Chapter 4
Modal Testing and Finite Element Model Updating of a Fast-Floor Specimen: A Modular All-Steel Floor System

Sahabeddin Rifai, Rajshri Chidambaram Muthu Kumar, Onur Avci, Benjamin W. Schafer, Matthew R. Eatherton, W. Samuel Easterling, and Jerome F. Hajjar

Abstract This paper presents the results of modal testing and finite element model updating of an all-steel floor system, designed to increase the speed of construction by eliminating the traditional concrete-on-deck component. A 10 ft $\times$ 40 ft laboratory specimen, comprising three W24 beams attached to a top plate with a raised access floor, was tested to obtain its modal frequencies and mode shapes. The experimental results were used to update a finite element model in SAP2000, which was then validated against the experimental data. The validated model is used to predict the dynamic behavior of a larger 30 ft $\times$ 40 ft system, representing a full bay at an elevated building floor. The study provides valuable insights into the dynamic behavior of steel floor systems and highlights the importance of experimental validation and model updating in ensuring the accuracy of finite element models. The findings contribute to the development of more accurate and efficient design methods for modular steel floor systems.

Keywords Steel floor systems · Modal testing · Finite Element model updating · Dynamic analysis · Modular construction

Introduction

FastFloor is a modular all-steel floor system developed in response to the "Need for Speed" initiative launched by the American Institute of Steel Construction (AISC). This initiative aims to reduce steel construction time by up to 50%. FastFloor achieves this goal by eliminating non-steel components in traditional composite floor systems, thereby increasing the speed of steel construction. The modular units of FastFloor are prefabricated off-site and then transported and erected on steel girders with field connections. Additionally, FastFloor offers several advantages, including reduced weight and a lower carbon footprint [1].

The original design of FastFloor consists of multiple wide-flange steel beams connected to a steel plate using bolts and staggered welding. A typical full-bay FastFloor is designed to be 30 ft $\times$ 40 ft, and the prefabricated full-bay floor can be easily installed and connected to steel girders, which results in significant time and labor savings. This paper presents

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the background and results of dynamic testing on an all-steel floor specimen. The specimen comprises three identical steel beams connected to a steel plate on their top flanges, with a raised access floor (RAF) installed on top of the steel plate. The RAF provides space for various mechanical system components.

Floor systems composed entirely of steel members are characterized by their relatively low self-weight and low inherent damping compared to traditional composite floors. This presents a challenge in achieving acceptable vibration levels in modular steel construction, as beam and girder spans need to be longer in modern building design [1].

This study aims to investigate the dynamic behavior of a scaled-down FastFloor specimen through experimental modal testing and finite element model updating. The experimental results provide valuable insights into the vibration modes and frequencies of the specimen, while the updated finite element model enables the prediction of the dynamic behavior of larger-scale FastFloor systems. The findings of this study contribute to the development of more accurate and efficient design methods for modular steel floor systems, ultimately enhancing the overall performance and sustainability of steel construction.

Test Specimen

The floor specimen tested in the laboratory measures 10 ft in width and 40 ft in length, as shown in Fig. 1-b. This specimen represents a single module of the full-bay FastFloor system, with minor modifications, including a 2 ft extension of the beams beyond the steel plate. The test specimen consists of three W24x68 steel beams and a 3/8 in. thick steel plate on top. Hex Structural Bolts with Shuriken nut keepers were used to connect the plate to the left beam's top flange on one side, while staggered welding was applied to the remaining beam-plate connections.

