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A STUDY ON THE EFFECT OF NON-STRUCTURAL MEMBERS ON THE EIGENPROPERTY OF 3 STORY PREFABRICATED STEEL BUILDING BASED ON FULL-SCALE VIBRATION TEST

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ABSTRACT

In order to understand the dynamic characteristics of a prefabricated steel building, several vibration tests with a wide range of amplitudes were carried out. Under excitation with relatively small amplitude levels, four different construction stages are prepared. The dynamic properties such as natural frequencies and damping ratios are evaluated based on observation records obtained from free vibration tests using an electromagnetic exciter. By comparing the results at different construction stages, the effect of non-structural members on the structural stiffness and damping ratio is studied. Using a mechanical exciter, forced vibration tests were carried out for several high excitation levels (100-3,000 kgf). Free vibration tests using a wire cutting method were also carried out for several initial displacement levels (5-25 tonf, as initial tensile force levels). Based on the results of these vibration tests with various amplitude levels, the effect of non-structural members on dynamic characteristics is studied from the view point of amplitude dependency.

KEYWORDS

Full-scale vibration test; 3 story prefabricated steel building; non-structural members; natural frequency; damping ratio; amplitude dependency; wire cutting method; forced vibration test; free vibration test.

INTRODUCTION

In Japan, large earthquakes occurred frequently during 1993-1995, and a lot of buildings were severely damaged, especially by the recent Hyogo-Ken-Nanbu Earthquake. However, the prefabricated steel buildings were only slightly damaged in spite of the large seismic ground motions. According to the latest survey in some area of Ashiya and Nishinomiya cities, 90 percent of conventional wooden houses were damaged and 30 percent of them collapsed. In contrast, only 30 percent of prefabricated houses were slightly damaged. It is well-known that prefabricated steel buildings have a lot of non-structural members, and it is considered that the effect of such non-structural members against the seismic forces is remarkable. Since prefabricated buildings are one of the most popular housing in Japan, it is of urgent necessity to clarify the dynamic properties of them under excitation with large amplitude levels.

Recently, many slender buildings have been built in Japan on the soft soil and small spaces, because of the lack of land and because of the subdivision of site due to the sharp rise of land price. In many cases, these buildings are built in an urban area, along a main street or a railroad, and a lot of problems caused by traffic or other environmental vibrations are reported. Therefore, it is also very important to study the dynamic properties of prefabricated buildings under excitation with small amplitude levels.

In spite of the urgent necessity and the importance, there are few reports of studies on the dynamic properties of prefabricated buildings. Because of the complexity of the plan of structures and because of the great contribution of non-structural members to the structural stiffness, it is difficult to analytically understand their properties.

In this paper, it is clarified that the stiffness of non-structural members plays an important role for the dynamic properties of the structure, and that the amplitude dependency of the non-structural members on the dynamic properties is remarkable, based on the vibration tests of full-scale three story steel prefabricated buildings in wide range of amplitude.

SUMMARY OF VIBRATION TESTS, BUILDINGS AND SOIL CONDITION

The Fourier amplitude spectrum of microtremor record observed on this ground (vertical direction) is shown in Fig.1. The predominant frequency of the ground is about 3.2 Hz. According to the result of standard penetration test conducted at the construction site, the surface soil is fill-up bank with thickness of about 1.5 m. Below this layer, there is a sand stratum with N-value of about 38. It is recognized that the soil condition of this site is relatively stiff.

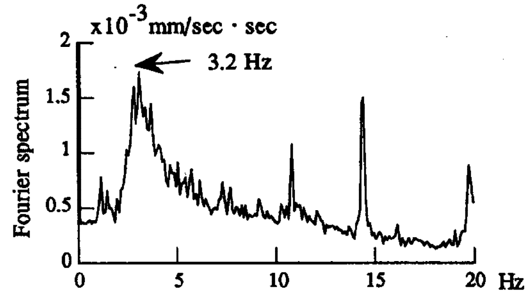


Fig.1 Fourier spectrum of microtremor record (UD direction)

