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Vibration Serviceability of Monumental Stairs

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Abstract

Monumental stairs have become a common addition to architectural designs in recent years. Due to their slenderness, complex shapes, and long spans, monumental stairs often cause vibration serviceability problems in architectural structures. This means that when people walk on the stair, vibrations of the structure, and sometimes the transmission of that vibration to other parts of the building, can cause discomfort to the occupants. To prevent the occurrence of such problems, the structural designers should be able to predict the dynamic properties and structural response of monumental stairs under users' loads. This is usually conducted using structural analysis software. Therefore, it is important to create a computer model that can accurately provide the required information. The main research question that is addressed in this paper is 'how monumental stairs should be modeled in a structural analysis software to reliably predict their natural frequencies.' To achieve this goal, the research methodology used in the study consisted of comparing the results of computer modeling and measured field data from two different monumental stairs. The stairs used in this study are made of steel structure. Electrodynamic shakers and accelerometers were used for modal tests. Computer models of the structure were adjusted to provide the best match between the analytical and field measured results. These included the comparison of the predicted and measured natural frequencies and mode shapes. Upon the completion of this research, important parameters for creating a realistic structural model of monumental stairs were identified. The study showed that the stringer stiffness, weight of structure, and inclusion of non-structural elements such as stair cladding are important factors that need to be accurately incorporated into a structural model of a monumental stair to estimate its natural frequencies for vibration serviceability evaluations.

Keywords: Vibration Serviceability, Monumental Stair, Vibration Testing

1. Introduction

Large movements of staircases may result in the annoyance and/or discomfort of the users. In extreme cases, they may also cause safety concerns for the building occupants. In recent years, renowned architects such a Frank Gehry, Zaha Hadid, etc. have designed slender, light and flexible monumental stairs, which have resulted in vibration serviceability issues which required the special attention by structural engineers[1-8].

This paper presents vibration serviceability studies of two monumental stairs located in buildings on the campus of Virginia Tech in Blacksburg, Virginia. The first monumental stair was located in Lavery Hall, which is a new dining hall whose construction completed in 2012. After opening it has had significant vibration serviceability issues. When one stands in line waiting for food, he/she noticeably feels the excessive movements of the floor as people ascend or descend the stair. While the stair is structurally sound, serviceability issues are causing discomfort to users.

The second monumental stair studied was located at the VT Classroom Building, which has been under construction since 2015. This afforded the opportunity to do field testing on a structural system without added finishes. The New Classroom Building's monumental stair spans two stories, unlike the Lavery Hall stair.

In the following sections of this paper a brief background on the vibration serviceability issues related to monumental stairs will be presented. This will be followed by a brief description of each stair, initial computer modeling, modal testing, and model updating of the structural systems to result in the natural frequencies and mode shapes that are close to those from the measurements[9-10].

2. Background

Serviceability is defined in the AISC Specification[11] as "a state in which the function of a building, its appearance, maintainability, durability, and comfort of its occupants are preserved under normal usage." International Building Code (IBC)[12] does not specify guidelines for vibration serviceability. This means that even buildings up to the code and structurally sound may have vibration serviceability issues. Vibration serviceability issues arise out of the response of people and objects to the behavior of structures under load. In most cases, vibration serviceability problems occur in lightweight steel or wood structures. Computer–optimized design of steel structures has resulted in lighter weight, slender, and more efficient structural systems. Light and slender structures, particularly of steel, are strong enough to carry loads, but susceptible to vibrations from everyday use.

Every structure has inherent natural frequencies. A natural frequency is regulated by the structural system's material, geometry and supports. Complex structural systems may vibrate at different frequencies at the same time. Each natural frequency corresponds to a mode shape. A mode shape is the physical deformation a structure takes when vibrating at a specific natural frequency. In general, a structure may have infinite mode shapes, but humans can only excite a few of the lowest of these modes.

Human walking also has a speed or frequency. The frequencies at which people walk up and down stairs range from 1.6 to 4 Hz[13]. When the frequency of an applied force, such as walking, matches the natural frequency of the structure resonance occurs. Resonance results in excessive deformation and vibration of the structure. This is how serviceability issues arise. Structural movement can be controlled by damping, an inherent material and structural property. It is important to note that the speed people are walking does not have to match the frequency of the structure 1 to 1. It can be multiples of each other. Say someone walks at 2 Hz. A mode of the structure at 2 Hz will become excited and result in large movements. A mode of the structure at 4 Hz will also become excited, but at a reduced level of vibrations. A mode at 6 Hz may also become excited but at diminishing amounts that are less noticeable.

