EFFECT OF NONSTRUCTURAL COMPONENTS ON AMPLITUDE-DEPENDENT DYNAMIC PARAMETERS. II: FREE VIBRATION TESTS

J. Ma(1), S. Nakata(2), A. Yoshida(3), Y. Tamura(4)

(1) *Researcher, China Construction Eighth Engineering Division Co., Ltd., mjbppc@163.com*
(2) *Researcher, Asahi Kasei Homes Corporation Co., Ltd., nakata.sb@om.asahi-kasei.co.jp*
(3) *Professor, Tokyo Polytechnic University, yoshida@arch.t-kougei.ac.jp*
(4) *Professor, Chongqing University, yukio@arch.t-kougei.ac.jp*

Abstract

A full-scale one-story one-bay steel frame with a precast cladding system was designed to investigate the effect of non-structural components on dynamic characteristics and dynamic behavior of steel frames. Various parts of the precast cladding system were attached to the frame, and ambient vibration, free vibration, and shaking table tests were conducted. This paper is an extension of a companion paper that describes outline of the experimental work and introduces ambient vibration test results. In this paper, the free vibration test results are reported, and the effect of precast cladding system on amplitude dependency and evaluation of dynamic characteristics are discussed. The precast cladding system is found to be the cause of amplitude dependency of dynamic parameters, and the stick-slip mechanism is adopted to explain the tendency of dynamic parameters. The contribution of precast cladding system on evaluation of dynamic parameters is discussed, that the effect of ALC cladding panels, plasterboard interior linings, and widow openings are discussed separately. ALC cladding panels provide a significant increase in both lateral stiffness and structural damping. The plasterboard and window openings have a slight effect in stiffening the structure, but have a negative effect on structural damping.

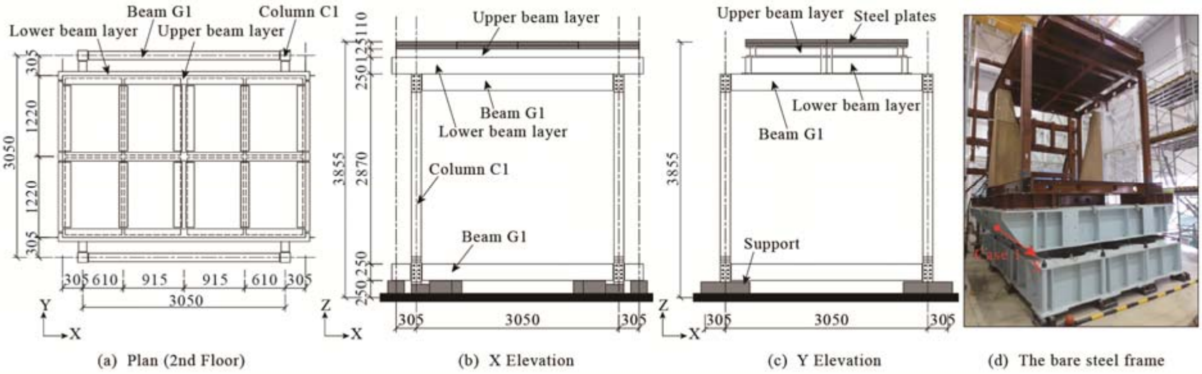
Keywords: Nonstructural component; Dynamic parameter; Amplitude dependence; Free vibration; steel frame

1. Introduction

Nonstructural components are often assumed to have negligible influence on the performance of building structure, and hence are usually ignored in structural design. However, a large number of researches have proved that nonstructural components have complicated interactions with the structure, the neglection or simplification of nonstructural components may result in an inaccurate analysis and lead to an unsafe design[1-4]. Steel frames with precast cladding systems are commonly used in many parts of the world, but the complex interactions between the steel frame and the precast cladding system are not yet understood. In an effort to better understand the complex interactions, a full-scale one-story steel frame with different parts of a precast cladding was tested under ambient vibration, free vibration, and shaking table tests. The amplitude dependency of dynamic characteristics, the effect of precast cladding system on evaluation of dynamic parameters, and the effect of precast cladding system on dynamic behavior of steel structures are examined. The experimental work and ambient vibration results have been reported in the previous part. In this paper, the free vibration test results are reported, the free vibration and ambient vibration test results are compared, and the effect of precast cladding system is discussed.

