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In-Situ Testing at Wood Innovation and Design Centre: Floor Vibration, Building Vibration, and Sound Insulation Performance

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In-Situ Testing at the Wood Innovation and Design Centre: Floor Vibration, Building Vibration, and Sound Insulation Performance

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Disclosure for Commercial Application: If your mill requires assistance to implement these findings, please contact FPInnovations.

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SUMMARY

In order to address the lack of measured natural frequencies and damping ratios for wood and hybrid wood buildings, and lack of knowledge of vibration performance of innovative CLT floors and sound insulation performance of CLT walls and floors, FPInnovations conducted a series of performance testing at the Wood Innovation Design Centre (WIDC) in Prince George, BC in April 2014, during construction, and in May 2015, after building completion and during its occupation.

The construction of the WIDC has provided a unique opportunity for FPInnovations and its partners to conduct non-destructive testing in order to measure the “as-built” priority aspects of the performance of a mid-rise wood building and its innovative CLT floors and walls.

Ambient vibration testing was conducted on the building to determine its natural frequencies and damping ratios. Hammer impact testing was conducted on the selected innovative CLT floors to determine their fundamental natural frequencies and damping ratios. Static deflection testing was performed on the floors to measure their deflections under 1-kN point static load. Informal subjective evaluations were conducted on the floors to assess the floor vibration performance subjectively. Sound transmission tests were carried out on selected floor and wall assemblies after building completion to assess sound insulation performance.

This report describes the building, tested floor and wall assemblies, test methods, and summarizes the test results. The preliminary performance data provides critical feedback on the design of the building for resisting wind-induced vibration and on the floor vibration controlled design. The data can be further used to validate the calculation methods and tools/models of dynamic analysis.

1 INTRODUCTION AND BACKGROUND

Over the last decade interest in using engineered wood products to construct moderately tall wood buildings has increased, and a number of buildings, with heights ranging from 7 to 14 storeys, have been built worldwide. In Canada, recent efforts to relax the height and area limits for wood construction have amplified the interest within the design and construction communities. There is a need to better understand the performance of taller and larger wood buildings, as well as to assist architects, engineers, code consultants, developers, building owners, and Authorities Having Jurisdiction (AHJ) in assessing solutions unique to developing and constructing tall wood buildings. Therefore, FPInnovations and a multi-disciplinary team of professionals recently developed and published a *Technical Guide for the Design and Construction of Tall Wood Buildings in Canada* (Karacabeyli and Lum 2014). Its publication has paved the road towards designing high-rise wood buildings in Canada.

Chapter 9 of the *Technical Guide* includes general technical information about testing and monitoring of tall wood buildings, by which non-destructive methods are used to measure important aspects of performance and fill priority knowledge gaps for such buildings. Testing and monitoring of initial and in-service performance are needed in order to confirm actual performance and refine design assumptions, and to improve designs to make them more cost-effective.[1] The measurements of building and floor vibration performance, as described by their natural frequencies and damping ratios, were recognized by the reviewers of the *Technical Guide* as important tasks to perform.

1.1 Building Vibration Performance: Natural Frequencies and Damping Ratios

Lateral building vibration induced by wind is mostly a serviceability issue, although it is related to both wind and seismic design. Excessive vibration can cause occupant discomfort and disturb proper operation of sensitive equipment and appliances (e.g., elevators).

If a building meets one of the following conditions, the National Building Code of Canada (NBCC) 2010 (Institute for Research in Construction (IRC) 2010) requires that it be checked during design for vibration serviceability:

- the building height is greater than four times its minimum effective width;

[1] Based on the information provided in Chapter 9 of the *Technical Guide*, a master testing and monitoring table, summarizing the detailed technical information related to building testing and monitoring were created in Chapter 9. This table, called the Tall Wood Demo Projects Monitoring and Measurement Table and Guide, was developed in cooperation with the National Research Council, the Canadian Wood Council, and the building design community. The proposed table was proposed to Forestry Innovation Investment (FII) and proved by FII for funding the work.

- the building height is greater than 120 meters;
- the building is lightweight;
- the building has low frequencies, or
- the building has low damping properties.

Recognizing the lightweight nature of wood and the fact that mid-rise to high-rise wood buildings and hybrid wood buildings are lightweight, the vibration performance of such buildings must be checked during design according to the NBCC requirements.

