Chapter 2
Development of a Laboratory Test Program to Examine Human-Structure Interaction

Nicholas C. Noss and Kelly A. Salyards

Abstract Vibration serviceability is a widely recognized design criterion for assembly-type structures likely subjected to rhythmic human-induced excitation. Current design guidance is based on the natural frequency of the structure. However, a phenomenon known as human-structure interaction suggests that there is a dynamic interaction between the structure and the occupants, altering the natural frequency of the system. It is unknown if this shift in natural frequency is significant enough to warrant consideration in the design process. Therefore, there is a need to identify the circumstances under which human-structure interaction should be considered because of its potential impact on serviceability assessment. Because the influence of the structural properties on human-structure interaction cannot be separated from the influence of the crowd characteristics, this study explores the interface of both factors through experimental testing. To do so, a laboratory test structure is designed, constructed, and operated based on particular design criteria selected with knowledge from previous human-structure interaction studies. This study provides a review of the design and construction of the test structure, methods used to validate a finite element computer model to the as-built structure, and the experimental testing procedure for testing with occupants.

Keywords Human-structure interaction • Experimental modal analysis • Crowd dynamics

2.1 Introduction

Assembly-type structures are subjected to dynamic loading generated by the crowd occupying the structure. Motion of the crowd has the potential to induce vibrations that may be of concern to the occupants. Structural engineers refer to this as vibration serviceability. Vibration serviceability is of particular concern when the crowd is synchronized in its movement creating a significant dynamic force on the structure. Because structural designs are utilizing higher-strength materials and advanced analysis methods, assembly-type structures are designed and constructed with longer and lighter spans which are more susceptible to excitation by such crowd motion. It is likely that these structures have a fundamental frequency in the range of 4–8 Hz [1] which corresponds to the frequency range over which humans are most sensitive to vibrations. Occupants of such structures can perceive and be disturbed by these vibrations and if vibrations are excessive [2], widespread panic can occur amongst the crowd, ultimately risking the safety of the occupants. For these reasons, it is important that research continues in the area of vibration serviceability to improve upon the design guidance currently available to structural engineers.

In the United States, the design guidance available for the vibration serviceability design of assembly-type structures subjected to rhythmic excitation is limited. Design for rhythmic excitation is addressed in guidance published by the American Institute of Steel Construction (AISC) for floor structures [2]. This guidance specifies a minimum natural frequency of the structure to be achieved such that resonance with the expected rhythmic excitation is avoided. It assumes that only a single mode of vibration contributes to the dynamic response of the structure and also requires the identification of an appropriate acceleration limit for the purpose of the space. Whilst these assumptions may be reasonable for floor structures, the application of such assumptions to other types of structures, such as stadium grandstands, can be

N.C. Noss (✉) • K.A. Salyards
Department of Civil and Environmental Engineering, Bucknell University, Lewisburg, PA 17837, USA
e-mail: nick.noss@bucknell.edu; kas046@bucknell.edu

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inappropriate. In addition, this guidance, along with others, utilizes the natural frequency of the empty structure for its assessment of serviceability. Although this may be representative of the extreme condition where all occupants are actively engaged in the rhythmic loading, it may not address all possible scenarios where some occupants are not engaged in the motion.

In addition, it has been observed by several researchers that the natural frequency of a structural system is also affected by another phenomenon. This phenomenon is known as human-structure interaction and addresses how occupants act more as a spring-mass-damper system rather than mass alone, ultimately affecting the dynamic properties of the overall structural system. The majority of these observations indicate that the natural frequency of the system is decreased from that of the empty structure and the damping ratio is increased from that of the empty structure [3]. This is potentially problematic because the natural frequency could be lowered into a frequency range excitable by rhythmic loading. A short discussion of these observations, ensuing research, and the current guidance for incorporating such effects aims to provide the impetus for the research described in this paper.

2.2 Evidence of Human-Structure Interaction

The human-structure interaction phenomenon was first acknowledged in 1966 in a floor vibration study by Lenzen at the University of Kansas [4]. It was not further examined until 1991 when in-situ monitoring of a stadium grandstand structure provided further evidence of this interaction with a lower natural frequency when the structure is occupied along with an additional mode of vibration [5]. The natural frequency of another assembly structure was found to be reduced from 16 Hz to around 5 Hz when occupied by a crowd [5]. Littler [6] provided further evidence of human-structure interaction, including its dependence on posture, through the in-situ testing of several retractable grandstands. These results from in-situ testing prompted further investigation and laboratory testing.

