SEISMIC RESPONSE OF A 3-STOREY STRUCTURE UNDER VARIABLE ENVIRONMENT CONDITIONS

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Abstract

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One of the major issues with damage detection is the inability to separate multiple factors that contribute to a change in the nominal structure. For example, it is difficult to identify if damage is based on accumulation of snow, change in temperature, or solely based on the excitation. New facilities at the University of Sheffield's Laboratory for Verification and Validation allow for a combined testing scenario. The three main components of the combined testing scenario are changes in environmental temperature, accumulated mass through occupancy or snowfall, and 6-DOF ground excitation. Testing and analysis of this work utilises a server based digital twin operational platform. This platform works as a centralization of both experimental results, validated models, and prediction models. Experimental procedures are performed on a scaled 3-storey structure mounted to a 6-DOF shaking table in a climate controlled environmental chamber. In addition to variable temperatures, mass is added to the structure to represent accumulated snowfall and occupancy. This work demonstrates the results from the experimental testing that was limited due to mechanical issues.

1. Introduction

One of the major causes of catrastophic failue of civil structures is seismic excitations. These vibrations cause two main issues, the first being the effects on the foundation: The excitation changes the soil mechanics, such as rigidity and compactness, that can lead to an unstable base [1-4] . The other main effect is the vibrational loading that is experienced by the structure itself. These can excite the structural resonances causing large deflections that create plastic deformation and damage, which this work will focus on.

To compound the effects of the seismic excitation, a structure will typically experience additional loading that can modify the structural properties. Some commonly experienced loadings are environmental conditions (such as hot/cold temperatures), building occupancy, additional weight due to weather (snow and rain for example), and various surroundings not part of the design such as electrical cables and wildlife. All of these factors contribute to modify the structural properties that can possibly lead to damage or failure.

Since there are multiple factors that can contribute to failure, it is often difficult to isolate the causation of damage. Damage can come from an individual, a superposition, or a nonlinear combination of factors. In order to acurately determine the cause of damage, the individual factors and the combination of these factors need to be tested. This work will focus on two factors, the environmental temperature and added mass (from either occupancy or weather).

2. Experimental Capabilities

To accurately test varied temperatures with design modifications, advanced facilities are required. The University of Sheffield has a specialized testing facility called the Laboratory for Verification and Validation (LVV). This contains environmental chambers with one specifically designed for vibration testing. This chamber can work within a temperature range of -50 C to +50 C. Within this chamber, there is a ground mounted multi-axis shaker table that can exert 3g accelerations with 6 axis control. A photo of these chambers is presented in Figure 1 with the shaker chamber being in the middle.

Figure 1: Environmental Chambers at the LVV

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2.1 Experimental System

The experimental system tested in this work is a scaled 3 storey building. This is constructed using extruded T-slot aluminium that is mounted to the shaker table. The general dimensions of this building are 2.42 m tall with a cross-section of 930x820 mm. A photo of the test system mounted to the shaker table within the environmental chamber is shown in Figure 2.

Figure 2: 3-Storey Building

One aspect of the experimental system is the sensor layout. For these tests, there are two single-axis accelerometers for each pillar on each floor with a total of 24 accelerometers. In addition to these 24, there is also a baseline accelerometer on the shaker table to measure the input and additional sensors on a single pillar at the half floors to identify if there are any local modes in the support pillars experienced for this system in the range of interest. As a validation for this system, a calibrated beam model is generated. This model has an adjusted Young's modulus because the exact heat treatment of the aluminium is unknown, to match the first three bending frequencies that were obtained through some preliminary impact hammer testing. The accuracy of the calibrated model for the first three natural frequencies are within 1.5%.

2.2 Test Schedule

For the results shown in this work, there are two main variable parameters of interest, temperature and added mass. To get an accurate representation of the design space, the testing schedule is based on a quasi-uniform sampling of the variable parameters. For the added mass, four different masses are added for each temperature tested. In these tests, the added masses are 0, 5.72, 11.44, and 18.2 kg. Relative to the mass of

the structure, these correspond to 0%, 4.0%, 8.0%, and 12.7% respectively. The additional masses are connected to the structure via the T-slots at the top floor. Figure 3 shows how the added mass are attached to the structure, particularly for the 11.44 kg added mass tests. These plates all have a universal bolting pattern, but some are different thicknesses. To get an accurate measurement of the added mass, each set of plates are weighed. For the 5.72 kg tests, there are a total of two plates, while 11.44 kg has four plates (as seen in Figure 3) and 18.2 kg has a total of six plates.

