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Vibration Control Effect of Locally Resonant Metamaterials on Serviceability of Floors: An Analytical Investigation

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Abstract

This study aims to contribute to the improvement of vibration serviceability through vibration control of CFS floors. To investigate the effect of the application of locally resonant metamaterials (LRMs) on the serviceability of CFS floors, an analytical investigation study was conducted by targeting the slab model of the LRMs-incorporated CFS system. For this study, the software MIDAS was used, and the target model was designed according to the criteria presented in previous research on CFS modeling. Analysis was conducted by evaluating the natural frequencies and acceleration responses of the bare slab structure and slabs with different numbers of LRMs attached under dynamic loads and assessing their serviceability. As a result, based on the criteria presented in AIJ 1991, it has been evaluated that the use of LRMs for vibration control has a significant effect on improving the serviceability of the CFS floor.

Keywords: vibration serviceability, vibration control, locally resonant metamaterials, CFS framed building, joist

1 Introduction

A cold-formed steel (CFS) framed building is composed of structural members such as joist, track, stud, and bracing with CFS as the main material [1]. CFS framed building has the advantages of low cost, high strength-to-weight ratio, high durability and ductility, resistant to corrosion, and recyclability, so it is widely used in mid- and low-rise buildings around the world. Until now, most of the research on CFS framed buildings has focused on the development of CFS design methods and seismic behavior models [1].

Meanwhile, the increasing application of CFS framing in residential buildings has raised the need for research to evaluate and improve the vibration performance of CFS floor systems [2]. Compared to traditional wood-framed floors, CFS floors are relatively lighter in weight and have longer spans, making them more prone to vibration serviceability issues caused by human activities [3]. However, the structural properties of CFS floor edges (e.g., rotational restraints) are difficult to evaluate accurately [4], and appropriate design guidelines for improving vibration performance are lacking [2], Therefore, evaluating and improving the vibration serviceability of CFS floors is challenging [4], and research on the vibration serviceability of CFS floor systems is limited [5].

The serviceability of CFS floor system is directly affected by floor vibration [6], so it needs to be improved through vibration control, and vibration absorption devices using local resonance have been actively researched [7, 8]. However, in the civil field, unlike the acoustic field, small-scale studies of member units are mainly conducted, and large-scale verification of real structures is rarely performed.

With the goal of contributing to the improvement of vibration serviceability through vibration control of CFS floors, this study conducted an analytical investigation to investigate the effect of the application of locally resonant metamaterials on the vibration serviceability of CFS floors.

2 LRMs–incorporated CFS system model

2.1 LRMs

Locally resonant Metamaterials (LRMs) are a type of unit that acts as an absorption device for vibration control. LRMs unit is a mass-spring system consisting of soft material, which is elastic, and hard material, which has high density, and vibration absorption effect appears by forming a bandgap based on local resonance [8].

In this study, LRMs were designed as shown in Figure 1. The sandwich type unit is attached to the inside of the C-shape CFS joist. It is composed of EPS, a soft material, at the upper and lower flanges, and steel, a hard material, in the middle, and operates as a spring-mass-spring. The properties of the material are as shown in Table 1.

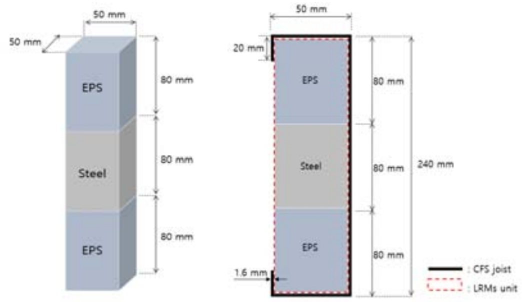


Figure 1: (a) LRMs units and (b) section of LRMs incorporated CFS joist.

Material	**Size [mm*mm*mm]**	**Property**	
Steel	50*50*80	**Density [kg/m^3]**	7850
EPS	50*50*80	**Dynamic stiffness [MN/m^2]**	5

Table 1: Material property of LRMs.

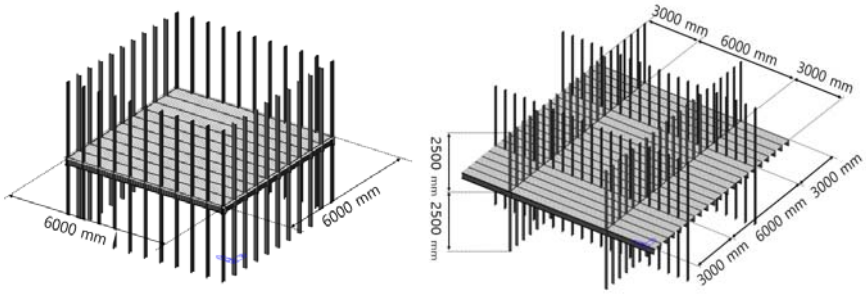
2.2 Modeling

The objective of this study is to investigate the effect of locally resonant metamaterials on vibration serviceability. Therefore, the focus is on simplifying the finite element model and analyzing the change in vibration serviceability with and without the application of locally resonant metamaterials under the same conditions. To that end, the following assumptions were made in the design of the finite element model.