Three types (A, B, C) of full-scale three story prefabricated steel buildings are constructed for the series of vibration tests. The external view of the building is shown in Fig.2, and its plans and elevations are shown in Fig.3. In NS direction, there are plenty of openings and the length is short. On the other hand, in EW direction, there are no openings and the length is long. The external walls consist of ALC (autoclaved lightweight concrete) panels with thickness of 100 mm which do not bear the shear stiffness of the structure under strong ground motion. Building of type A is tested at four different construction stages as shown in Tab.1. Buildings of type B and C do not have stairs or cantilevers. The weight of each floor for the all types of buildings is also shown in Tab.1. Tab.1 shows that the weight of ALC external

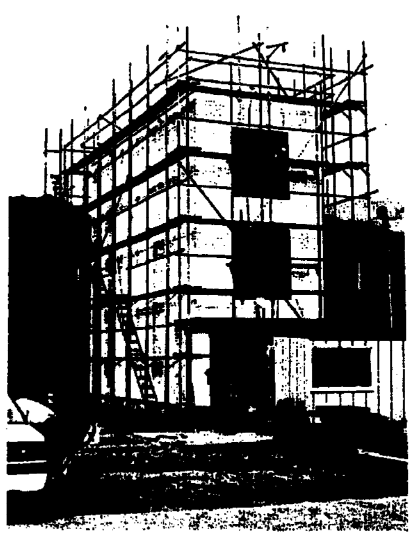


Fig.2 Photo of building

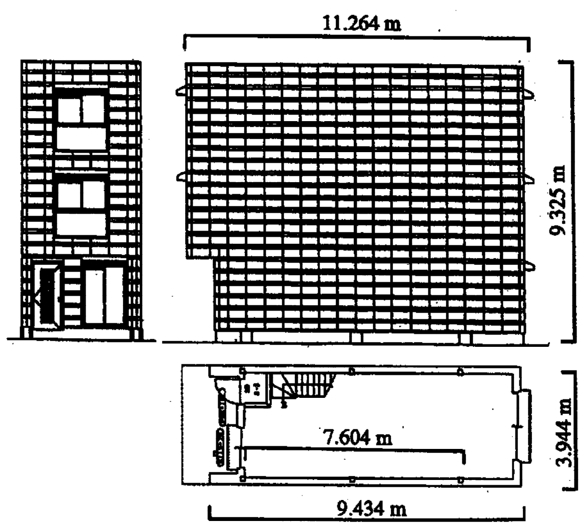
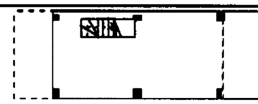
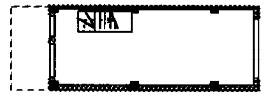
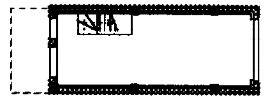
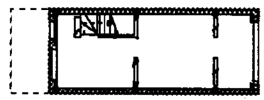


Fig.3 Plans and elevations

Tab.1 Construction stage and weight of each floor

Type	stage	structure	weight (ton) 1F	2F	3F	RF	total	plan of first story
A	1	steel frame + ALC floor slab + stair	33.1	4.9	4.8	4.0	46.7	
	2	+ ALC wall panel	35.1	10.6	10.7	7.3	63.7	
	3	+ inner plaster board + ceiling	35.2	12.2	12.4	8.9	68.8	
	4	+ partition wall	35.5	13.0	13.9	9.3	71.7	
B	3	steel frame + ALC floor slab + ALC wall panel + inner plaster board + ceiling	35.2	9.1	12.2	7.0	63.5	
C	3		35.2	9.1	9.1	7.0	60.4	

walls accounts for about 68 percent of the weight increase from the bare steel frame. An electromagnetic exciter or a mechanical exciter (2 tonf) is installed on the third floor slab. In Fig.4, the arrangement of the wire cutting test for the building of type C is illustrated.