To avoid reaching resonance between the structure and people walking we want to raise the natural frequencies of the structure as much as possible. Generally, structures do not have vibration serviceability issues if they have a vertical natural frequency over 8 Hz, and a lateral natural frequency over 4 Hz. Increasing the natural frequency of a structure can be achieved by increasing the stiffness by using more rigid connections, increasing the size of structural elements, or adding structural members/supports.

3. Vibration Studies of the Monumental Stairs

3.1. Lavery Hall monumental stair

3.1.1. description of the structure

Figure 1 shows the monumental stair at Lavery Hall. It connects the ground floor to the second level of the building located in the dining hall area. It is a steel structure with a 4,000 psi concrete composite deck. The guardrail is made of glass. Stair treads are precast concrete bolted to a steel plate, which is welded to the steel stringers.

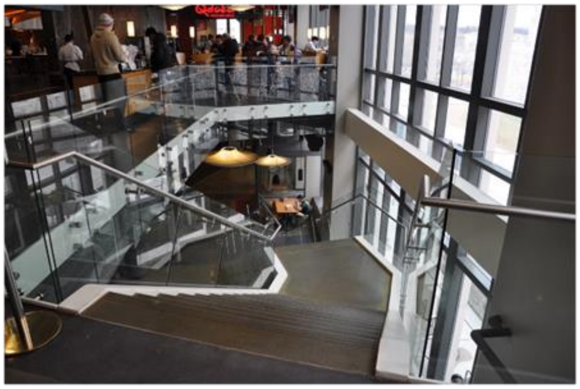


Figure 1. photo of Lavery Hall staircase

3.1.2. *computer modeling*

Using the structural drawing of the stair as shown in Figure 2, a computer model of the staircase and part of the floor was created with SAP2000[14] structural analysis program as seen in Figure 3.

Frame and shell structural elements were used in the model. Property modifiers on the moment of inertia of the beams were used to represent the increase in the beams' stiffness due to the composite action of the floor slabs. The glass guardrail was modeled as a distributed load acting on the stringer, since it is not a part of the structural system. Initially the treads were modeled as steel with a concrete mass added to them to represent the precast element.