Experimental testing was performed in the laboratory by several researchers on simple structures. Ellis [7] examined the effects of human-structure interaction on a simply supported concrete beam ($f_n = 18.68$ Hz) with a single individual. Similarly, Brownjohn [8] explored the effects of a single individual on a precast plank ($f_n = 3.16$ Hz) varying posture. Falati [9] advanced the previous studies by examining the effects of two people on a concrete structure. Yao et al. [10, 11] expanded the range of structural frequencies examined through the use of a testing rig with a single individual. These laboratory experiments provide additional evidence of the phenomenon but are limited in their direct application because they utilize only one or two people.

The experimental evidence indicates that the crowd behaves as a dynamic spring-mass-damper system attached to the supporting structure. Several analytical studies have been undertaken to provide guidance for modeling this type of combined system and to identify the appropriate dynamic properties of the system representing the crowd. Several numerical models have been developed to model the human body for civil engineering applications [9, 12, 13]. Dougill et al. [14] provides a detailed modeling theory that accounts for human-structure interaction for structures with a single dominant natural frequency. Yet, no guidance for incorporating the human-structure interaction into the design process had been presented prior to 2008.

In 2000, a Joint Working Group was formed with members from the Institution of Structural Engineers (IStructE), the Department for Transport, Local Government (DTLG), and the Regions and Department for Culture, Media and Sport (DCMS) in the United Kingdom. This Joint Working Group published comprehensive design guidance aimed specifically toward grandstands entitled “Dynamic Performance Requirements for Permanent Grandstands Subject to Crowd Action” [15]. Currently, this publication is the only to address the human-structure interaction phenomenon, recognizing that previous recommendations for grandstands with dense crowd loading and natural frequencies below 7 Hz gave “insufficient consideration to the nature of the loading or to the effects of the mechanical interaction between individuals and the structure” [15]. The recommendations for modeling are based on Dougill’s analytical results [14] which have been corroborated with experimental measurements from bobbing on a flexible test rig structure at the University of Manchester. Additional experimental results are desirable to further validate the modeling recommendations.

2.3 Overview of Experimental Study

The test structure described herein is critical to the planned experimental investigation of the effects of human-structure interaction. The test structure is specifically design to represent a range of dynamic properties representative of cantilevered grandstands. The planned study addresses how crowd characteristics, such as posture and location, combine with structural characteristics, such as frequency and mass, to influence the dynamic properties of the combined system. Several of the limitations of previous experimental studies, as referenced above, are addressed in this study. One such limitation is the experimental consideration of a structure occupied by more than a single individual. In addition, this study is designed to investigate a wider range of natural frequencies of the structure as opposed to previous studies or experimental measurements which were limited to a single frequency of the constructed structure. The objectives of the experimental work are:

1. To experimentally identify the circumstances for which the effects of human-structure interaction should be considered because of its potential impact on serviceability assessment.
2. Provide experimental evidence of the influence of structure and crowd characteristics on the recommended dynamic parameters for an appropriate crowd model.

To accomplish these objectives, a cantilevered steel test structure was designed as shown in Fig. 2.1. The natural frequency of the empty structure can be varied between 4.35 and 6.25 Hz or higher through the relocation and addition of supports which fasten to the wide-flange shape support beams. The test structure accommodates a maximum of nine passive occupants in various postures and locations on a concrete plank decking surface. The constructed structure is shown in Fig. 2.2. Experimental testing is planned to determine the dynamic properties of the human-structure system and how it is influenced by the structural and crowd characteristics when the test structure is occupied.