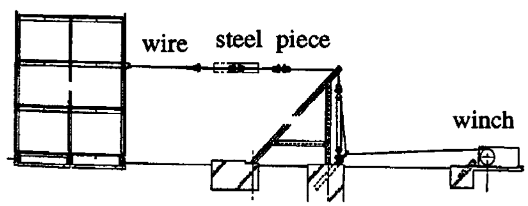


Fig.4 Free vibration test using wire cutting method

EFFECTS OF NON-STRUCTURAL MEMBERS ON EIGENPROPERTIES (TYPE A)

The effects of non-structural members on dynamic properties of the building in relatively small response amplitude levels (0.1 μm-0.6 mm) are examined based on free vibration tests using an electromagnetic exciter. Four kinds of construction stages are examined for the building of Type A as shown in Tab.1. Estimated natural frequency and damping ratio at each construction stage are shown in Fig.5. In Fig.6, the ratios of natural frequency, weight and stiffness of the building at each construction stage to those of bare steel frames are shown.

At the first construction stage, the building consists of pure steel frames and ALC floor slabs. There are no non-structural members except for steel stairs. At this stage, the natural frequencies are nearly identical in the NS and EW directions, and damping ratio is very small.

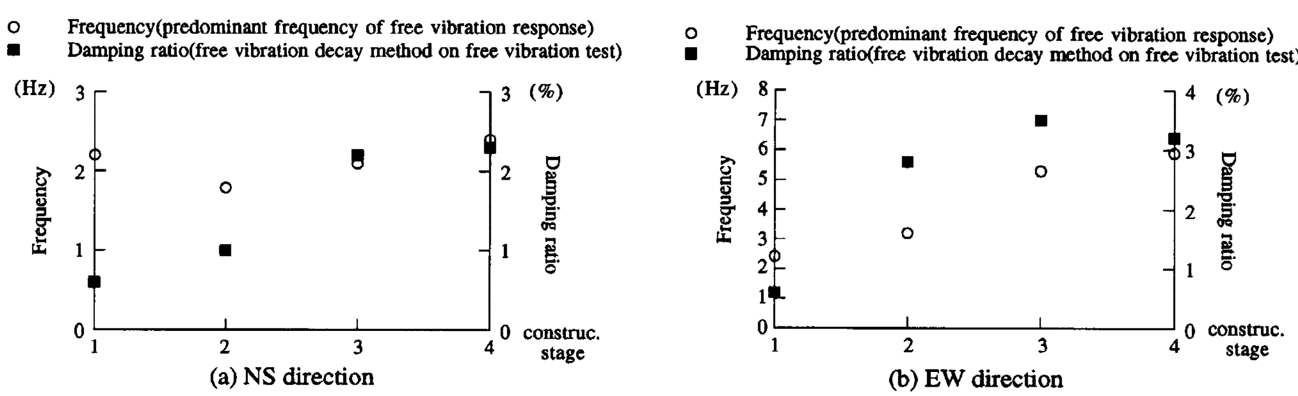


Fig.5 Natural frequencies and damping ratios for different construction stages

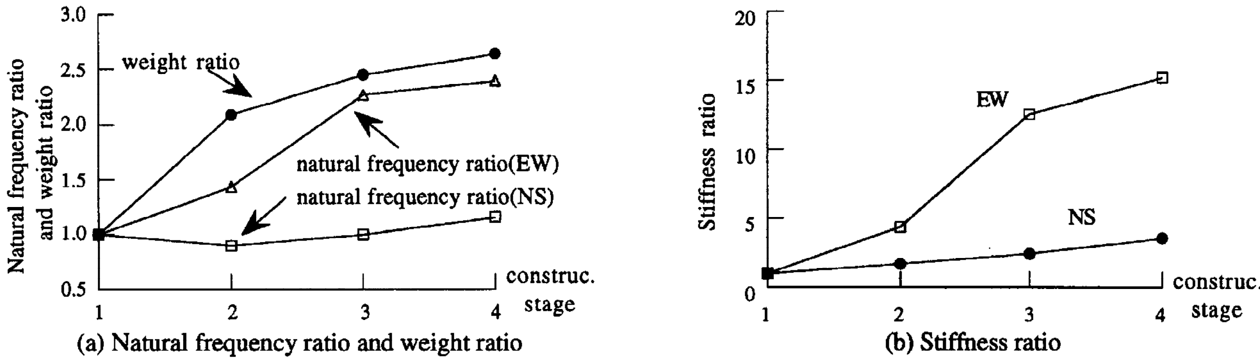


Fig.6 Ratios of natural frequency, weight and stiffness at each construction stage to those of first construction stage