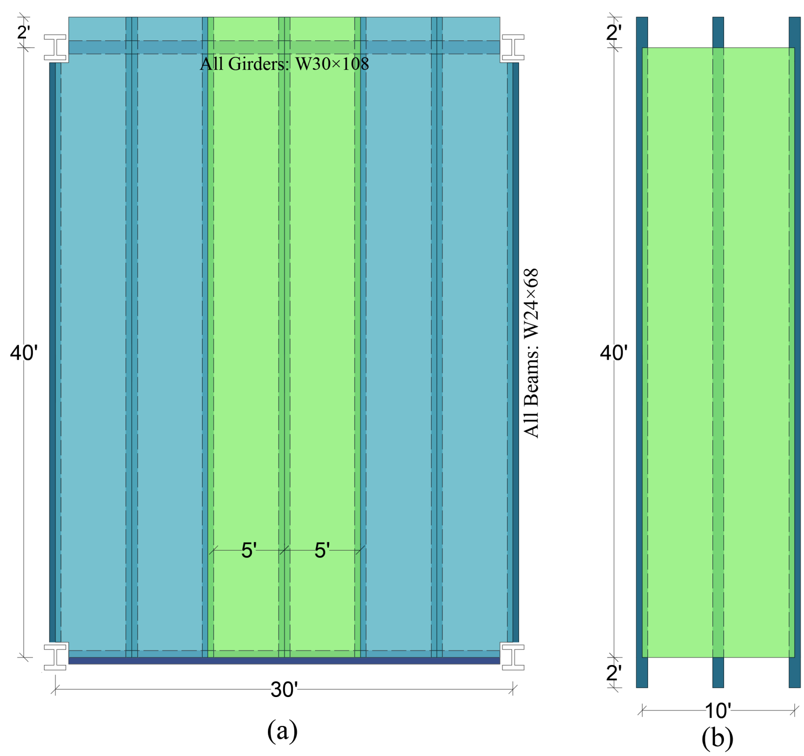

Fig. 1 Layout of the full-bay and single FastFloor modules. (a) A 30 ft × 40 ft full-bay FastFloor module. (b) The 10 ft × 40 ft single FastFloor module tested in the laboratory.

To prevent sway deflection in the short direction, web stiffeners with a thickness of 1/2 in. and a width of 4 in. were welded to the beam webs at the support locations. The beam bottom flanges were connected to the bearings using C-clamps to simulate a pin connection. The raised access floor (RAF) was supported by steel pedestals with adjustable heights, which were attached to the steel plate. A total of 125 pedestals were used to support 100 floor panels, each measuring 2 ft × 2 ft in plan.

Fig. 2 View of the test specimen with W24x68 beams, a 3/8 in. thick plate, and raised access floor (RAF) on top.

Dynamic Modal Testing of the Steel Floor Specimen

To obtain accurate dynamic properties and high-resolution mode shapes, acceleration data were collected from 99 points on the raised access floor (RAF). These points were spaced at 15-inch intervals in the short direction and 48-inch intervals in the long direction. The points were more densely spaced in the short direction because most vibration modes exhibit deflection primarily in this direction. Uniaxial accelerometers were attached to the floor to measure vertical vibrations. Fig. 3 illustrates the locations of the excitation and data acquisition points. A dynamic mass shaker was used to excite the specimen at various frequencies, with both low- and high-amplitude excitations.

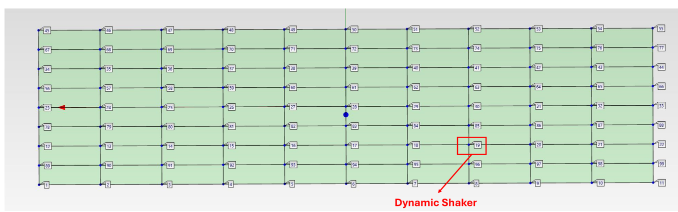

Fig. 3 Accelerometer and dynamic shaker locations on top of the RAF.

The input of the dynamic shaker excitations is measured by the accelerometer placed at point 19 (shown in Fig. 3), placed near the dynamic shaker. Excitations are classified as low-amplitude when the accelerations recorded at point 19 are below 5%g, and as high-amplitude when the accelerations exceed 15%g [2, 3]. Fig. 4 presents 99 overlaid frequency response functions (FRFs) used to identify natural vibration modes, obtained with low-amplitude dynamic shaker excitations. The