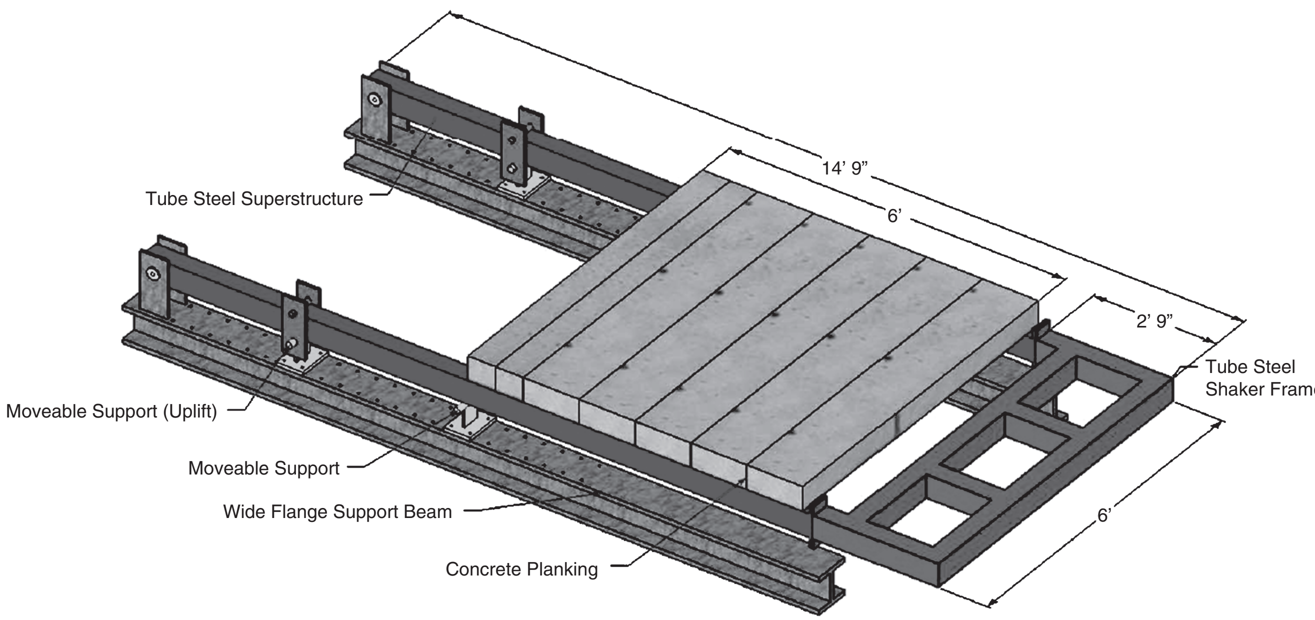

Fig. 2.1 Conceptual model of the cantilevered test structure

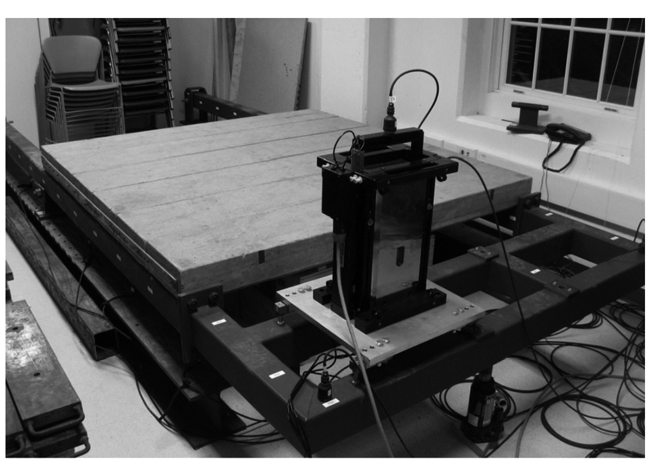

Fig. 2.2 As-built cantilevered test structure

This paper will describe how the conditions for the study are achieved through the design and construction of the test structure. A summary of the design and construction of a cantilevered test structure with a tunable fundamental natural frequency is presented first. The process of how experimental modal analysis, using shaker excitation and acceleration response, is employed to determine the dynamic properties and validate the finite element model of the structure is described.

2.4 Test Structure Design and Construction

This section describes how the required conditions for the experimental study are translated into design criteria implemented in the design and construction of the cantilevered test structure. The conditions to be met for the study include:

1. The test structure must safely accommodate small groups of individuals that have a combined mass which is in a desired proportional range to the mass of the empty structure.
2. The test structure must have dynamic properties that are representative of typical cantilevered grandstands.
3. The natural frequency of the test structure must be adjustable through the relocation and/or addition of supports.
4. Data collection techniques must yield reliable experimental data.