2. Brief description of the experimental work

The test steel frame was a full-scale one-story one-bay moment frame, as shown in Figure 1. It was 3050 × 3050mm in plan and 3120mm high. It consisted of four corner columns and steel beams set on the first and second floor. Sixteen steel plates were adopted to simulate real surface loads, and two beam layers were set on the second floor to support the steel plates. A precast cladding system composed of ALC external wall cladding panels, gypsum plasterboard interior linings, and window openings was attached to the steel frame, as shown in Figure 2. Each ALC external wall was composed of three vertically installed general ALC panels and two corner panels, and the gaps were infilled with silicone sealing compound. The ALC panels were installed using a “Rocking installation method”, so that the ALC panels can rotate slightly to follow deformation of the steel frame, and the earthquake input can be reduced. Plasterboard with a thickness of 12.5mm was used as the interior lining material, and three types of windows were adopted.



(a) Plan (2nd Floor) (b) X Elevation (c) Y Elevation (d) The bare steel frame

Fig. 1 – The test steel frame (unit: mm)

Fig. 2 – The precast cladding system

Table 1 – Summary of test cases

Test cases	Structural members	Nonstructural components			Direction
		ALC claddings	Plasterboard	Window openings	
1	Steel frame	--	--	--	X
2	Steel frame	ALC claddings	--	--	Y
3	Steel frame	ALC claddings	Plasterboard	--	Y
4	Steel frame	ALC claddings	--	Small window	X
5	Steel frame	ALC claddings	Plasterboard	Small window	X
6	Steel frame	ALC claddings	--	Middle window	Y
7	Steel frame	ALC claddings	Plasterboard	Middle window	Y
8	Steel frame	ALC claddings	--	Large window	X
9	Steel frame	ALC claddings	Plasterboard	Large window	X
10	Steel frame	ALC claddings of two layers	--	--	X

Ten test cases were designed, as listed in Table 1. Different parts of the precast cladding system were attached to the steel frame, and the effect of ALC panels, plasterboard interior linings, and window openings were examined independently. Two test cases were attached to the steel frame simultaneously in order to speed up the experimental process, one was set along the X direction and the other was along the Y direction, as shown in Figure 2.

3. Free vibration test results

Free vibration test was conducted following ambient vibration test for each case. An electromagnetic shaker was used to excite the structure, and its excitation orientation was kept along with the direction of each case. The shaker was used so that it excited each case at the fundamental resonance frequency and then stopped suddenly to allow the free vibration to occur. In order to obtain accurate results, the free vibration tests were repeated three times for each case.

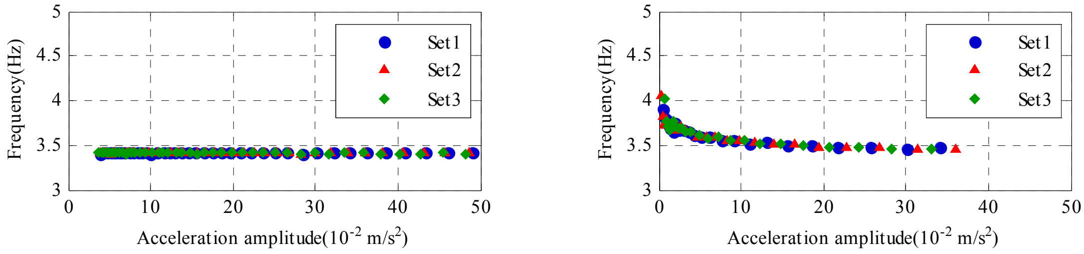
The amplitude-dependent dynamic parameters were estimated from free vibration test data in the following way. The information of the target mode was first extracted from the response acceleration data. The filtered free vibration signal was then decomposed into a series of subsignal, the subsignal was defined as the oscillation cycle between two successive positive peaks. The dynamic parameters were then estimated from the subsignals using curve fitting technique, and the starting positive peak of each subsignal was defined as the vibration amplitude, so that the amplitude-dependent dynamic parameters were estimated from free vibration data.