In general, a CFS floor system consists of ceiling, blocking, joist, subfloor, and topping [5]. Furthermore, since the vertical mid-span displacement of CFS floor is very small, the interface shear and slip can be neglected during vibration problems [3]. Thus, a full composite action between CFS joists and steel deck is assumed [3, 9]. Furthermore, a sufficient shear connector is usually designed between steel deck and concrete slab to ensure the full composite action [10], Therefore, in this study, only the joists and the concrete slab are considered as the components of the CFS floor, and full composite action was assumed between them, as in the study of Xu, et al. [3].

In this study, the steel deck, ceilings, blocking, etc. of the CFS floor were not modeled separately, but were considered indirectly through the damping ratio. In this study, the equivalent viscous damping ratio of CFS floor is assumed to be 0.05, which is based on previous similar studies [11, 12]. It is also reported that the joist ends of CFS framed building have rotational stiffness [13-15], This is known to affect the prediction of the natural frequency of CFS floors [3, 14],]. Therefore, in this study, the joint condition of the joist ends is assumed to be semi-tight (K = 0.5), referring to previous similar studies [16, 17].

To conduct an analytical investigation based on the above assumptions, a model was designed as shown in Figure 2 using the software MIDAS [18]. In addition to the central target slab, studs (LC-140*40*10*1.2) corresponding to adjacent slabs and walls were also modeled for vibration serviceability evaluation. Only the central target slab was considered in the eigen analysis for the later mode frequency. For the slab, only 40 mm thick concrete floor and CFS joist (LC-240*50*20*1.6) were modeled, with an interval of 600 mm for each member. This used the design dimensions generally used in CFS systems, unlike the existing concrete slab. Furthermore, ceiling gypsum board, wood, deck, etc. were modeled with a finishing load of 0.5 kN/mm².



(a) (b)

Figure 2: (a) Target model for Eigen analysis and (b) Whole model for vibration serviceability.

For the input load, we designed a dynamic nodal load in the form of a heel drop. The frequency of human hill drop is 2 Hz to meet the AIJ criteria for serviceability to be evaluated later. As shown in Figure 3, the dynamic nodal load is applied diagonally only the target slab.

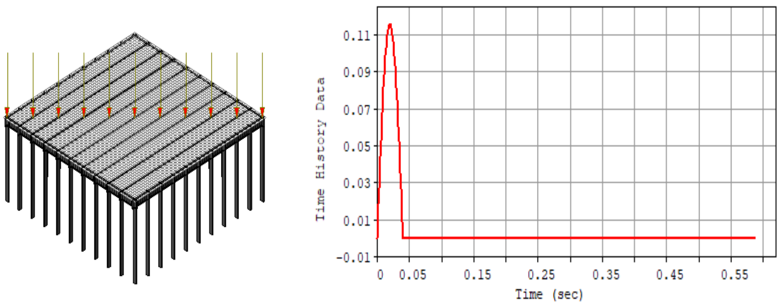


Figure 3: Position and design of dynamic nodal load

The analytical investigation study consists of three cases. Case 1 is a bare slab. Case 2 and 3 are slabs with LRMs applied at regular intervals of 1000 mm and 500 mm, respectively. As shown in Table 2, Case 2 has a total of 40 LRMs units staggered and attached in a grid. In Case 3, a total of 81 LRM units are applied. Figure 4 shows a schematic of the CFS joist with LRMs in Case 2.