Figure 3: Added Masses Attached to System

To discuss the relevance of these masses, a simple scaling is needed to compare the experimental system to a physical structure. This simple scaling is based on the length scaling factor and the percentage of weight. Current work is being performed to fully incorporate the scaling of inertial forces via the Buckingham Pi Theorem [5]. In the experimental system, each storey is 780 mm that is a 5.5x scaling to a typical 4.3 m storey. Using this scaling, the floor has dimensions of 5.12x4.51 m, resulting in an area of 23.1 m^2. To expand this scaling into weight, a typical pre-built house has a density of 244 kg/m^2 for a single floor. This results in a total mass of 16,909 kg. With an average person's weight being 62 kg, to match the 12.7% added mass, there would need to be 35 people within the structure (or 12 per floor). While being crowded, this amount of people is not outrageous especially if there are other objects, such as climate control, being considered. One aspect to note is that the experimental system does not have the same stiffness properties as a real construction due to the difference in materials used. Any conclusions made on the experimental system do not directly reflect any physically constructed building.

With regards to the environmental temperature, the range is designed around typical temperatures in a seismically active area. For this work, the area considered is northern Japan, with particular focus on

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Sapporo and Fukushima. In a typical year, the temperatures can range from -10 to 30 C. To get an accurate spread over this range, 6 different temperatures are tested ranging from -15 to 35 C in increments of 10 C. It is important to note that for each temperature, thermal equilibrium with the chamber is achieved and is measured using a thermocouple. However, mechanical issues disrupted this plan, as explained in Section 3.2.

The last aspect to note is the vibration testing performed on the system. The goal of these tests is to properly characterize the joint response of a loaded structure under various temperatures. To do this, a swept sine excitation is used in the structurally weak lateral direction (left-right denoted as Y in Figure 2). This sweep goes from 3 to 30 Hz at a linear rate of 0.1 Hz/s and an amplitude of 0.8 m/s^2. The low range is chosen based on the abilities of the shaker table, and the upper range is based on characterizing the first three bending modes with the third natural frequency being around 25 Hz according to preliminary impact tests. To ensure robustness and to characterize the experimental errors, each excitation is performed three times for each configuration of temperature and added mass.

2.3 Digital Twin Operational Platform

One novel aspect of this research is the utilization of a server based Digital Twin Operational Platform (DTOP). The concept of digital twins is the amalgamation of physics-based models, experimental data, and data-driven models [6-8]. For this work, the DTOP is used to centralize the parametric beam finite element model and accessing/post-processing the experimental results. The operational platform is the terminology used for the interface via which an analyst interacts with the digital twin. A visualization of the main page of this DTOP is presented in Figure 4. There are two main parts, the analysis selection and a visualization of the system. The interactive 3D visualization of the system is based on CAD models of the construction materials used to describe the geometry. For the analysis selection, there are currently two options, one is to create the beam finite element model using ABAQUS and the second is to access the results from the sweep tests performed for this work. This DTOP is accessible through an internet browser and appears as a webpage.

Figure 4: DTOP Selection Page

The DTOP used in this work is unique in a few aspects. Firstly, and mainly, this is considered a server based DTOP. This means that it is accessible (with the required permissions) to any computer with internet access. This allows for users to access this information from both the lab and office without the need to transfer large amounts of data and simulation version control. One advantage of this is the ability to perform sanity checks while gathering the experimental data, more advanced simulations later, or collaborative work by another researcher at a different location. In addition to the server based nature, this DTOP also has a PostgreSQL database and can schedule finite element simulations using ABAQUS. While the finite element simulations are not used in this work, it is an intriguing aspect of the capability of digital twins and specifically this DTOP.