A detailed description of the geometry and layout of the test structure is given before addressing the specific design criteria.

2.4.1 Geometry and Layout

A cantilevered test structure is chosen for this study because cantilevers are widely used in assembly type structures, like stadiums, for the benefit of improved sightlines. However, they are often subject to vibration serviceability issues. The typical fundamental frequency range for cantilevered stadium sections is between 4 and 8 Hz [1], which can be achieved in a small scale experimental test structure. During the design phase a finite element model of the test structure was created in SAP2000 [16]. Initial design consisted of experimenting with various structural configurations, cantilever lengths, support conditions and material types. Controlling factors leading to the final design were the target frequency range, material stresses, and the deflection of the cantilever.

The final design resulted in a test structure with a fundamental frequency ranging from 4.35 to 6.25 Hz with only two supports and higher with the addition of a third support. The base dimensions of the structure measures 14.75′ long by 6′ wide. The structural configuration that results in a lower bound natural frequency of 4.35 Hz was achieved with a 6′ backspan and a 6′ concrete decking surface. The decking surface is constructed of reinforced concrete planks (12″W × 72″L × 5.25″D) spanning between the cantilevered sections. The last 2.75′ of the test structure's cantilever provides a mounting location for the electrodynamic shaker.

Increasing the natural frequency of the test structure from a range of 4.35–6.25 Hz is accomplished through shortening the length of the decking surface from 6′ to 4′ by moving a knife edge support in 4″ increments. The natural frequency of the test structure can be further increased though the addition of a support on the backspan of the structure as depicted in Fig. 2.3. The constructed connections are depicted in Fig. 2.4. A steel bushing connection in Fig. 2.4a was fabricated to represent an idealized pinned condition to restrain vertical, horizontal, and lateral movement. The pin was oiled to reduce friction and wear. The connection in Fig. 2.4b was designed and constructed to restrain vertical movement along the backspan of the test structure. A pin and eyebar connected to a knife edge support reduces deflection on the backspan of the test structure, increasing the natural frequency. The connection depicted in Fig. 2.4c is a knife edge support located at