At the second construction stage, ALC external walls are added. The difference in dynamic properties between NS and EW directions is remarkable, because of the difference of the quantity of effective external walls. Fig.6 shows that in NS direction, the effect of the weight increase is more dominant than the effect of the stiffness increase, accordingly, the natural frequency decreases by less than 10 percent. On the other hand, in EW direction, the natural frequency increases by 50 percent. The weight of the structure except for the foundation increases by 200 percent because of additional external walls, and the stiffness of external walls corresponds to 60 percent of that of the bare steel frames in the NS direction and 350 percent in the EW direction. The increase of the damping effect partially caused by the friction of ALC panels is remarkable. The degree of the increase of damping ratio corresponds to the amount of external walls.

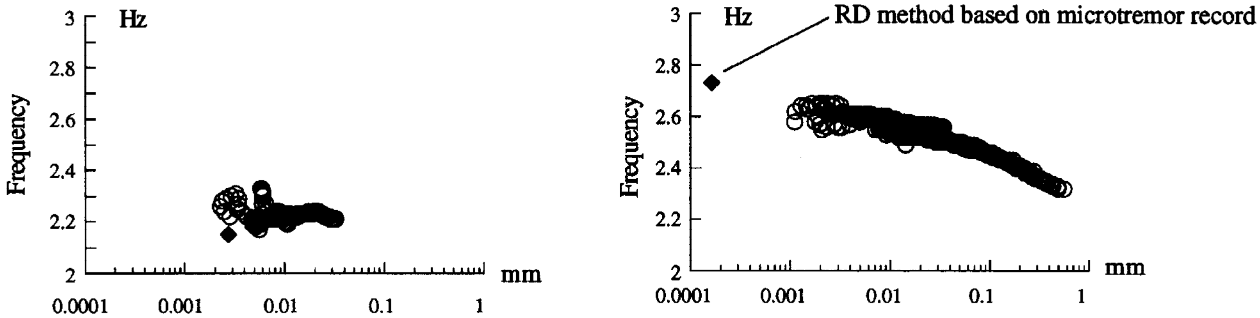
At the third construction stage, inner plaster boards and ceilings are installed, leading to the increase of both natural frequency and damping ratio. The weight does not increase very much from the second stage. The stiffness of the building with non-structural members is about 1.8 times larger than that of bare steel frames in NS direction and about 12.3 times in EW direction.

At the fourth construction stage, partition walls are installed in NS direction. The increase of natural frequency is large in NS direction; however, the damping ratio does not vary much. At this stage, the stiffness of this building is about 4 times that of the bare steel frames in the NS direction and about 15 times in the EW direction.

These results show that the stiffness of non-structural members plays an important role under excitation with small amplitude levels such as traffic vibration problems. The difference of dynamic properties between NS and EW directions is caused by the difference in the arrangement of the non-structural members. The natural frequency of a building can be adjusted relatively easily, and accordingly, the vibration of the building can be controlled by arranging non-structural members appropriately.

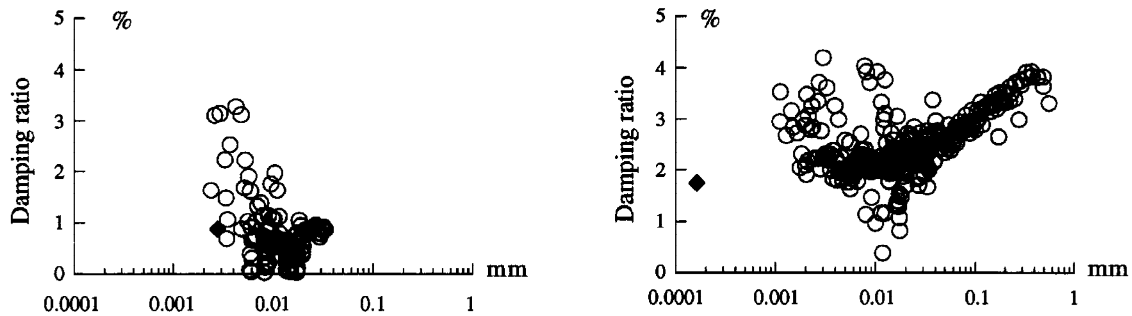
EFFECTS OF NON-STRUCTURAL MEMBERS ON AMPLITUDE DEPENDENCY (TYPE A)