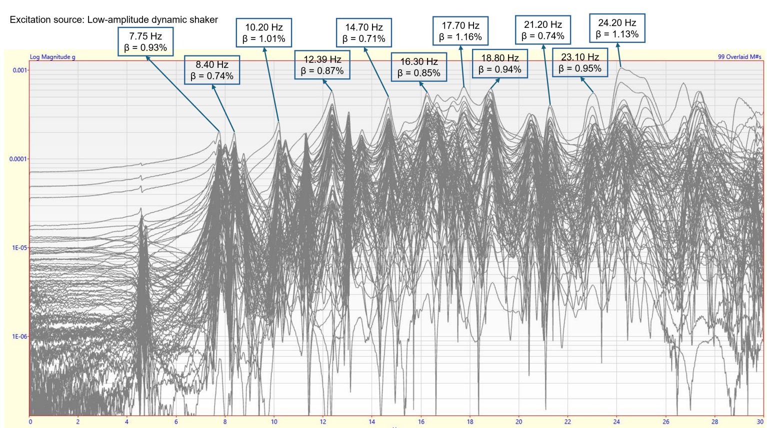

Fig. 4 Frequency response functions (FRFs) with natural frequencies and damping ratios of major vibration modes, obtained using low-amplitude dynamic shaker excitations.

corresponding FRFs for high-amplitude dynamic shaker excitations are shown in Fig. 5. The plots in Fig. 4 and Fig. 5 show the results of experimental modal testing, where acceleration data were processed using MEScope software [4].

The natural frequencies and damping ratios of the global modes are reported in these figures. Local modes are not presented, as they are not utilized in the model updating procedure. The results indicate that the frequency content of the specimen comprises closely spaced multiple vibration modes. Furthermore, the dynamic excitation amplitudes have an impact on the natural frequencies and damping ratios, which is consistent with previous findings [3, 4, 5]. For the purpose of finite element model updating, the natural frequencies obtained from the low-amplitude shaker results were used, as human walking is a low-amplitude activity that is most relevant to the study.

The mode shapes of the first four global vibration modes, obtained from dynamic modal testing and finite element analysis, are illustrated in Fig. 6. For improved visibility, the raised access floor (RAF) components are not shown in the mode shape visualizations. The finite element model in SAP2000 accurately captures the lateral deflection of the beams in all four modes (shown in Fig. 6) and showcases the global dynamic behavior of the specimen in three-dimensional view.

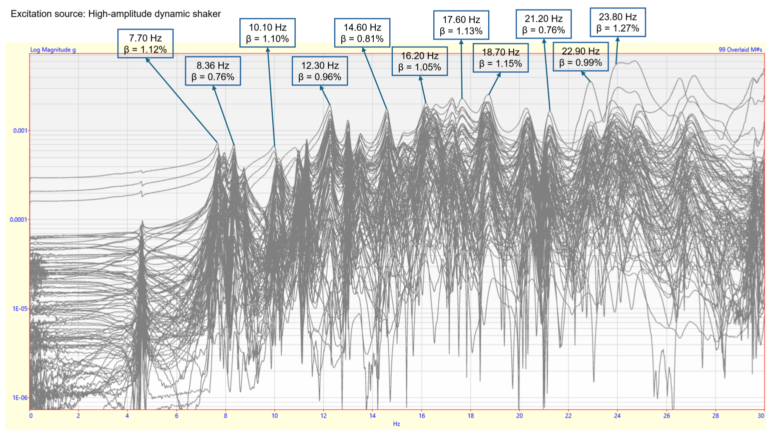

Fig. 5 Frequency response functions (FRFs) with natural frequencies and damping ratios of major vibration modes, obtained using high-amplitude dynamic shaker excitations.

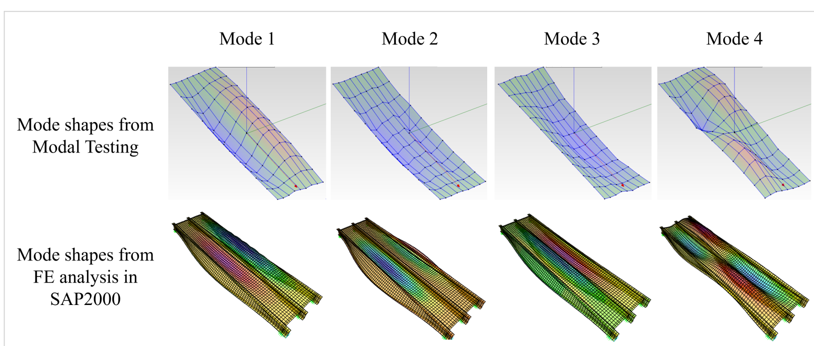

Fig. 6 Mode shapes of the first four global modes, obtained from experimental modal testing and finite element analysis in SAP2000.