The amplitude-dependent natural frequencies estimated from free vibration data are illustrated in Figure 3. As shown in the figure, the response acceleration amplitude in free vibration test was significantly larger than that in ambient vibration test, thus significant amplitude dependency of natural frequencies can be observed. It is noticed that natural frequency is not affected by response amplitude in the bare steel frame case. However, it is observed that natural frequencies vary with amplitude in cases where nonstructural components are attached to the frame. The natural frequencies are generally observed to decrease with amplitude. The natural frequencies in the high amplitude range are appropriately 0.2~0.5Hz lower than the initial values. The amplitude-dependent damping ratios estimated from free vibration data are illustrated in Figure 4, and significant amplitude dependency of damping ratios can also be observed. It is also noticed that damping ratios are independent of vibration amplitude in the bare steel frame case, but the amplitude dependency of damping ratios appears obviously with the addition of nonstructural components. Damping ratios are generally observed to increase with amplitude in the low amplitude range and then decrease with amplitude in the high amplitude range.

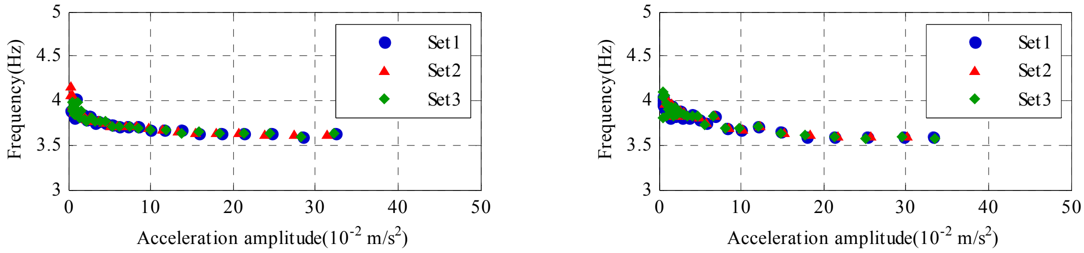
Table 2 – Dynamic parameters estimated from free vibration data

Test cases	**Peak acceleration ($\times10^{-2}$ m/s^2)**	**Natural frequency**			**Damping ratio ζ (%)**
		f (Hz)	**σ_f (Hz)**	**COV (%)**	
1	96.2	3.41	0.007	0.21	0.1~0.5
2	36.1	3.63	0.132	3.64	1.5~3.2
3	32.5	3.77	0.128	3.40	1.3~3.1
4	33.5	3.81	0.146	3.83	0.8~3.4
5	32.1	4.16	0.118	2.84	0.8~3.0
6	44.9	3.70	0.106	2.86	0.7~2.8
7	39.8	3.95	0.100	2.53	0.5~2.7
8	94.0	3.44	0.042	1.22	0.5~2.0
9	94.3	3.53	0.048	1.36	0.5~2.2
10	21.9	4.53	0.134	2.96	0.9~3.5

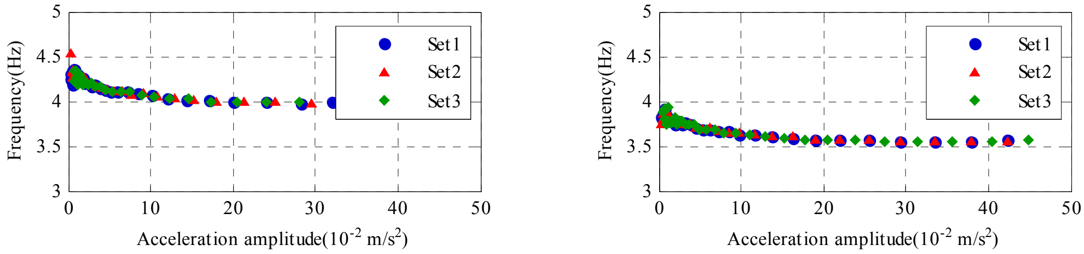
The values of natural frequencies and damping ratios are listed with peak accelerations in Table 2. It is noticed that the precast cladding system provides an apparent increase in lateral stiffness and structural damping. The natural frequency of the bare steel frame is 3.41Hz, but the natural frequencies range from 3.44Hz to 4.53Hz when the precast cladding system is attached to the steel frame. An increase of up to 33% in natural frequency is contributed by nonstructural components. A significant increase in damping ratio values due to nonstructural components is also observed. The damping ratio of the bare steel frame only varies from 0.1% to 0.5%, but the upper bound values of damping ratios are 4 to 8 times larger than that of the bare steel frame due to addition of the precast cladding system.