Amplitude dependencies of natural frequencies and damping ratios on the non-structural members are examined under excitation with relatively small amplitude levels. Generally, it has been pointed out that amplitude dependency of damping ratio is observed in structures with many non-structural members (Tamura *et al.*, 1993). The natural frequencies and damping ratios of the building estimated from the free vibration response in NS direction by taking the moving averages of three adjoining peeks (Okada *et al.*, 1993) are shown in Figs.7 and 8, respectively. The dynamic properties estimated from microtremor records by random decrement (RD) method (Jeary, 1986) are also plotted in these figures. The natural frequency does not depend on the amplitude at the first stage; while it does at the fourth stage. As the amplitude level increases, the natural frequency decreases remarkably. Although at the first stage, the estimated damping ratios are scattered, little dependency of the damping ratio on amplitude levels is observed. At the fourth stage, as the response amplitude level increases, the damping ratio increases. These results are similar to that obtained from the tests of a high-rise building (Okada *et al.*, 1993). These results show that the non-structural members contribute not only to the increase of stiffness and damping ratio but also to the amplitude dependencies on dynamic properties, when the excitation level is relatively small.



(a) Construction stage 1 (b) Construction stage 4

Fig.7 Amplitude dependency of natural frequencies (NS direction)



(a) Construction stage 1 (b) Construction stage 4

Fig.8 Amplitude dependency of damping ratios (NS direction)

EIGENPROPERTIES IN THE RANGE OF LARGE AMPLITUDE LEVELS (TYPE B AND C)

Two kinds of vibration tests (the forced vibration test using a mechanical exciter and the free vibration test using the wire cutting method) were carried out in order to identify the dynamic properties of the building under excitation with large amplitude levels such as large earthquakes.

Forced Steady State Excitation Tests Using Mechanical Exciter (Type B)

Building of type B is excited with three levels in both directions, and the responses of the building to the steady state excitation are observed. Building of type B corresponds to the third construction stage of Type A, except for the steel stairs and cantilevers.

The relation between response amplitude and resonance frequency and the relation between response amplitude and damping ratio, which are estimated from the response curves obtained from the forced vibration tests under different excitation levels, are shown in Figs.9 and 10, respectively. The predominant frequency decreases as the response amplitude of the building increases. It is expected that under excitation with larger amplitude level, the contribution of non-structural members to the stiffness is smaller than that with small amplitude level.

After the forced vibration tests, damage to the inner walls was observed. To clarify the effect of such damage to the non-structural members, the dynamic properties of the building before the forced vibration tests are compared with those after the tests. The Fourier spectra of free vibration responses obtained before and after the forced vibration tests are shown in Fig.11. Both responses are caused by almost the same small excitation force levels. The predominant frequencies in both directions decrease, and it is expected that the contribution of non-structural members to the stiffness declines because of the damage to them. This phenomenon is remarkable especially in EW direction in which there are a large quantity of non-structural members, and the increase of damping ratio is also observed in this direction.