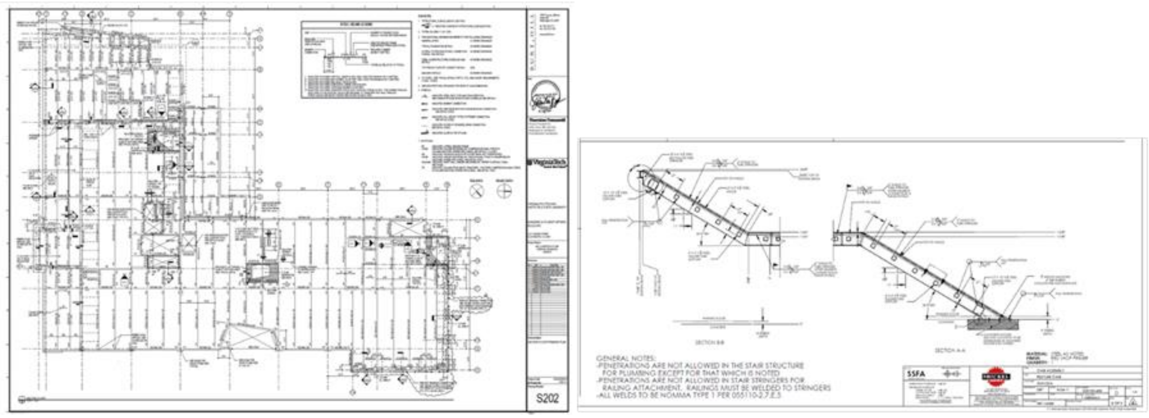


Figure 2. Lavery Hall construction drawings

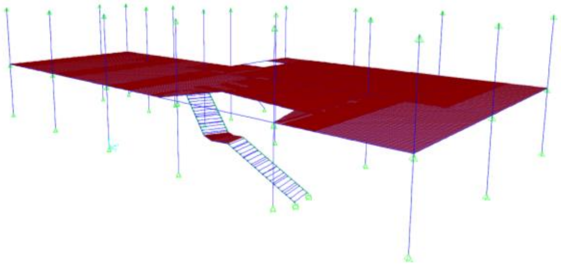


Figure 3. computer model of Lavery Hall stair

3.1.3. modal testing

A modal test of the stair was conducted to estimate its natural frequencies and mode shapes. An electrodynamic shaker that excited the stair within a frequency band, in conjunction with accelerometers which read the acceleration of the structure at many points were used (Figure 4). The acceleration for all of the frequencies are recorded onto the computer and saved for further modal analysis to estimate the natural frequencies, mode shapes, and damping ratios.

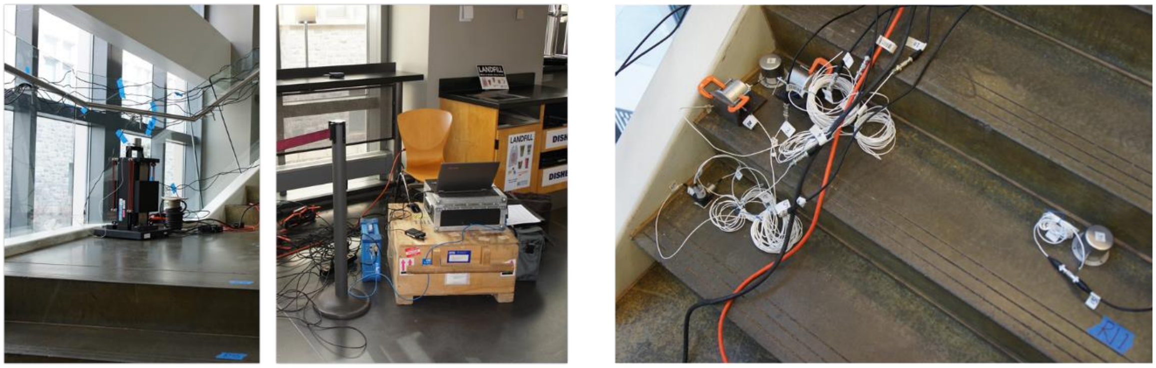


Figure 4. shaker, computer, and accelerometers used to test stair

3.1.4. modal analysis

For the modal analysis of the measurements collecting during the modal tests, the ME'scope VES[15] computer software was used. To facilitate the process of defining the geometric model of the staircase and floor the SAP2000 model was saved as a dxf file and imported into ME'scope. Figure 5 shows the ME'scope model of the structure.

Using the curve-fitting feature of the software, eight modes of the structure were identified along with their associated natural frequencies and damping rations as shown in Figure 6.