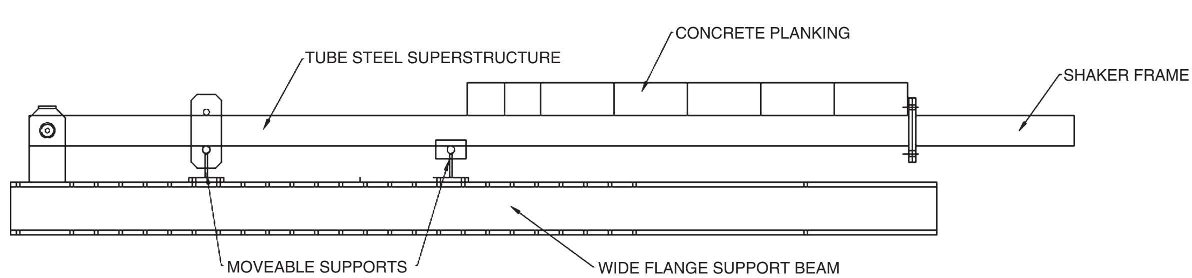

Fig. 2.3 Elevation view of the test structure

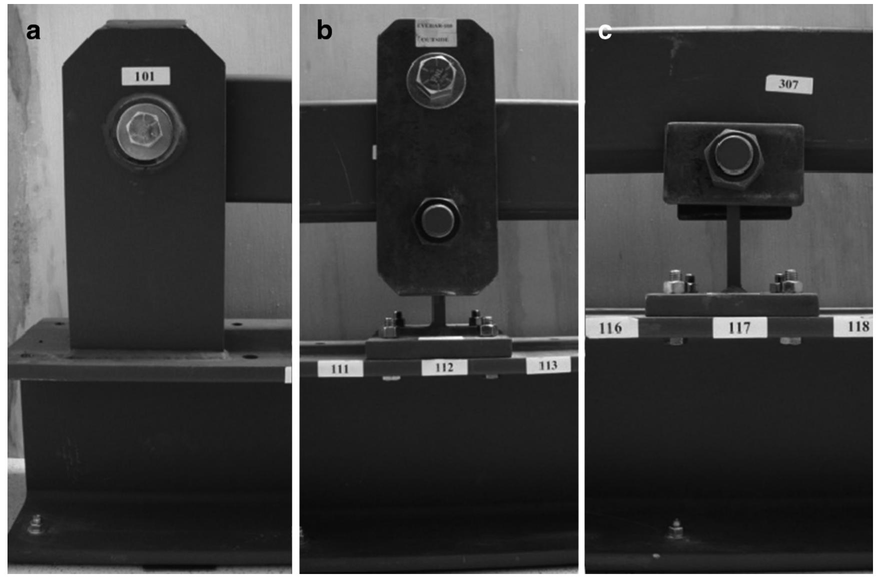

Fig. 2.4 (**a**) Pin support, (**b**) moveable backspan support, (**c**) moveable knife edge support

the transition between the backspan and the cantilever. This support will always remain in compression. Steel plates are attached to the knife support to reduce lateral movement of the tube steel superstructure.

The movable supports are bolted to wide-flange beams (W8 × 48) that have holes drilled along their top flange every 4″. The support beams were used for two main reasons. The support beams distribute the concentrated compressive and uplift forces from the supports along the length of the beam through the laboratory slab-on-grade. The support beams also provide a safe, consistent, and fast method for movement of the supports when adjusting the natural frequency of the test structure. The movable supports can be relocated and/or added by lifting the structure with a hydraulic bottle jack located under the tube steel frame at the end of the cantilevered decking surface, effectively removing the load from the supports temporarily.

2.4.2 Design and Materials

The test structure was designed using Load and Resistance Factor Design (LRFD) for static loading. ASCE 7–10: Minimum Design Loads for Buildings and Other Structures [17] recommends 100 psf live loading for stadium seating. This loading was compared to situations where nine individuals at 95th percentile weight (255 lb) were represented in the finite element model occupying the structure in loading scenarios that would be considered extreme for this type of experimental testing. An example of an extreme situation would be where all nine occupants are located within 3 ft of the end of the cantilevered decking surface; another would be unbalanced loading where all of the occupants would be located to one side of the structure. The ASCE 7–10 recommended static live loading of 100 psf on 36 ft^2 of the decking surface produced higher bending stresses and reaction forces than that of the "extreme" loading conditions described above.

The superstructure of the test structure was constructed of 5″ × 4″ × 3/16″ tube steel sections with a minimum yield stress of 46 ksi. These steel tubes provided the flexibility for a low fundamental frequency of the structure, yet still remained in the elastic bending range for the factored dead and live loads applied. However the deflection of the cantilever is quite noticeable when loaded to capacity. The deflection of the cantilever under design load condition is approximately 0.82 in., which is in the range of L/90 where L is the length of the cantilever. This is slightly more than the recommended cantilever deflection of L/140 [18]. The recommended deflection limit is not applicable as the structure is not attached to other systems which would be impacted and the deflection is not likely to be visually objectionable to the occupants as it is a test structure and not a regularly occupied structure. The 5″ × 4″ × 3/16″ tube steel sections are also considered compact eliminating the potential for local buckling; this is not the case for wide flange beams with a similar stiffness. The natural frequencies of vibration modes in the horizontal direction are increased with a higher moment of inertia in the lateral bending direction provided by the tube steel and the addition of the tube steel shaker frame attached to the end of the cantilevered decking surface.

Reinforced concrete planks (12″W × 72″L × 5.25″D) are designed to span from one tube steel cantilever to another, using a maximum of six planks to provide 36 ft^2 of decking surface for the occupants. The connection between the concrete planks and the steel structure is a simple gravity connection. The decking surface was designed as reinforced concrete planking for the following reasons:

1. Additional mass was needed to achieve the lower bound of frequency at 4.35 Hz and the desired mass ratio range of 0.06–0.58.
2. Narrow planks without a mechanical connection to the steel structure limit the level of potential composite action of the cantilever.
3. Reinforced concrete planks are sufficiently rigid to resist excitation of local vibrations modes of the decking surface caused by occupants.
4. Planks can be added or removed to change the length of the cantilevered decking surface.