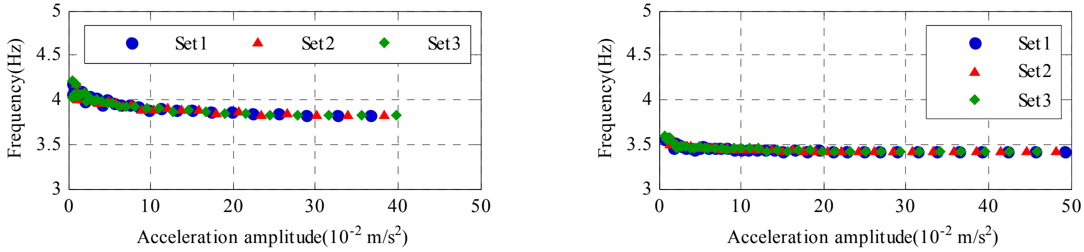
(a) Case1 (b) Case2



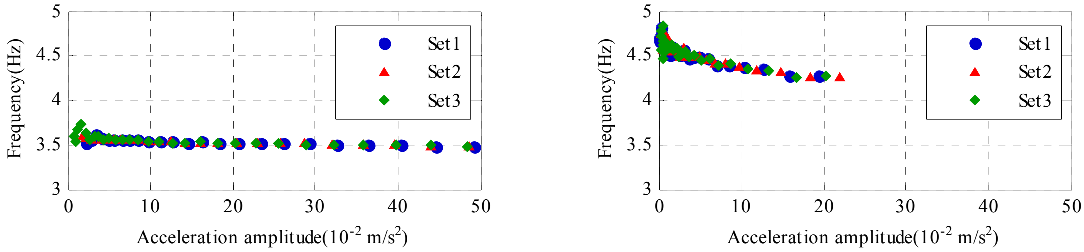
(c) Case3 (d) Case4



(e) Case5 (f) Case6

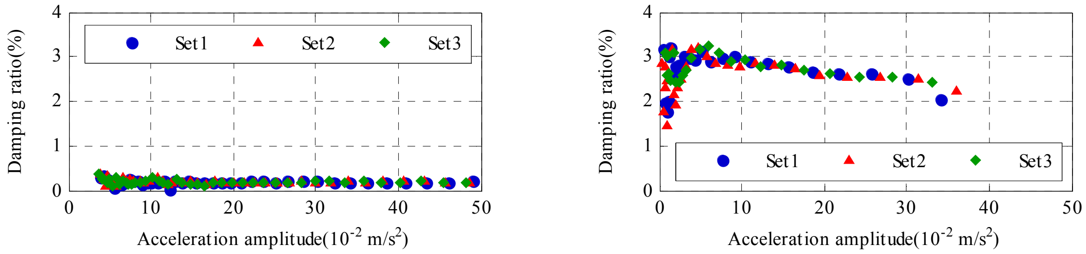


(g) Case7 (h) Case8

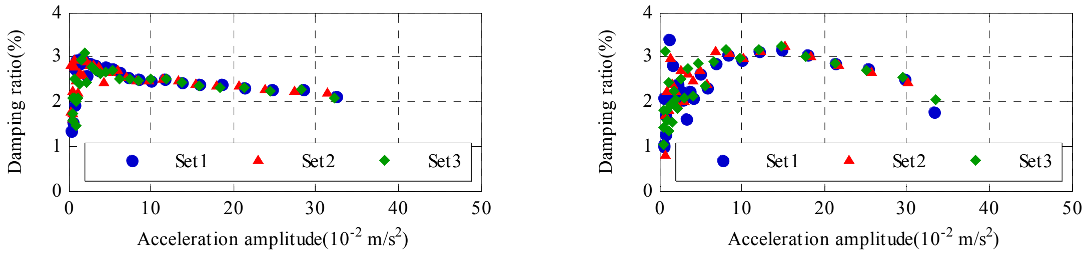


(i) Case9 (j) Case10

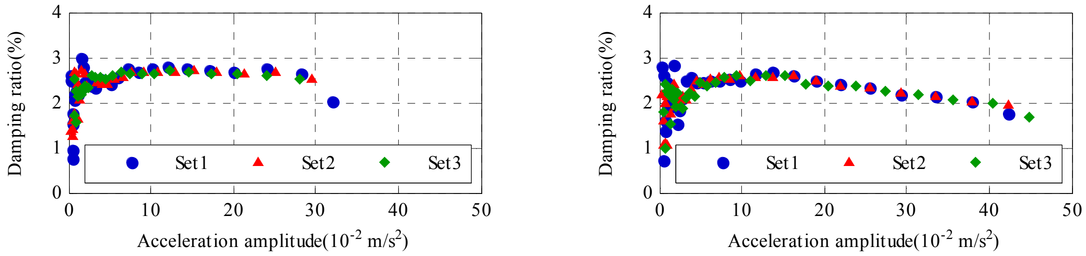
Fig. 3 – Amplitude-dependent natural frequencies estimated from free vibration data



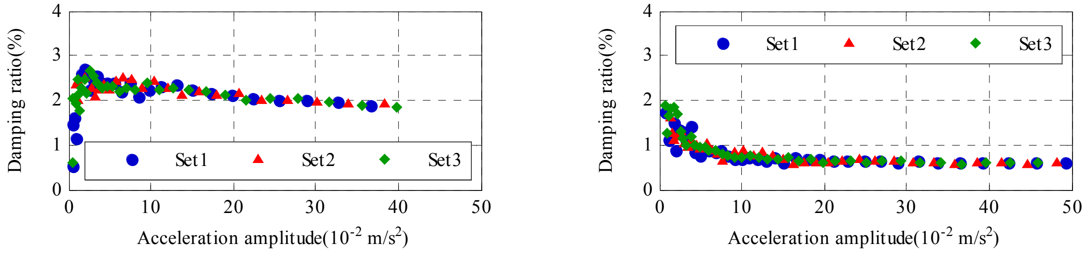
(a) Case1 (b) Case2



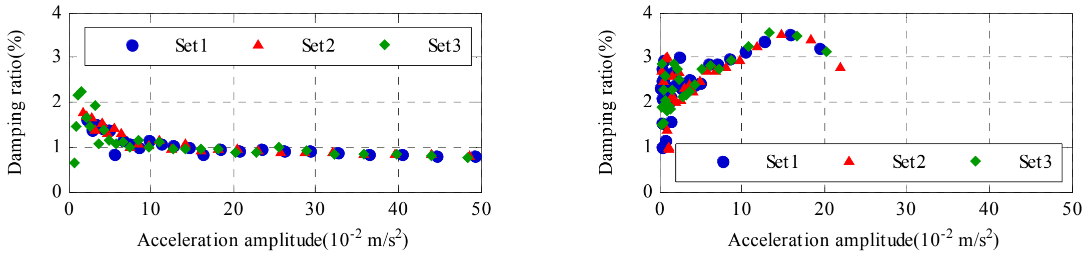
(c) Case3 (d) Case4



(e) Case5 (f) Case6



(g) Case7 (h) Case8



(i) Case9 (j) Case10

Fig. 4 – Amplitude-dependent damping ratios estimated from free vibration data

4. Discussion

4.1 Effect of nonstructural components on amplitude dependency of dynamic parameters

The amplitude dependency of dynamic parameters takes place when nonstructural components are attached to the steel frame. A typical tendency of amplitude-dependent natural frequency and damping ratio is illustrated in Figure 5. It can be noticed that natural frequency tends to decrease with amplitude, and damping ratio first increases and reaches its maximum at a critical tip drift ratio point in the low amplitude range, and then decreases with amplitude in the high amplitude range.