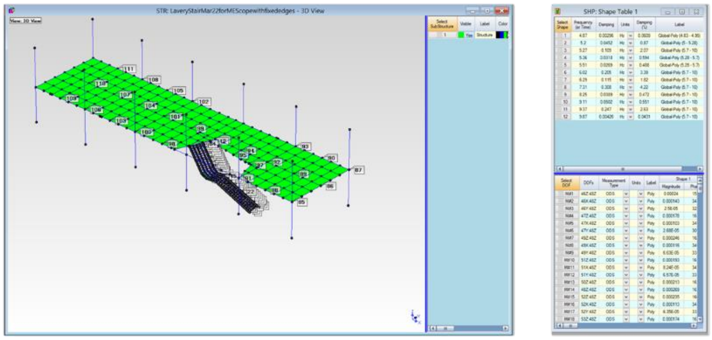
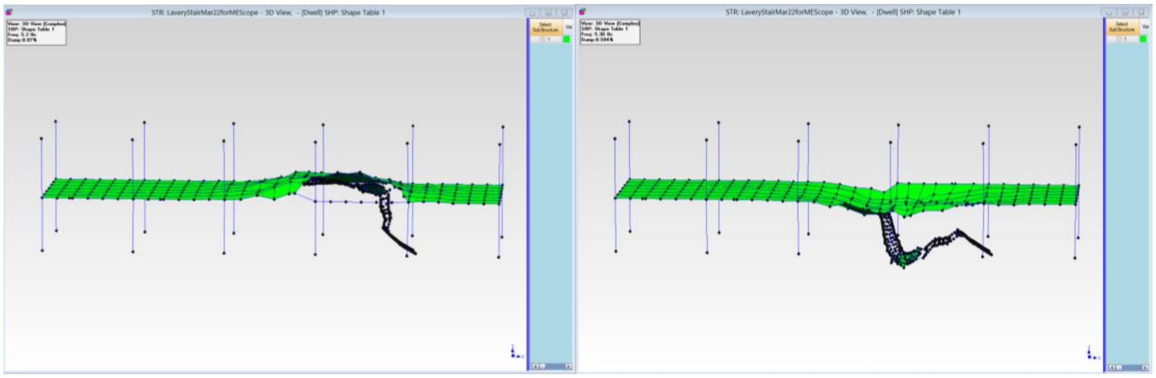
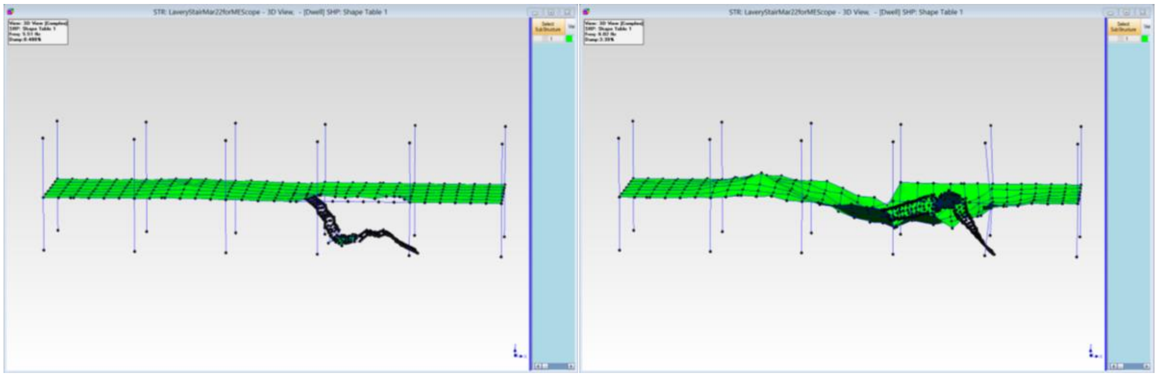


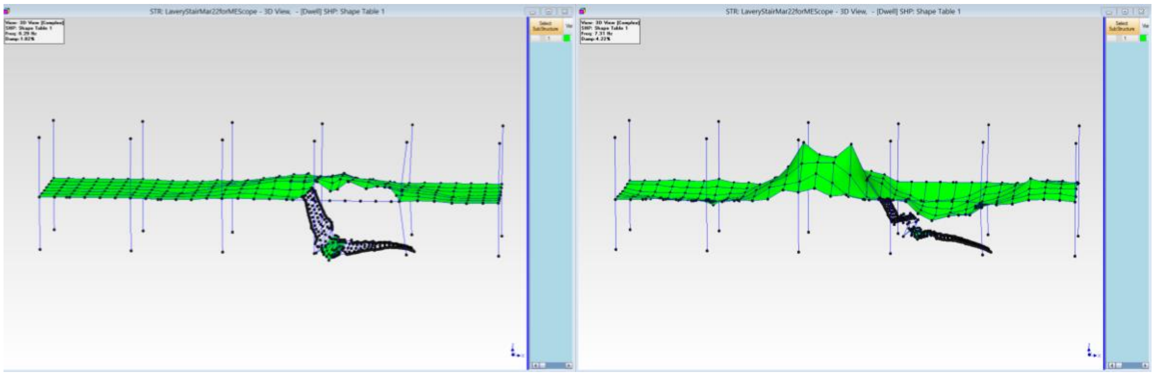
Figure 5. ME'scope model with accelerometer points from modal test and associated shape table



(1) *5.2 Hz, 0.87% damping* (2) *5.36 Hz, 0.6% damping*



(3) *5.51 Hz, 0.5% damping* (4) *6.02 Hz, 3.39% damping*



(5) *6.29 Hz, 1.82% damping* (8) *7.31 Hz, 4.22% damping*

Figure 6. ME'scope animated mode shapes

3.1.5. updating the computer model

After estimating the measured modal properties in ME'scope, the SAP computer model was updated to represent the measured dynamic properties of the structure as close as possible.