3. Test Results

Because of the nature of the server based DTOP, each experimental result can be uploaded to the digital twin database almost immediately. Within the database, there are two main results that are stored aside from the testing parameters, like environmental temperature and added mass, and meta-data. These results are the time history and the resultant auto Power-Spectrum Density (PSD). Using these two results, most of the post-processing can be performed. Storing this information in a database within the DTOP allows for a researcher to investigate the results in near real-time to ensure the quality of the results. Having this setup is particularly helpful for the multiple days of testing and the added limitations of social distancing.

3.1 Operational Platform Visualization

The main method of data transfer between the experimental setup and the researchers is through the database embedded within the DTOP. This eliminates the need to transfer the information via physical connections (USB drives) or email. Because of this method of data transfer, the DTOP is specially designed to display the experimental results, perform some simple post-processing (such as natural frequency/damping information), and give the ability to download the database entry to a local drive for other post-processing purposes (such as comparing the temperature effects).

This visualization occurs in two steps, a selection then a visualization. For the selection, a list is populated of all the various test configurations (temperatures and added mass) queried from the database. Once a test is selected, the database entry is queried and displayed on screen. An example of this display is seen in Figure 5 for a case near room temperature and no added mass. In the visualization, there are 5 main sections (as numbered in Figure 5). Section 1 displays the testing meta-data giving the temperature, added mass, and the test name and date. In Section 2, the average scalar post-processing results (natural frequencies and associated damping) are shown. This uses peak picking for the natural frequency and the half-power method for the damping ratio. These are averaged over all the sensors in the excitation direction over the 3 tests per configuration.

Figure 5: Experimental Visualization

Section 3 in Figure 5 plots the PSDs for the excitation direction sensors over the 3 tests on the specified floor. The displayed floor can be changed via the drop-down menu. This can be used to visually identify the floor-to-floor variations in modal importance. Additionally, this shows the three modes of interest between 3 and 30 Hz. Section 4 gives the ability to download the database information (PSD and time history) to a local drive. The final Section 5 shows the variability of the scalar post-processing values. This gives a histogram of the natural frequencies and the associated normal distribution fit to the data. These 5 sections are thought of giving enough information to ensure that the experimental data is valid and provides enough information for more complex simulations.

3.2 Mechanical Issues

While performing these experiments, there was a mechanical issue experienced in the environmental chamber after performing two of the six temperatures. This issue prevented the chamber from reaching a set stable temperature. Because of this issue, only the tests performed at 25C and 35C are available for this paper at the time of the submission deadline. The repair for this issue is scheduled and will occur shortly after the submission deadline. During the presentation of this work, all the results will be reported, but this paper will only contain the two temperatures recorded. This limits the number of conclusions that can be drawn. For example, with only two temperatures, the nonlinearity of the response to temperature cannot be examined.

3.3 Post-Process Results

Because of the issues with the experimental setup that led to only collecting two temperatures, it is difficult to make quantitative conclusions about the temperature effects. However, some remarks can be made on the trend that the added mass has based on temperature. To discuss this, both temperatures will be discussed individually, then some remarks are made about the differences.