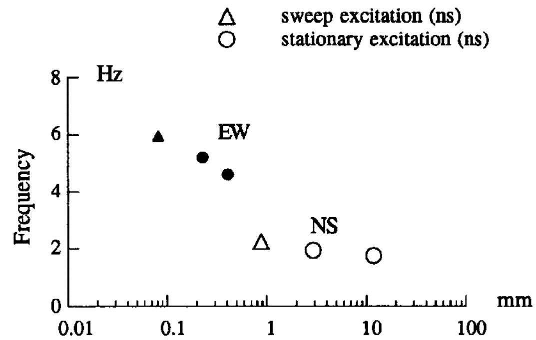


Fig.9 Response amplitude-natural frequency relation based on forced excitation test

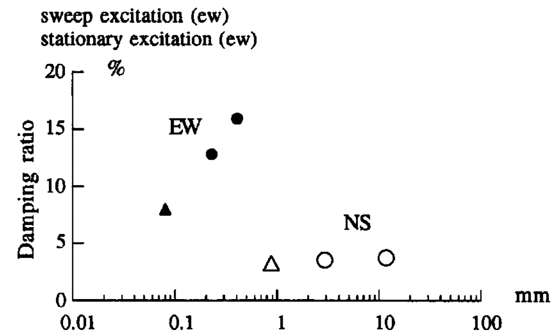


Fig.10 Response amplitude-damping ratio relation based on forced excitation test

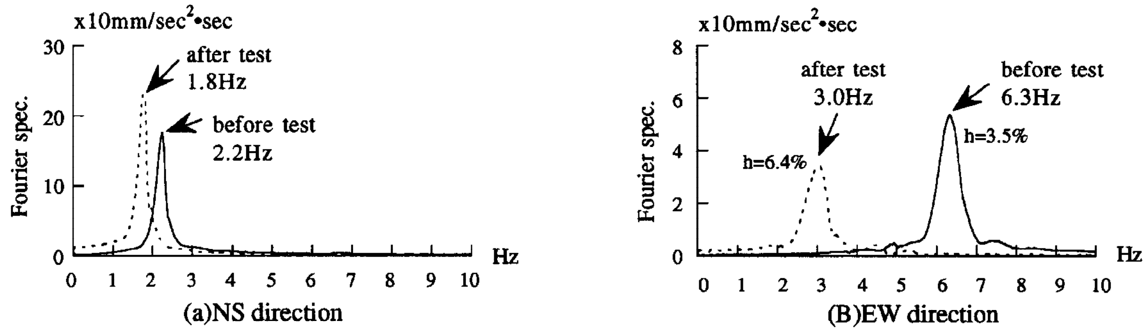


Fig.11 Difference of Fourier spectra of free vibration responses between before and after tests

<u>Free Vibration Tests Using Wire Cutting Method (Type C)</u>

The free vibration tests in EW direction using the wire cutting method are carried out for the building of type C. Four initial tensile load levels (5 tonf, 10 tonf, 20 tonf, 25 tonf) are prepared, and after the steel piece is broken (see Fig.4), the free vibration responses of the building are observed.

The relation between initial displacement and natural frequency and the relation between initial displacement and damping ratio, which are estimated from the free vibration responses on the roof obtained from the tests for each tensile load level, are shown in Figs.12 and 13, respectively. The decrease of natural frequency is observed as the initial displacement increases. Unlike the previous results under excitation with small amplitude, the damping ratio decreases as the response increases above 10-20 mm, although it increases at first. In order to examine the amplitude dependency in detail, the natural frequencies and the damping ratios estimated from the free vibration responses by the moving average method are shown in Figs.14 and 15. These figures show similar amplitude dependency of dynamic properties to that observed in Figs.12 and 13. It should be noted that the natural frequency decreases, as the tests with large load which would cause damage to the non-structural members are repeated.

The static loading test from 0 to 50 tonf is also carried out. After all the tests finished, the microtremor response on the third floor is observed to clarify the effect of the damage to the non-structural members.

The free vibration responses on the third floor generated by RD method before the series of tests are compared with those after the tests in Fig.16. In Fig.16, the estimated natural frequencies and damping ratios are also shown. In the EW direction in which all the tests are carried out, the decrease of natural frequency is large; on the other hand, it is small in NS direction. Based on the results of the static loading test, the load-displacement relation and the load-tangent modulus relation are compared to those calculated using the bare steel frames in Figs.17 and 18, respectively. It is shown in Fig.17 that the steel frames of this building are in elastic region at the load of 25 tonf, though the ultimate strength of the building assumed in the design is 25 tonf. Fig.18 shows that after the static loading test, the non-structural members are severely damaged; however, the stiffness of this building remains to be about 2 times larger than that of the bare steel frames.