2.4.3 Occupancy and Mass Ratio

The test structure was designed to accommodate small groups of individuals in either standing postures or seated positions. It was determined that a test structure with an occupant capacity of nine people would provide additional insight into the human-structure interaction phenomenon when compared to previous experimental testing that used only one or two occupants on a structure. Previous research, along with the recommended modeling guidance, suggest that the relative size of the crowd compared with the size of the structure can be a factor in the level of interaction between the occupants and the structure [3, 15], this can be interpreted as a function of the crowd and structure mass.

Mass ratio is defined to be the ratio of the combined mass of the occupants to the mass of the empty structure [5]. A mass ratio of 0.25–0.75 is suggested for typical stadiums at full capacity [19]. Previous laboratory studies involving test structures used to investigate human-structure interaction had estimated mass ratios ranging from 0.067 to 0.431 [8, 20]. Further investigation of several in-service stadiums has shown that mass ratios vary between 0.27 and 0.63 at full occupancy based on ASCE 7–10 recommended live loading for stadium structures. For this study, the upper mass ratio was chosen to be roughly 0.60 when the test structure is at full capacity with nine occupants.

Knowing the desired mass ratio and number of occupants at full capacity, the weight of the empty structure is estimated by assuming an average weight of each occupant. Studies have indicated that the average weight of an adult is 180 lb [15]. Therefore, the weight of the empty test structure is designed to be 2,800 lb in order to achieve the desired mass ratio range. The platform size for the occupants is determined based on the space needed for an occupant to be in either a seated or standing position. An area of four square feet per occupant was deemed adequate.

2.5 Finite Element Model

The original finite element model used for the design of the test structure was created in SAP2000. The model was constructed of nodes and frame elements that represent the 5″ × 4″ × 3/16″ tube steel members and 12″ × 72″ × 5.25″ concrete planks as shown in Fig. 2.5. Nodes of the model are at locations of support conditions and accelerometer locations.