One change that was made, was in how to model the stair treads. The precast tread geometry can be seen in Figure 7. It was found that the best results came from modeling the treads as concrete 'beam elements' with 'property adjustments' to account for the steel plate's effect on mass and moment of inertia. Another important modeling aspect was accounting for only the steel being attached to the stringer and not the concrete tread. To do this a 'frame release' at every tread connection to the stringer was used, which helped simulate the real world joint more accurately in the software.

One more update was fixing the bottom of the stair to the ground. This lead to better natural frequencies that matched with the measurements and was more accurate to the construction drawings. The 'fixed' connection was more accurate than the flexible 'pin' connection.

From the mode shape animations it was found that the stair vibrations and floor vibrations were linked. Starting off only modeling 2 floor bays, the model was gradually expanded to 10 bays until the floor stiffness and mass were being portrayed accurate enough to simulate the mode shapes for the stair area. The orthotropic action, having different properties in different directions, of the composite metal deck was considered using the property modifiers on the shell elements used for modeling the floor. The properties were found in AutoCAD and added to the SAP model. Lastly, 30psf of superimposed dead load was assumed for the floor finishes, furniture, and mechanical system equipment present during the modal tests.

Figure 8 shows the mode shapes from the updated SAP2000 computer model.

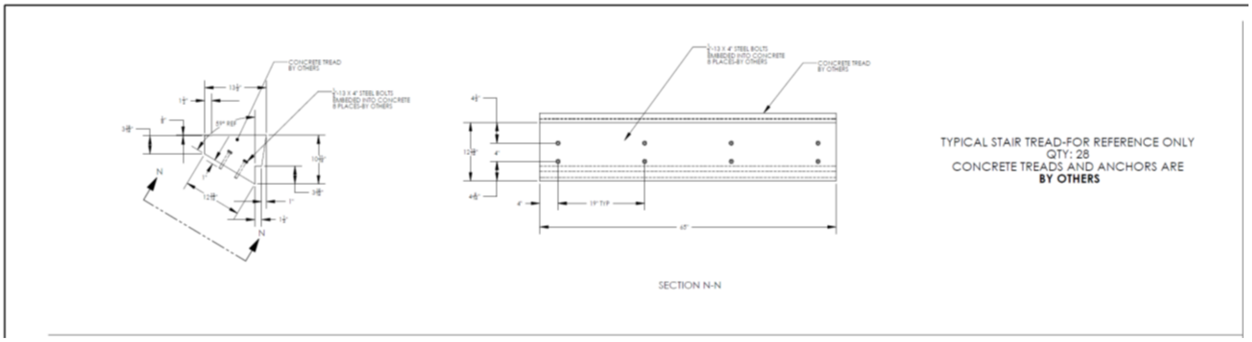
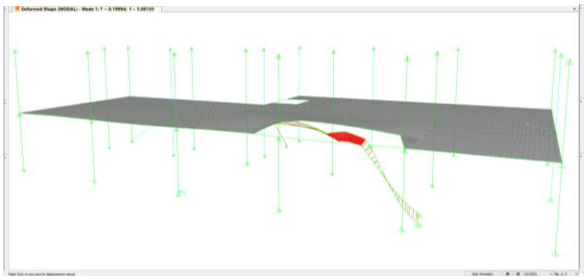
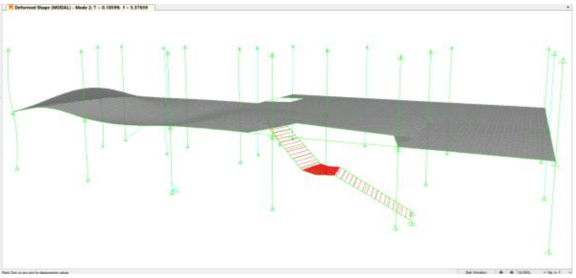


