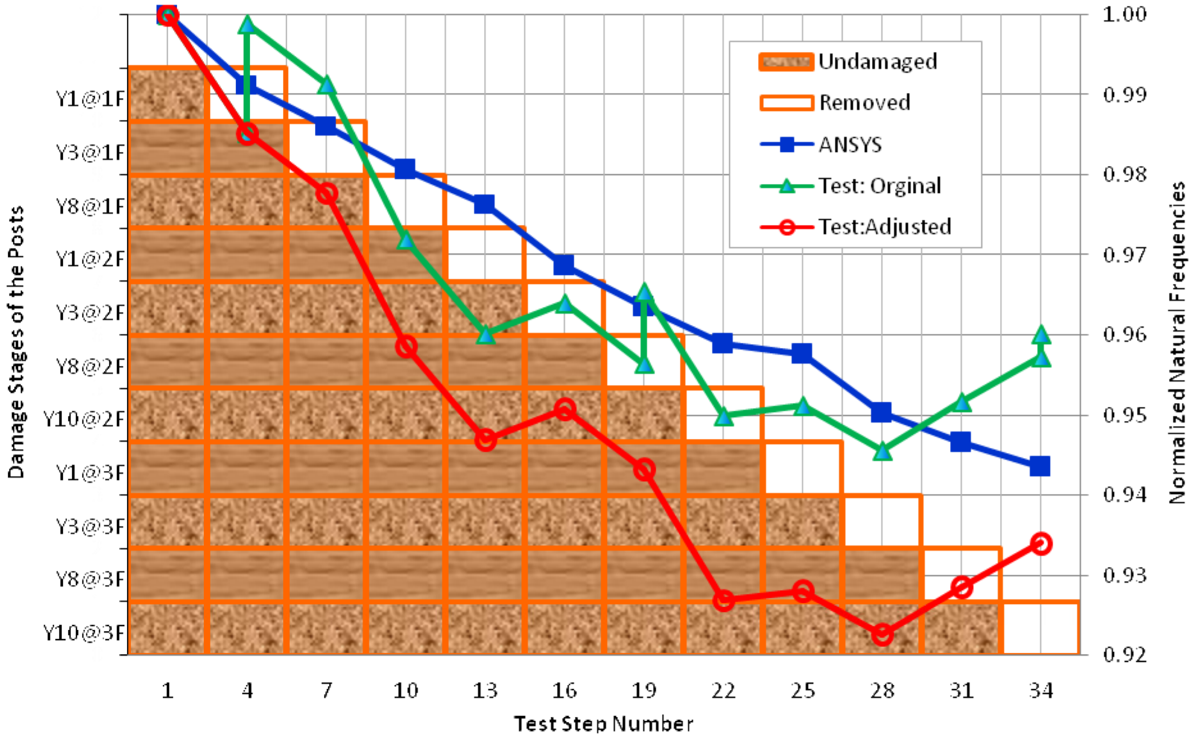

Fig.6. Natural Frequencies of Selected Steps

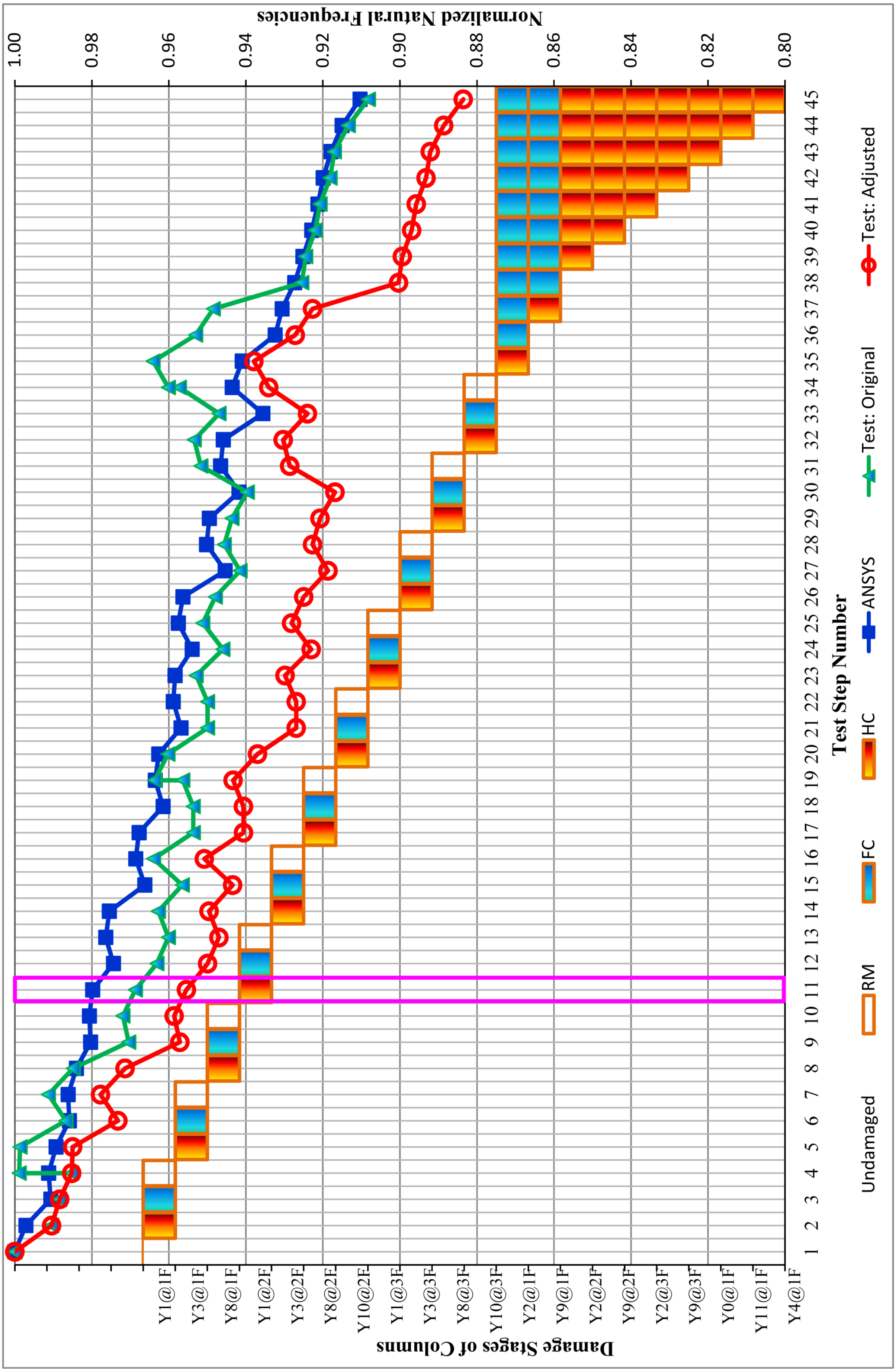

Fig.7. Damage Stages Versus Natural Frequences