The amplitude dependency of dynamic parameters is quite different from the general constant assumption, and the tendency of dynamic parameters is explained by the stick-slip mechanism[5]. The stick-slip mechanism assumes that the contact surfaces between the primary structural members and secondary nonstructural components are in stuck or slip condition. As the vibration amplitude increases, the contact surfaces transit from stuck condition to slip condition. This transition leads to an increase in friction but a loss of stiffness, thus dynamic parameters are observed to be in relationship with the response amplitude. In the low amplitude range, almost all contact surfaces are in stuck condition and almost all secondary nonstructural components contribute to the lateral stiffness. As the vibration amplitude increases, the contact surfaces start to slip at their particular amplitudes, and the stiffness contribution from nonstructural components is reduced, thus natural frequency is observed to decrease with amplitude. On the other hand, all contact surfaces may have turned into slip conditions after the critical tip drift ratio point. The friction force causing structural damping at the contact surfaces does not increase any more, but the vibration amplitude is still increasing. It is known that the damping ratio is proportional to the friction force and is inversely proportional to the vibration amplitude, thus damping ratio is observed to decrease with amplitude after the critical tip drift ratio point.

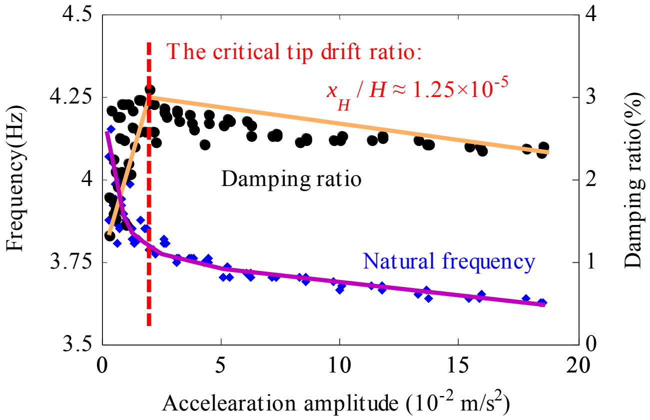
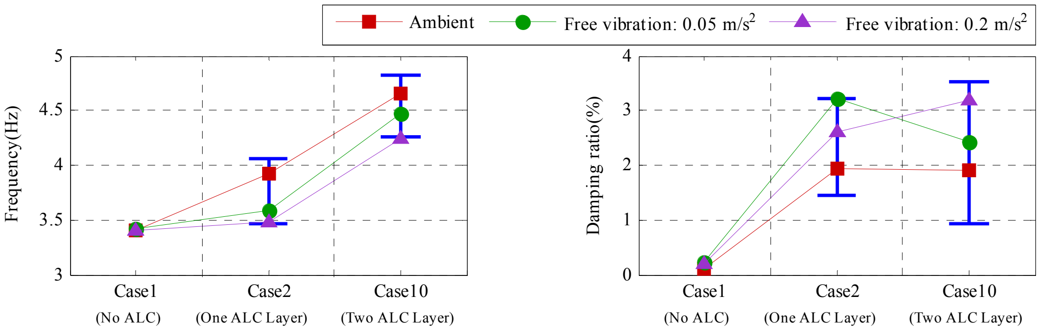


Fig. 5 – Amplitude dependency of dynamic parameters

4.2 Effect of nonstructural components on evaluation of dynamic parameters

The effect of precast cladding system on evaluation of dynamic parameters is discussed using the free vibration and ambient vibration test results. The mean values of ambient vibration test results are adopted, and the ranges of free vibration test results are used. In addition, the free vibration test results corresponding to the amplitude of 5×10^{-2} m/s^2 and 20×10^{-2} m/s^2 are used, representing dynamic parameters in the low- and high amplitude range separately.