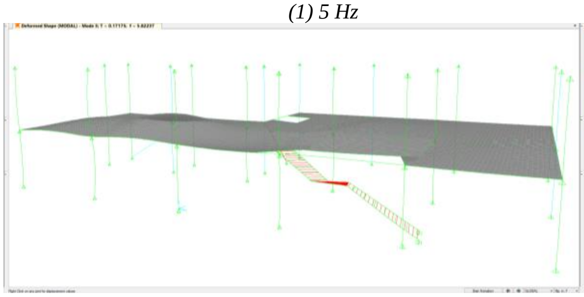
Figure 7. stair tread detail



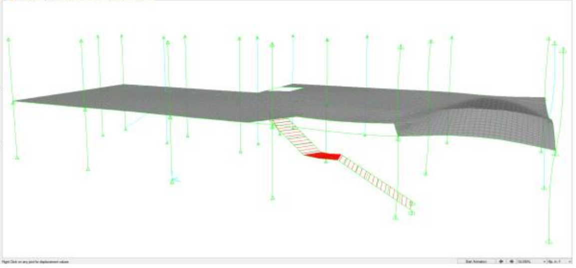
(1) 5 Hz



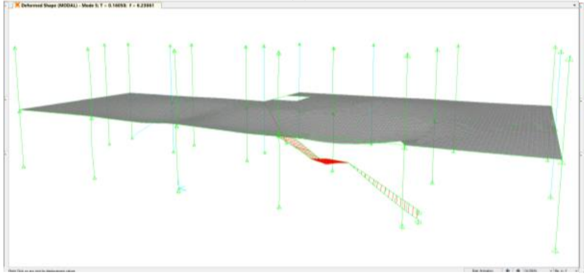
(2) 5.38 Hz



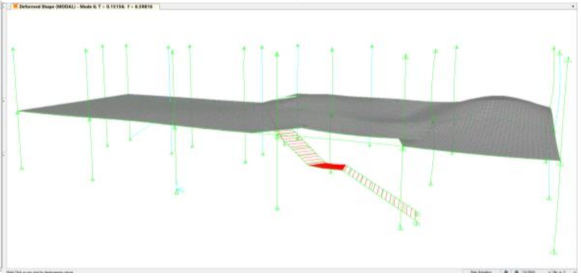
(3) 5.82 Hz



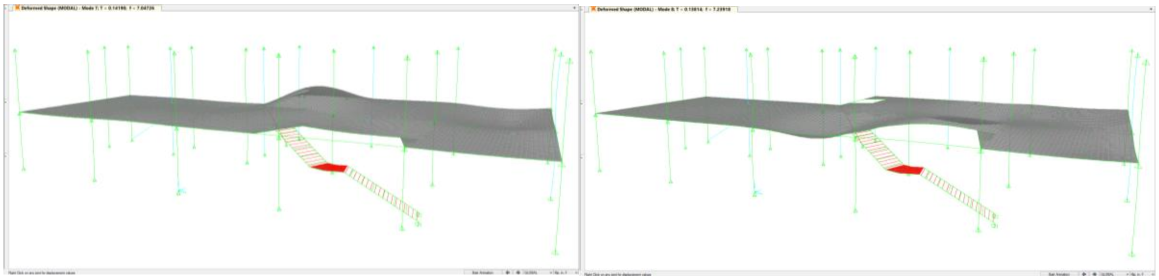
(4) 6.03 Hz



(5) 6.23 Hz



(6) 6.6 Hz



(7) 7.05 Hz *(8) 7.24 Hz*

Figure 8. SAP animated mode shapes

3.1.6. results

The measured and computed natural frequencies based on the updated model are shown in Table 1 along with their percentage differences. As can be noted, the maximum difference is less than 6%. Therefore, the structural analysis model is successful in its accuracy to predict the natural frequencies. Mode shapes were compared visually to check that the computed and measured natural frequencies resembled each other.