Finite Element Model Updating

A well-calibrated finite element model of the 10 ft wide floor specimen is a valuable tool for understanding the dynamic behavior and predicting the response of larger-scale FastFloor systems and full bays, which are impractical to build and test in a laboratory setting. For this reason, the authors focused on updating the finite element model of the tested specimen using SAP2000. Fig. 7 illustrates the 3D floor model in SAP2000. In the initial finite element model, the beams, plate, and RAF panels of the floor specimen were modeled as thin shell elements, while the RAF pedestals were modeled as frame elements.

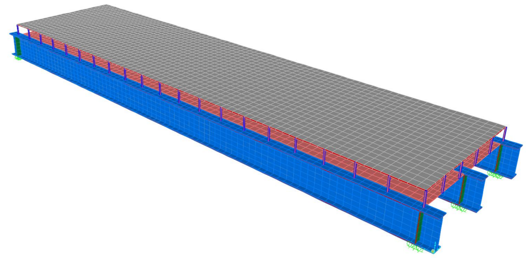

Fig. 7 3D view of the Finite element model of the floor specimen.

The average mean absolute error of the initial finite element model indicates that, on average, the analytical natural frequencies are 30% higher than the experimental natural frequencies, as shown in Table 1. Therefore, model updating was conducted to match the natural frequencies between the experiment and analysis. Since natural frequencies are proportional to the stiffness, the initial finite element model exhibited higher stiffness than the tested specimen. As a result, the authors focused on adjusting model parameters that could reduce the stiffness of the finite element model. The mass of the specimen was kept constant throughout the model updating process, and the mass in SAP2000 was verified using hand calculations.

Table 1 Comparison of experimental and analytical modal frequencies before model updating

Mode	Experimental Frequency (Hz)	Analytical Frequency in SAP2000 (Hz)	Error (%)
1	7.75	10.5	35.5
2	8.40	10.96	30.5
3	11.31	11.29	0.2
4	12.39	18.94	52.9

The main parameters used in the finite element model updating were (1) the continuity of beam-plate connections, (2) the boundary conditions of the specimen, and (3) the modeling of RAF panels. In the initial finite element model, the beam-plate connections were treated as continuous, despite the presence of intermittent welded and bolted connections, with the welded connections considered stiffer than the bolted ones. To accurately reflect the beam-plate connections in the SAP2000 model, the connection joints were first disconnected, then some were reconnected discretely. Different spacings of connected joints were tested depending on the type of connection. In Fig. 8, the discrete beam-plate connections are illustrated where reconnected joints on the bolted side were spaced by 35 in. and on the other three welded connections, spacing of reconnected joints was 24 in. Those spacing values resulted in the lowest frequency errors.

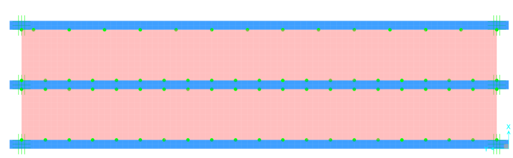

Fig. 8 Modeling of beam-plate connections: The upper connection is bolted, while the remaining three connections are welded [7].

A few adjustments were made to the boundary conditions; however, this parameter did not significantly affect stiffness or frequencies, as only combinations of pin and roller supports were used. The objective of the model updating was to match the frequencies of the global modes with frequencies lower than 16 Hz. The updating process was performed manually by adjusting the three parameters mentioned above while monitoring how changes affected the mode shapes and frequency error values. Model updating attempts were stopped when no further improvement or reduction in the error was observed. Table 2 presents the final updated frequencies from SAP2000 compared to the experimental results. It is noteworthy that the higher the mode, the less it contributes to the overall response. Also, matching the first two frequencies can result in larger discrepancies for higher modes.

Table 2 Experimental and analytical natural frequencies at the end of model updating.

Mode	Experimental Frequency (Hz)	Analytical Frequency in SAP2000 (Hz)	Error (%)
1	7.75	8.18	5.5
2	8.40	8.72	3.8
3	11.31	10.28	9.1
4	12.39	14.72	18.8

Conclusions

This paper presented the results of modal testing and finite element model updating of a 10 ft $\times$ 40 ft all-steel floor module. The research team successfully matched the frequency values of the global modes via finite element model updating with reasonable precision. Future work will include experimental and numerical investigations of a full-bay FastFloor laboratory specimen.

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