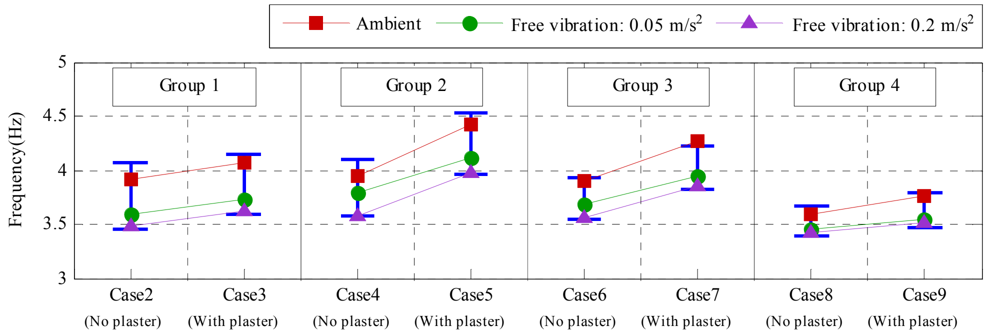
The effect of ALC cladding panels on evaluation of natural frequency and damping ratio is illustrated in Figure 6. The results of bare steel frame, the steel frame with ALC claddings, and the steel frame with ALC claddings of two layers are compared. An increase in both natural frequency and damping ratio due to ALC claddings is noticed. The free vibration maximum natural frequency increases by 20% and 40% respectively due to the addition of ALC claddings and ALC claddings of two layers, and the upper bound values of damping ratios estimated from free vibration data of Case 2 and Case 10 are 7 and 8 times larger than that of the bare frame respectively.



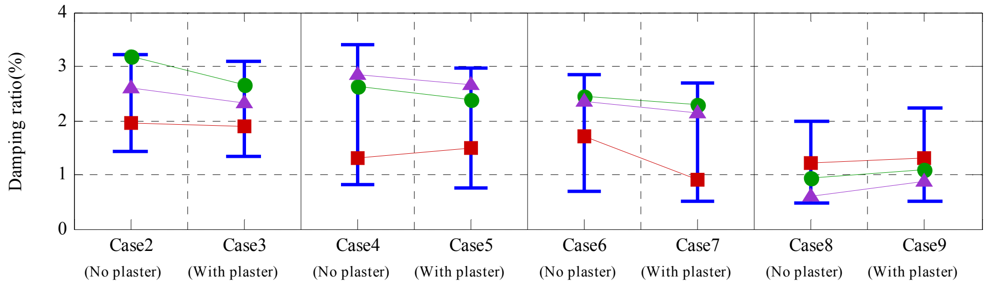
(a) Fundamental natural frequency (b) Fundamental damping ratio

Fig. 6 – Effect of ALC cladding panels on evaluation of dynamic parameters

The effect of plasterboard on evaluation of natural frequency and damping ratio is illustrated in Figure 7. Case 2 to Case 9 are classified into four groups to evaluate the effect of plasterboard, and each group consists of a test case without plasterboard and another test case with the addition of plasterboard. The comparisons demonstrate that plasterboard has a slight effect in stiffening the structure, that the free vibration maximum natural frequencies increase by 3% to 9% due to the addition of plasterboard. On the other hand, it is noticed that plasterboard has a negative effect on damping ratio, that the damping ratio tends to decrease with the addition of plasterboard. The reason for the decline is that the rotation capability of ALC panels is restricted by the plasterboard. As mentioned above, damping ratio is related to the number of slip contact surfaces between the primary structure and secondary nonstructural components. The plasterboard is attached to the ALC cladding by a wood stud framing, and the wood stud framing combines the general ALC panels into a whole, thus the rotational capacity of ALC panels is limited and the number of slip contact surfaces is reduced, and the damping ratio decreases.