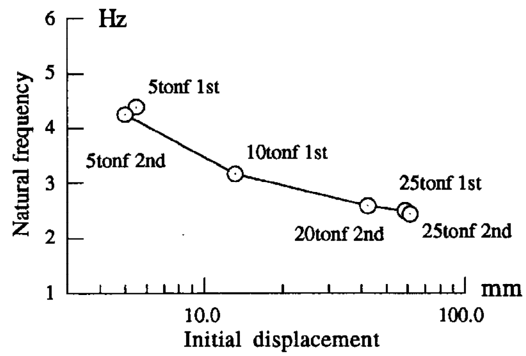


Fig.12 Initial displacement-natural frequency relation based on wire cutting method

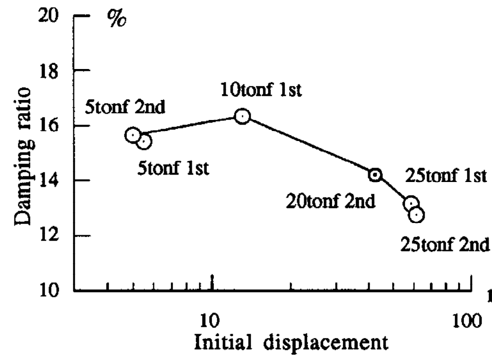


Fig.13 Initial displacement-damping ratio relation based on wire cutting method

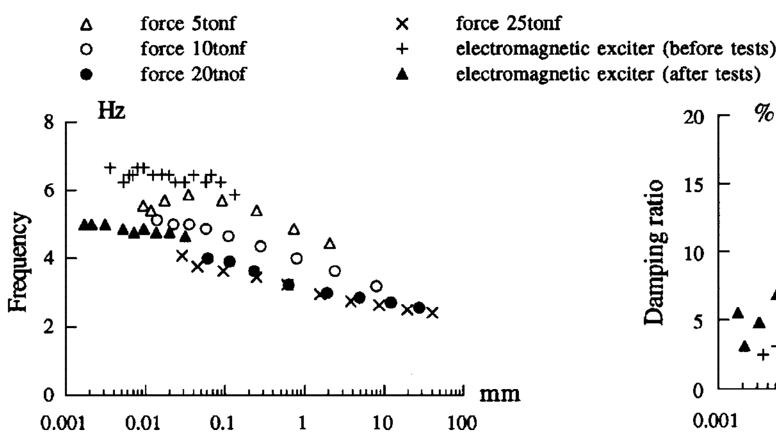


Fig.14 Amplitude dependency of natural frequencies based on free vibration tests

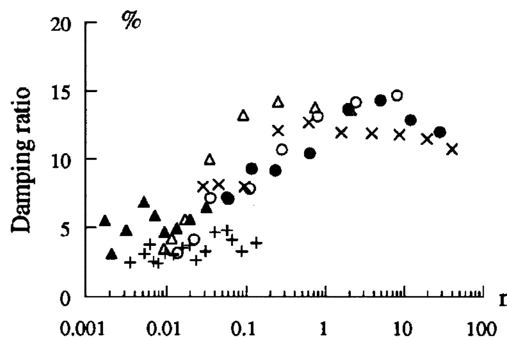
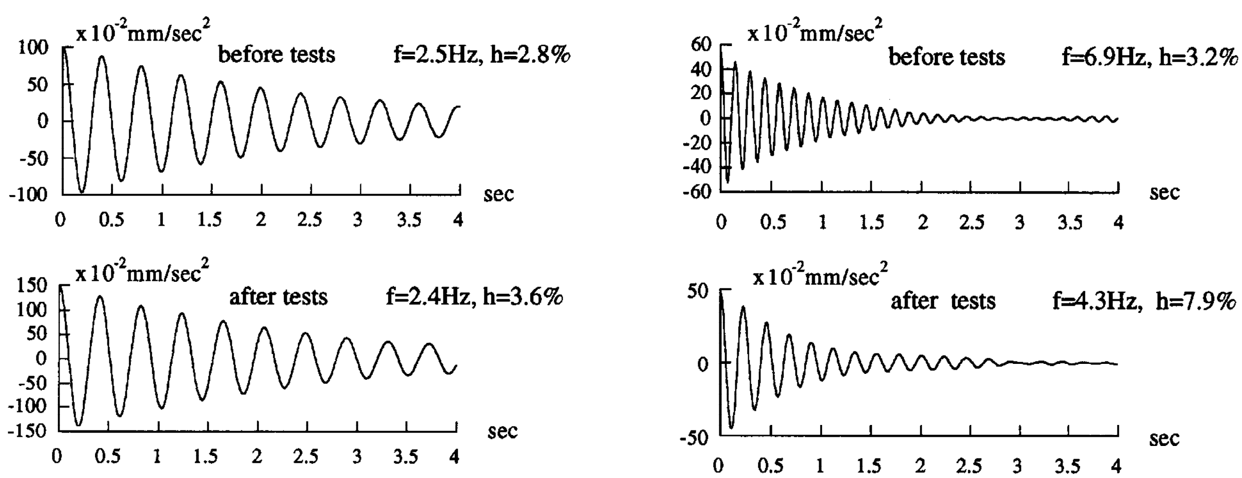


Fig.15 Amplitude dependency of damping ratios based on free vibration tests



(a)NS direction (b)EW direction

Fig.16 Free vibration response generated by RD method

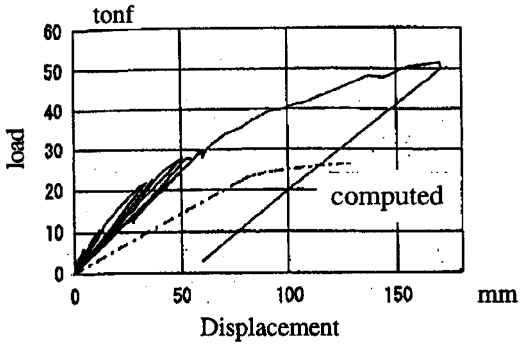


Fig.17 Displacement-load relation based on static loading tests

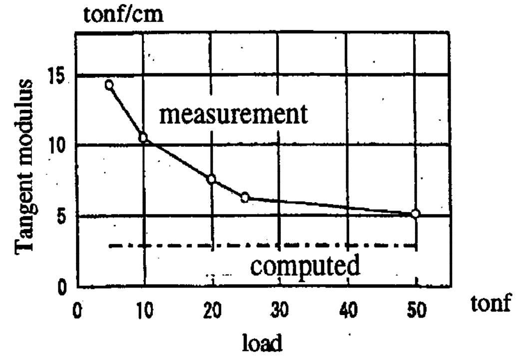


Fig.18 Load-tangent modulus relation based on static loading tests

CONCLUSIONS

The results of the series of vibration tests over a wide range of amplitudes using the full-scale buildings can be summarized as follows.

1. Putting the non-structural members such as ALC walls, inner plaster boards and partition walls on the bare steel frames, the natural frequency increases from 2.4 Hz to 6.1 Hz in EW direction in relatively small response levels. Taking the increase of the weight of building into account, the non-structural members provide 14 times larger stiffness than structural members. The damping ratio also increases with the non-structural members.
2. The eigenproperties strongly depend on the response amplitudes when the non-structural members exist.
3. By the experience of large response, the natural frequency of the building decreases from 6.9 Hz to 4.3 Hz in EW direction. This large decrease is due to the damage by large deformation to a lot of non-structural members arranged in EW direction.

When the response amplitude level is small, the non-structural members play an important role for the dynamic properties of a building. In the range of large amplitude level, the contribution of non-structural members to the stiffness decreases. However, the stiffness and the ultimate strength become almost twice as large as those of the bare steel frames and large damping can also be expected. It is necessary to evaluate properly the effects of non-structural members depending on amplitude levels, when the dynamic structural model of prefabricated building is established.

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