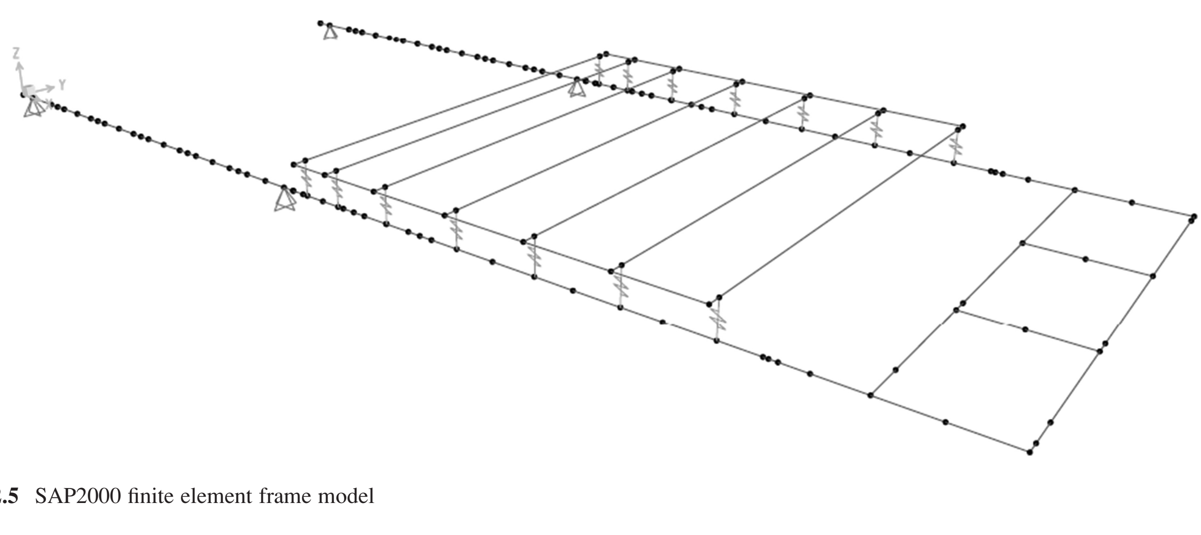

Fig. 2.5 SAP2000 finite element frame model

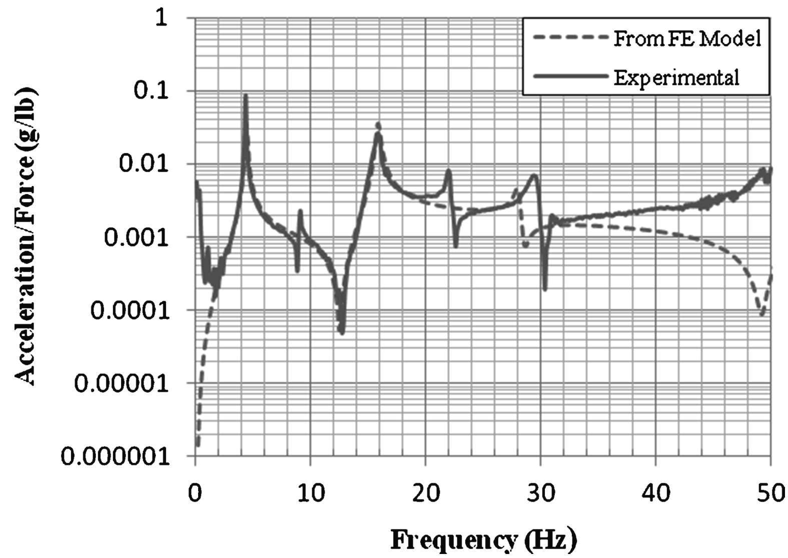

Fig. 2.6 Frequency response function (FRF) created from SAP2000 modal results and compared with the corresponding experimentally measured FRF

The wide flange support beams were not modeled in SAP2000 because they are a rigid base for the supports. During the modeling process, several assumptions were made when creating the original finite element model:

1. Pin connections of the as-built test structure are frictionless and allow free rotation.
2. The gravity connection between the concrete planks and the tube steel cantilever beams are best modeled as a pin connection.
3. Material properties from the AISC database in SAP2000 are representative of the materials used during actual construction.
4. The geometry of the as-built structure is identical to the geometry of the finite element model (no fabrication or installation errors).

The test structure was designed and constructed based on the finite element model and the above assumptions. Strength design of the structure is of the utmost concern for safety; however the dynamic properties such as natural frequency and modes shapes are also of particular interest in this study. SAP2000 is used to perform modal analysis to determine vibration modes of the modeled structure using Eigenvector analysis for undamped free-vibration modes and frequencies. The modal displacements at the accelerometer locations and natural frequencies of the modeled test structure are used to generate a series of analytical frequency response functions, illustrated in Fig. 2.6, to aid in the validation of the finite element model by comparison with experimentally measured frequency response functions from the as-built test structure.

2.6 Validation of Design

2.6.1 Experimental Testing

In order to better understand the behavior of the as-built test structure and validate the original finite element model created in SAP2000, dynamic properties of the empty test structure are determined using experimental modal analysis (EMA). EMA is based on the evaluation of the dynamic response of a structure due to a known excitation force. A swept-sine dynamic force is applied to the structure through the use of an electrodynamic shaker located on the end frame of the cantilever. The acceleration response of the structure is measured by accelerometers that are attached to the steel superstructure at various locations. The input force and the acceleration response are analytically combined to form a frequency response function in the eZ-Analyst data acquisition software [21]. From these response functions, modal properties such as natural frequencies, damping ratios, and mode shapes were estimated using curve-fitting techniques utilizing Vibrant Technology's ME'scopeVES 5.0 [22].

Fig. 2.7 Accelerometer attachment to the armature of the shaker

Ten PCB model 393A03 uniaxial seismic accelerometers are fastened using threaded steel studs at locations along the backspan and cantilever of the steel superstructure. The excitation source for cantilevered test structure is an APS Dynamics, Model 400 electrodynamic shaker. The sinusoidal input force from the shaker is calculated using the acceleration response and mass of the shaker armature. A PCB model 393A03 uniaxial accelerometer was attached to the armature to measure acceleration as shown in Fig. 2.7.