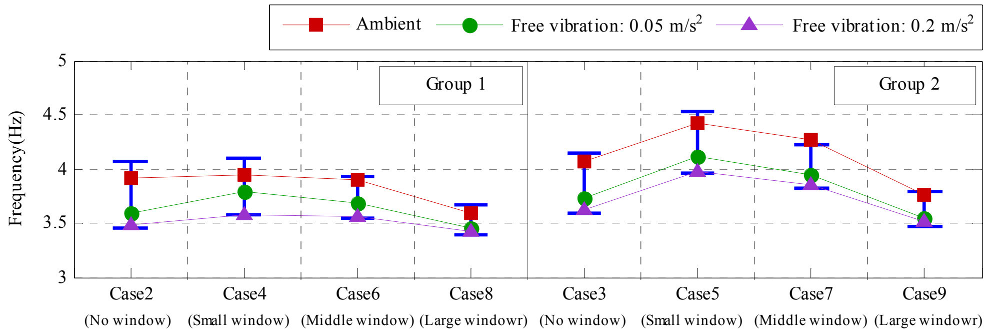
(a) Fundamental natural frequency



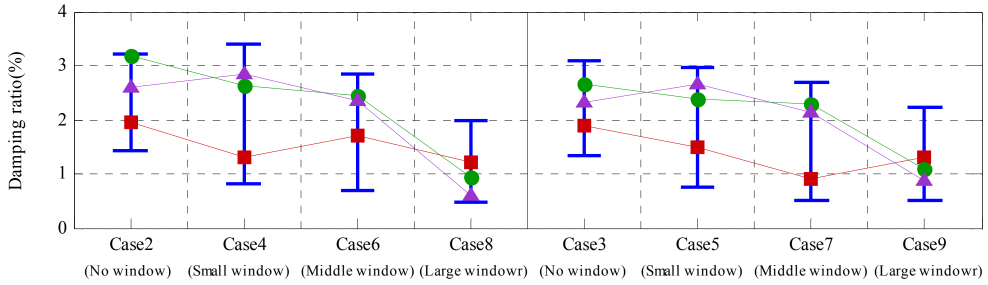
(b) Fundamental damping ratio

Fig. 7 – Effect of plasterboard on evaluation of dynamic parameters

The effect of window glazing system on evaluation of natural frequency and damping ratio is illustrated in Figure 8. Case 2 to Case 9 are classified into two groups to evaluate the effect of window openings, one with consideration of plasterboard and the other without. An increase in natural frequency is observed when small windows are attached to the frame, and then the natural frequency declines as the window size increases. Damping ratio generally declines with the size of window openings, that the damping ratio decreases as window size increases. The tendency of natural frequency is induced by the window frame and window size. Window frames are fixed to the steel frame for the purpose of holding windows in place, and have a slight effect in stiffening the structure, but the window size has a negative effect on lateral stiffness. Thus the natural frequency increases in the small window case, but starts decreasing when window openings become larger. The declining tendency of damping ratio is due to window size. As the window size increases, the number of slip contact surfaces decreases, thus the damping ratio is found to decrease.



(a) Fundamental natural frequency



(b) Fundamental damping ratio

Fig. 8 – Effect of window glazing system on evaluation of dynamic parameters

5. Conclusions

A full-scale one-story steel frame with a precast cladding system was tested to investigate the effect of non-structural components on dynamic characteristics and dynamic behavior of steel frames. In this paper, the free vibration test results are reported, and the effect of precast cladding system on dynamic characteristics of steel frames is discussed. The results are summarized as follows.

a. Amplitude dependency of dynamic characteristics takes place with the existence of precast cladding systems. Natural frequency tends to decrease with amplitude, and damping ratio first increases and reaches its maximum at a critical tip drift ratio point in the low amplitude range, and then decreases with amplitude. The amplitude dependency of dynamic parameters can be explained by the stick-slip mechanism.

b. The precast cladding system provides a significant increase in lateral stiffness. ALC claddings provide an increase of up to 40% in natural frequency, and the plasterboard and window openings provide an increase of up to 10% in natural frequency separately.

c. The precast cladding system has a significant effect in improving structural damping. ALC claddings contribute an up to 18-fold increase to the structural damping. Plasterboard and window openings have a negative effect on the damping ratio.

6. Acknowledgements

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7. References

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