Mode	Location	Computed Natural Frequency (f)	Measured Natural Frequency (f)	% Error	Damping %
1	Stair	5	5.2	3.85	0.87
2	Floor bay E / stair	5.38	5.36	0.37	0.6
3	Floor bay D / E / stair	5.82	5.51	5.63	0.5
4	Floor bay A / B / stair	6.03	6.02	0.17	3.39
5	Floor bay B / stair	6.23	6.29	0.95	1.82
6	Untested floor bay	6.6			
7	Untested floor bay	7.05			
8	Floor bay C	7.24	7.31	0.96	4.22

Table 1. Lavery Hall measured and computed natural frequencies

3.1.7. analysis of model updating results

The vibration of the Lavery stair causes the floor around it to vibrate, which is where serviceability issues are most noticeable. So modeling the floor in conjunction with the stair is imperative. Modeling the mass and stiffness of the stair and floor structure is key, since mass and stiffness are variables for natural frequency. When modeling the mass of the stair it is important to be precise by adding the mass of the concrete floor slab, the finish materials like the glass guardrail, and the dead loads of tables and equipment on the floor. When modeling stiffness the stair's stringer connections to the ground and to the treads have the largest impact. Therefore it is important to model joints, floor area, and loads accurately to match the built conditions.

3.2. VT Classroom Building monumental stair

3.1.1. description of the structure

Figure 9 shows the monumental stair at the VT Classroom Building. It connects the ground floor to the third level of the building. It is a steel structure with a concrete composite deck, containing a 6 inch foam EPS layer and concrete topping. Here, the guardrail is part of the structural system. Stair treads are a metal pan filled with concrete, which is field welded to the steel stringers.

Figure 9. photo of VT Classroom staircase

3.1.2. *computer modeling and modal testing/analysis*

Following the process used in the Lavery Hall staircase, the model was created in SAP2000, as shown in Figure 10, based on the structural drawings of the stair as shown in Figure 11. A modal test of the stair was performed in the same manner as previously mentioned to estimate the natural frequencies and mode shapes. In ME'scope 4 natural frequencies were identified.

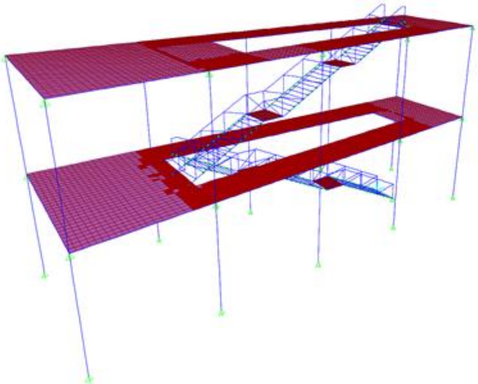


Figure 10. computer model of VT Classroom staircase

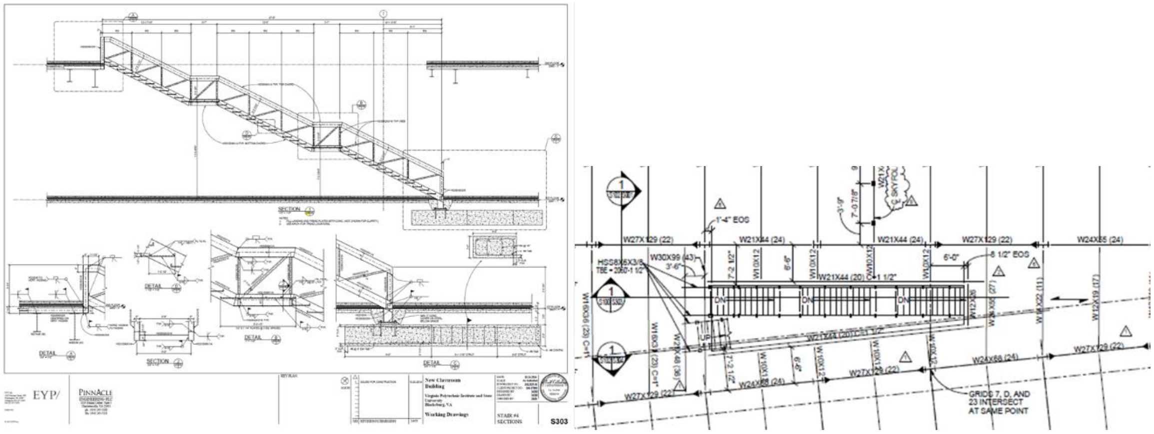
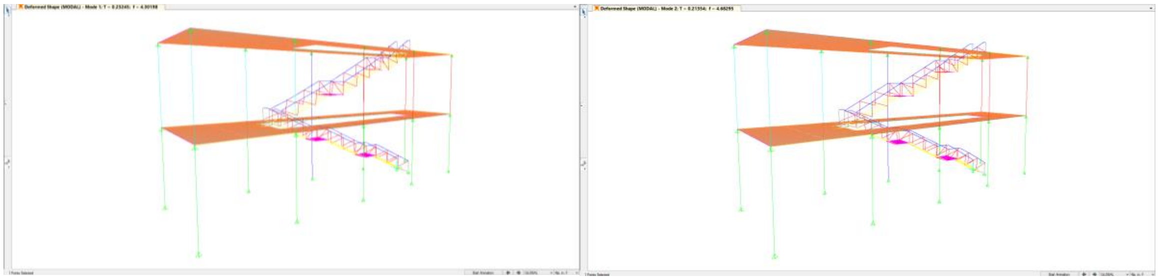