The data acquisition system for this study, an IOTech Wavebook 516E with WBK18 signal conditioning module, is connected to a computer and used in conjunction with eZ-Analyst software to output and collect real-time voltage signals. Amplified output voltages operate the shaker over a frequency range of 1–50 Hz in an 8 s time frame. The sampling rate for data collection is 128 samples/s corresponding to a frequency step of 0.125 Hz over a bandwidth of 50 Hz. The experimental data collection plan consists of collecting a minimum of three individual data sets for each experimental configuration of the empty test structure. Each of the data sets is a linear average of a minimum of three complete cycles of the electrodynamic shaker (24 s of data). The test structure was also loaded with steel weights to simulate an equivalent mass test from 500 to 2,000 lb in 500 lb increments. EMA was used to determine the modal properties associated with each configuration of the test structure and static deflections were measured along the backspan and cantilever.

2.7 Results

The modal parameters of the as-built test structure varied slightly from the analytical modal results of the original finite element model, despite the highest attention to detail and acceptable tolerances during the construction of the structure. The natural frequencies of the test structure determined from EMA were slightly higher than the natural frequencies predicted by the model. Two contributing factors to the inconsistency are the inappropriate modeling of the connections, and the slight imprecision in the cross-sectional properties of the structural steel sections.

The reinforced concrete planks were originally modeled as pin-connected to the tube steel since they bear directly on top of the cantilevered tube steel beams. However, an increase in frequency of the torsional mode of the structure indicates that the planks add stiffness to the second mode of vibration which is a torsional mode of the cantilevered section. The connection was adjusted in the FE model to a fixed connection as most modeling guidance suggests for vibration serviceability. However, the frequency of the torsional mode increased beyond that of the as-built structure. As a result, the plank connection to the cantilevered tube steel beam is modeled as a rotational spring to simulate the torsional behavior of the as-built test structure.

The finite element model was further modified by updating the cross sectional properties of the $5'' \times 4'' \times 3/16''$ tube steel to represent the actual dimensions of the tube steel that was used in the construction the test structure. The changes were

Table 2.1 Comparison of analytically predicted and experimentally measured natural frequencies

Mode	6′ deck, 6′ cantilever		4′ deck, 5′ cantilever		4′ deck, 4′ cantilever	
	FE model (Hz)	Experimental (Hz)	FE model (Hz)	Experimental (Hz)	FE model (Hz)	Experimental (Hz)
1	4.36	4.35	5.05	5.00	6.33	6.25
2	15.8	15.8	16.7	15.4	22.6	19.1
3	28.0	30.5	33.0	32.0	40.8	36.4

slight; resulting in deviations of a few thousandths of an inch from the AISC specified properties. This simple updating of cross sectional properties affected the natural frequency by approximately 0.1 Hz bringing it in line with the experimental results. The updated finite element model is able to satisfactorily represent the dynamic behavior of the structure for a range of support conditions for the empty structure and for each phase of the equivalent mass testing previously described. The FE model is also able to replicate the static deflection associated with the equivalent mass testing.

The natural frequencies identified in the FE model for the first three modes are compared to the experimentally determined natural frequencies in Table 2.1 for three configurations of the adjustable test structure. The comparison is reasonable for the first mode of vibration for all three configurations. The second and third modes are less critical for this study as the effect of human-structure interaction is likely to be more dominant in the first mode of vibration. In addition to the numerical comparison of natural frequencies, the frequency response functions analytically synthesized from the updated finite element model are compared to the experimentally measured frequency response functions. One such comparison is shown in Fig. 2.6. The initial comparison between the synthesized FRF and the experimental FRF is visual. Key features that should align are the location, magnitude, and slope leading to the peaks of the FRF. Further evaluation will be made by comparing the mode shapes of the finite element model to the experimental test data using the modal assurance criterion (MAC). Additional model updating is currently being pursued to further enhance the agreement of higher modes of vibration.

2.8 Summary

The design and construction of a cantilevered test structure has been described as it applied to the experimental investigation of the effects of human-structure interaction and its potential impact on serviceability assessment. The test structure is representative of a cantilevered grandstand with respect to its natural frequency and cantilever construction. This test structure has been specifically designed to allow for the relocation and/or addition of support conditions providing the ability to adjust the natural frequency. The design considerations pertaining to the planned experimental study and the associated design criteria have been presented. A FE model of the test structure has been created and updated. The dynamic properties of the test structure in its empty condition were determined using experimental modal analysis; this data was used in the preliminary validation of this finite element model. The test structure described herein is to be utilized in the experimental program currently underway investigating human-structure interaction.

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