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As a first result, the PSDs of varying masses is presented in Figure 6. These results are for three sensors at the same corner for each floor and show the response with various added masses. To aid in the visualization, arrows have been added for each natural frequency to denote how the frequency changes with increasing mass. The first thing to note is that for increasing mass, all the peaks in the PSD decrease in frequency. This follows the common logic given from a single degree of freedom system where the natural frequency is inversely proportional to the mass. However, the magnitude of the peak varies depending on the natural frequency and the location. For a single sensor, take floor 1 for example, the fundamental frequency decreases in magnitude, the second frequency remains nearly constant, and the third frequency increases in magnitude. Both the fundamental and third natural frequencies appear to have nearly linear relationship to the added mass, while the second natural frequency does not show a trend but remains close to the same magnitude.
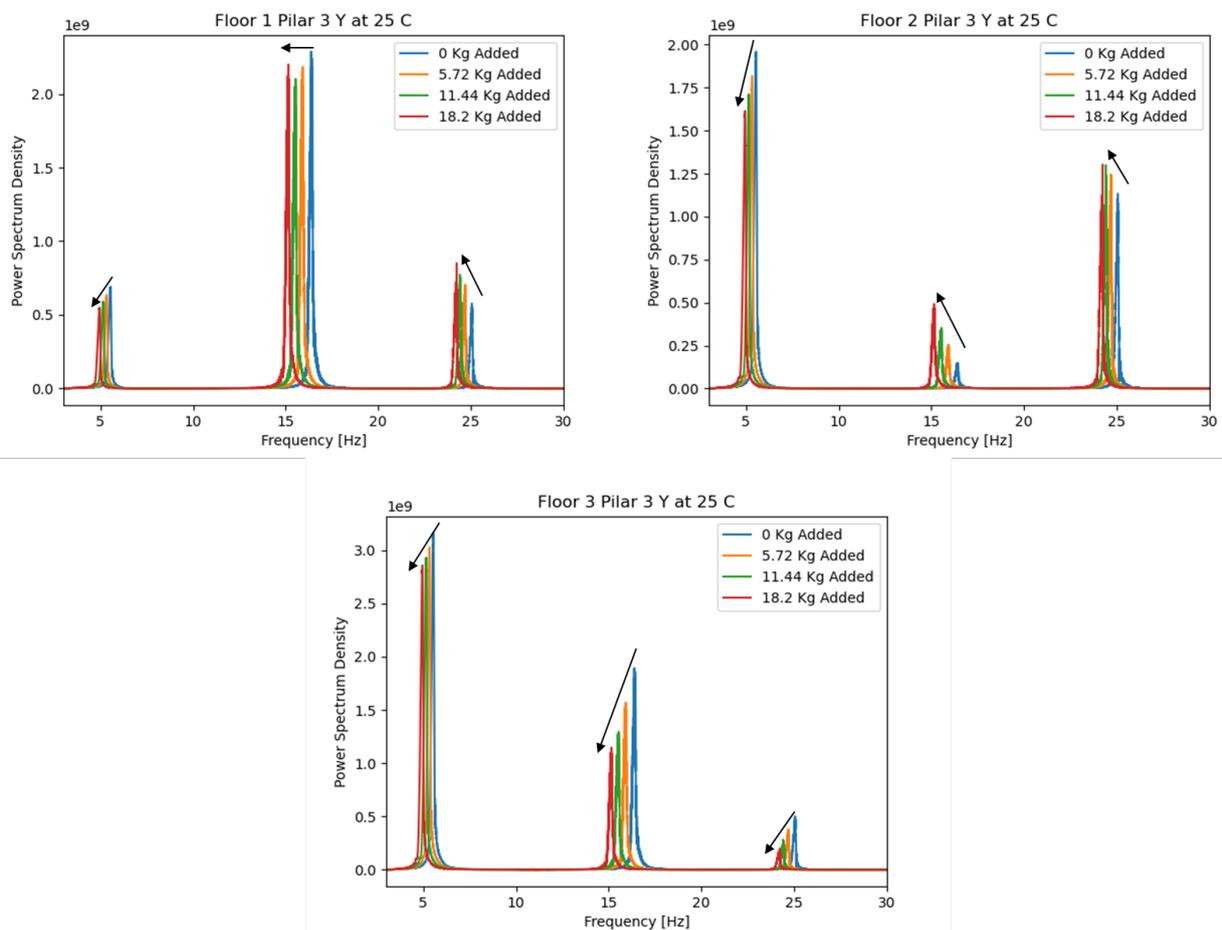

Figure 6: PSD for Varying Added Mass at 25C

One interesting aspect of Figure 6 is the comparison between floors. For the fundamental frequency, all three floors have a decrease in magnitude when there is added mass. However, the third natural frequency does not follow the same trend. For the first and second floor, there is an increase in magnitude while the third floor has a decrease in magnitude. The cause of this is unknown, but initial thoughts are that it is related to the change of the deformation shape. To validate this idea, the modal displacements calculated by the calibrated beam finite element model are used. For the fundamental frequency, the added mass solely just decreases the magnitude for each floor proportionally. Even with the decrease in magnitude, the general shape is nearly

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identical. For the third frequency the proportions change with the increase in mass. With no additional mass, the first and third floor have very similar displacements (2.75 to 2.70 in modal units). However, when additional mass is added, this proportion changes to greatly reduce the magnitude of the third floor (3.2 to 1.5 in modal units). This might be the cause of the observed phenomena, but more investigation is currently being performed since this trend is not experienced for the second floor that has nearly identical displacement but does show an increase is PSD magnitude for the third natural frequency.