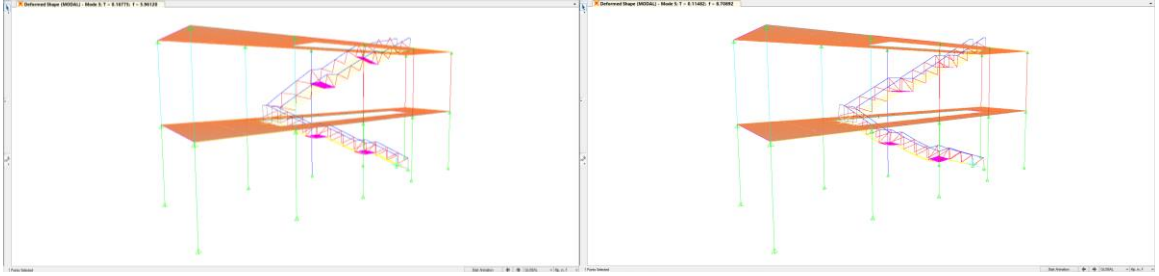
Figure 11. VT Classroom construction drawings

3.1.3. updating the computer model

The SAP computer model was updated to represent the measured dynamic properties of the structure as close as possible (Figure 12). This was done by adding 4 floor bays, modeling the treads as steel beam elements, and adjusting the stringer's connections to the floor. Four modes were found in the SAP computer model to compare with the measured natural frequencies in ME'scope.



(1) 4.3 Hz *(2) 4.68 Hz*



(3) 5.96 Hz *(5) 8.71 Hz*

Figure 12. SAP animated mode shapes

3.1.4. results

The measured and computed natural frequencies based on the updated model are shown in Table 2 along with their percentage differences. The structural analysis model is successful in its accuracy to predict the natural frequencies to a maximum difference of less than 7%. Mode shapes were compared visually to check that the computed and measured natural frequencies resembled each other.

Table 2. VT Classroom measured and computed natural frequencies

Mode	Location	Computed Natural Frequency (f)	Measured Natural Frequency (f)	% Error	Damping %
1	Top lateral	4.3	4.13	4.12	0.314
2	Bottom lateral	4.68	4.38	6.85	0.345
3	Top vertical	5.96	5.75	3.65	0.0208
4	Untested floor	8.3			
5	Bottom vertical	8.71	8.75	0.46	1.65

3.1.5. analysis of model updating results

Since the geometry of the entire structural system is impacting the stiffness and mass, and therefore natural frequency of the stair, it is important to model the stair in conjunction with the floor levels. The joints within the stair, and between the stair and floor impact the natural frequency of the structural system the most. The lateral frequencies of the stair are most impacted by the treads, and their joint to the stringer. The vertical frequencies of the stair are most impacted by the stair's relationship with the floor. The top stair's pin connection has a lower natural frequency at 5.75 Hz than the lower stair's fixed connection to the ground level with a natural frequency of 8.75 Hz.

The study showed that it is possible to accurately predict the natural frequencies of monumental stairs for vibration serviceability issues using a computer analysis software. The tread to stringer connection, proper modeling of stair treads, weight of structure, stiffness of the stair, stair to floor connection, floor structure, and inclusion of non-structural elements are important factors that need to be considered when creating a structural model of a monumental stair to evaluate its vibrations serviceability issues.

4. Acknowledgements

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