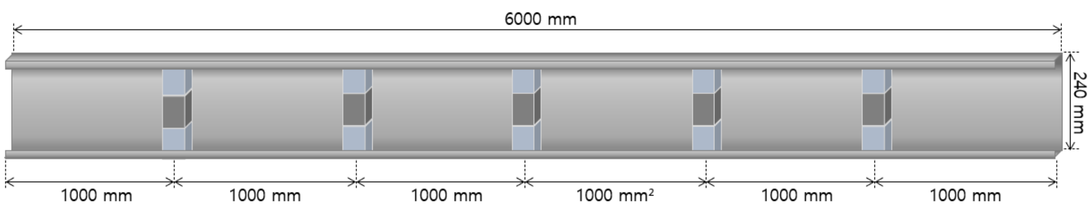


Figure 4: CFS joist with LRMs

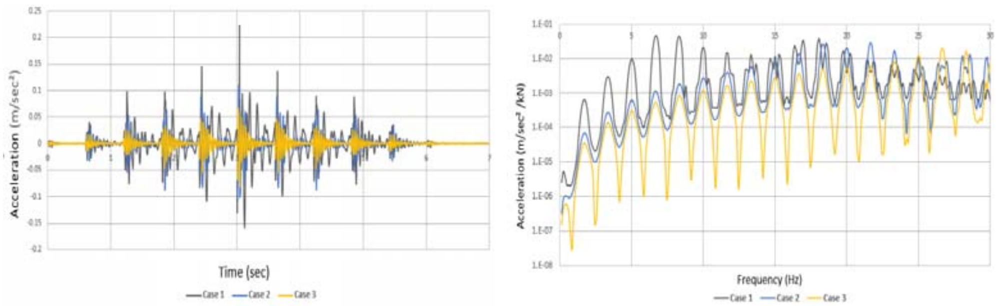
Category	Number of LRMs [units]	Mass ratio [%]
Case 2	40	0.00248
Case 3	81	0.00503

Table 2: Number of LRMs and Mass ratio

The analysis data is saved at the center node of the target slab to check the acceleration as a time history. Later, the mode frequency is calculated through eigenvalue analysis and the acceleration response is used to check the improvement of vibration serviceability with and without LRMs. As a usability evaluation method for representative buildings, vibration serviceability was evaluated according to AIJ 1991 (Architectural Institute of Japan) vibration performance criteria.

3 Results

In Case 1, where the slab is bare, the natural frequency is 7.35 Hz. However, in Case 2 and 3, where LRMs are applied at regular intervals, the natural frequencies increase to 18.99 Hz and 27.31 Hz, respectively. Additionally, the maximum amplitude in the acceleration response is 0.0663 m/sec2 for the case 3, which is significantly lower than the 0.2204 m/sec2 observed for the bare slab. Notably, Case 3 demonstrates the most substantial reduction in acceleration response, with a decrease of approximately 69.9%.



(a) (b)

Figure 5: (a) Time history, (b) Frequency spectrum

Category	Mode frequency [Hz]	Max amplitude [m/sec^2]	Reduction rate [%]
Case 1	7.35	0.2204	-
Case 2	18.99	0.1103	49.95
Case 3	27.31	0.0663	69.91

Table 3: Result of eigen analysis and decay rate.

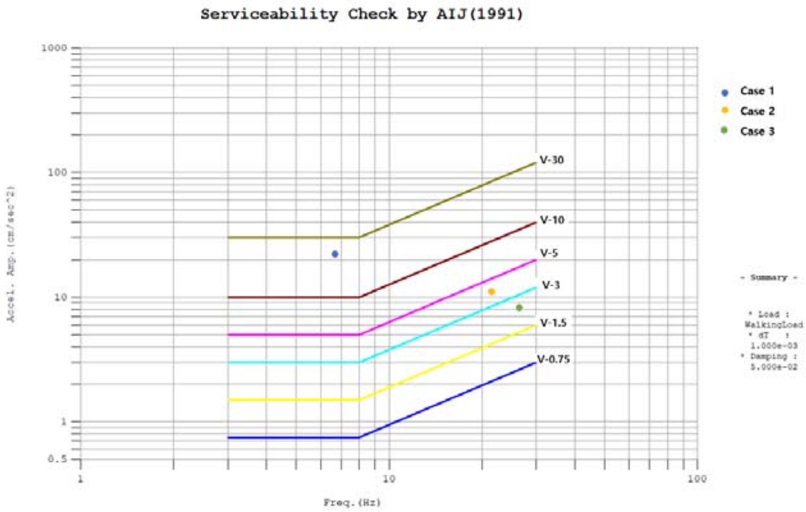


Figure 6: Serviceability Check by AIJ.

When comparing the serviceability of each case, Case 1, a bare slab, satisfied V-30. In cases 2 and 3, the natural frequency increased while the amplitude of the acceleration response decreased. As a result, Case 2 satisfied V-5 and Case 3 satisfied V-3.

4 Conclusions

A numerical study was conducted to investigate the slab vibration serviceability evaluation of CFS structures with and without LRMs. As a result of comparing the bare slab (Case 1) and the LRMs-incorporated slab (Cases 2 and 3), the direct vibration control effect of LRMs was confirmed, such as the maximum acceleration response was reduced by up to 69.9%. The adjacent slabs and studs were also modeled for serviceability evaluation, and much more stable results were obtained according to AIJ 1991 vibration performance criteria. Furthermore, the LRMs mentioned in this study have the advantage of being easy to construct and maintain and can be applied not only to new buildings but also to existing buildings.

Acknowledgements

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