In addition to the tests performed near room temperature (25 C), another test at the evaluated temperature of 35 C was performed and shown in Figure 7. One of the most interesting aspect is how the fundamental frequency peak magnitude changes with increasing mass. For the first floor, there is nearly no changes in magnitude. This is in comparison to the other floors that have a slight increase in magnitude.
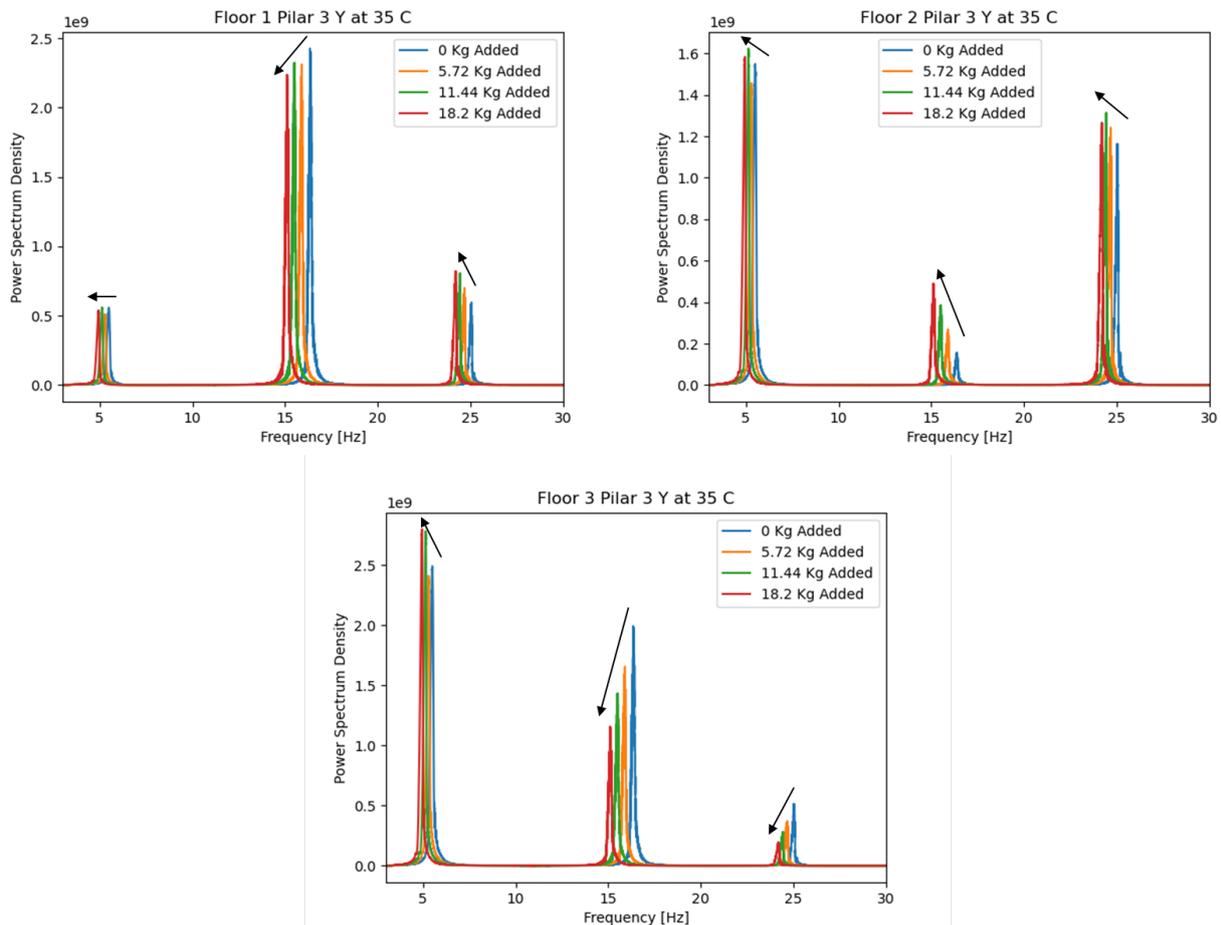

Figure 7: PSD for Varying Added Mass at 35C

There are a few aspects, considering the varied temperature, that remain the same while other aspects vary. One aspect that remains the same, because of the underlying physics, is that the increase in mass always decreases the natural frequencies. The main aspect to note in these results is the trend for the fundamental frequency. At 25 C, the magnitude of the peak universally decreased with the addition of mass, but at 35 C, this trend is different. There is no universality since the first floor has a different trend to the other floors, but also the second and third floor show an increase in magnitude. Conversely, the second and third natural frequencies show the same trend with the increase in temperature. This suggests that the fundamental

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frequency is more sensitive to the temperature, showing some more complex coupling between the environmental temperature and the addition of more mass.

4. Conclusions and Remarks

A common issue with determining damage causation is the coupling (possibly nonlinear) of various factors such as environmental temperature, occupancy, and other weather effects. This work sets out to classify and quantify the coupling between the environmental temperature and the added mass due to occupancy and weather. However, during the testing, there was a mechanical issue with the environmental chamber being used to perform these tests. Because of this failure, only two of the six temperatures were recorded by the time of this submission.

With these two temperature results, there are some interesting aspects to remark upon. The first aspect is the trend of how the increasing mass affects different floors at different temperatures. For the second and third natural frequency, the trend remains the same for both temperatures. However, the fundamental frequency shows different trends for the two temperatures. This suggests that the fundamental frequency has a more complex coupling between the temperature and added mass effects. When repairs are completed on the environmental chamber, the remaining suite of tests will be performed to determine the coupling between temperature and added mass.

Acknowledgements

References

[1] Boulanger, R. W., Curras, C. J., Kutter, B. L., Wilson, D. W., & Abghari, A. (1999). Seismic soil-pile-structure interaction experiments and analyses. *Journal of geotechnical and geoenvironmental engineering*, *125*(9), 750-759.

[2] Mylonakis, G., Gazetas, G. (2000): Seismic soil-structure interaction: beneficial or detrimental?, Journal of Earthquake Engineering, 4:3, 277-301, DOI: 10.1080/13632460009350372

[3] Stewart, J. P., Fenves, G. L., & Seed, R. B. (1999). Seismic soil-structure interaction in buildings. I: Analytical methods. *Journal of Geotechnical and Geoenvironmental Engineering*, *125*(1), 26-37.

[4] Stewart, J. P., Seed, R. B., & Fenves, G. L. (1999). Seismic soil-structure interaction in buildings. II: Empirical findings. *Journal of Geotechnical and Geoenvironmental Engineering*, *125*(1), 38-48.

[5] Curtis, W. D., Logan, J. D., & Parker, W. A. (1982). Dimensional analysis and the pi theorem. *Linear Algebra and its Applications*, *47*, 117-126.

[6] Worden K., Cross E.J., Gardner P., Barthorpe R.J., Wagg D.J. (2020) On Digital Twins, Mirrors and Virtualisations. In: Barthorpe R. (eds) Model Validation and Uncertainty Quantification, Volume 3. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, Cham. https://doi.org/10.1007/978-3-030-12075-7_34

[7] Wagg, D. J., Worden, K., Barthorpe, R. J., and Gardner, P. (May 12, 2020). "Digital Twins: State-of-the-Art and Future Directions for Modeling and Simulation in Engineering Dynamics Applications." ASME. *ASME J. Risk Uncertainty Part B*. September 2020; 6(3): 030901. https://doi.org/10.1115/1.4046739

[8] Worden, K., Cross, E. J., Barthorpe, R. J., Wagg, D. J., and Gardner, P. (May 12, 2020). "On Digital Twins, Mirrors, and Virtualizations: Frameworks for Model Verification and Validation." ASME. *ASME J. Risk Uncertainty Part B*. September 2020; 6(3): 030902. https://doi.org/10.1115/1.4046740