The NBCC provides acceleration criteria and equations for calculating peak accelerations so that designers can check wind-induced vibration performance (IRC 2010). This design check requires damping as an input to calculate the maximum accelerations. The NBCC also requires the calculation of fundamental natural frequencies, with several equations provided depending on construction type.

Design engineers in Canada approached FPInnovations for assistance in identifying the appropriate design equations for calculating fundamental natural frequencies equations and design values of wood building damping ratios, in order to perform the design check of building vibration performance of tall and large wood and hybrid wood buildings.

Lack of measured natural frequencies and damping ratios for wood and hybrid wood buildings, and for mid- and high-rise buildings in particular, are the first two major concerns for engineers when they endeavor to properly check vibration performance of a designed building. Up to now, very few field tests of wood and hybrid wood buildings have been conducted. Camelo *et al.* (2002) reported the measured natural frequencies and damping ratios of several one-to three-storey wood buildings, and Hu (2012) reported such performance data for two mid-rise wood buildings based on ambient vibration testing. Although the test results have been effectively disseminated in the design community, the current database is too small to make any solid recommendations regarding the selection of appropriate design equations for calculating fundamental natural frequencies or for identifying appropriate design values of damping ratios as they pertain to the design of mid- and high-rise wood and hybrid wood buildings. More data are needed.

1.2 Floor Performance: Fundamental Natural Frequency and 1-kN Static Deflection

Floor vibration performance is closely associated with the comfort levels of the occupants as well as the functions of sensitive equipment in the building (e.g. sprinklers and lights). To control floor vibrations, the designers need methods to determine vibration-controlled spans or the size of floor components according to the required floor spans. So far, the NBCC has provided the design method to determine vibration-controlled spans of lumber joist floor, using 1-kN static deflection as the design parameter (IRC 2005). FPInnovations' research found that the combination of fundamental natural frequency and static point load deflection correlated well with human perception of vibrations for a broad range of wood-framed floors (Hu 2000). Any wood floor vibration can be controlled by controlling the proper combination of the floor's fundamental natural frequency and 1-kN static deflection. FPInnovations developed a design method to determine vibration-controlled spans for CLT slab floors using 1-kN static deflection and fundamental natural frequency as design parameters (Hu and Gagnon 2011). However, there is currently no method available for determining vibration-controlled spans for non-standard or innovative CLT floors.

1.3 Sound Insulation Performance

Sound insulation performance of wall and floor assemblies is another critical aspect which is directly associated with the comfort level of the occupants. Minimum performance levels are specified in the building codes for airborne and impact sound insulation of wall and floor assemblies. These performance levels are generally based on standard tests carried out in laboratory environment that assess the direct sound transmission though the assembly tested. After installation of the assemblies in buildings, the sound insulation performance between adjacent rooms (which is what occupants normally hear) is typically less than that obtained in the laboratory tests (Quirt *et al.* 2006). This is because of the flanking (or construction errors and/or omissions), which accounts for all sound paths other than the direct sound path through the assembly. Requirements for sound insulation performance of wall and floor assemblies measured in the field are also provided in the building codes. The field ratings take into account flanking and correlate better with the level of sound transmission perceived by the occupants. Sound insulation performance of a wall or floor assembly in the field, which includes flanking, cannot be accurately predicted but only measured on-site after commissioning.

2 OBJECTIVES

Given the gaps in our knowledge and ability to measure building and floor vibration performance in mid-rise and tall wood buildings, and the fact that not many mid-rise and tall modern wood buildings have been built as yet, the construction of such a building in Canada presents a valuable opportunity to take measurements and accumulate data. Such is the case with the WIDC, an innovative 6-storey mass timber building built in Prince George, British Columbia. The Centre is a showcase for many wood products and components; among them is a unique and innovative CLT floor assembly.

Supported financially by Forestry Innovation Investment (FII), The Province of British Columbia, Natural Resources Canada, and otherwise by the designers, the engineers, and the contractor, on April 15–16, 2014, FPInnovations conducted building performance tests on the WDIC while the building was still under construction, to determine the natural frequencies and damping ratios of the building, and floor vibration tests on its selected innovative CLT floors to determine the floor natural frequencies, and to measure the stiffness of the floors as defined by the static deflections of the floors under 1-kN static load.

A second series of tests carried out on May 12-13, 2015 after the building was completed and occupied, focused on building vibration tests to determine the natural frequencies and damping ratios of the building after its completion and with occupants, and sound transmission tests.

The overall objectives of the vibration performance tests were to experimentally determine the dynamic properties, e.g., natural frequencies (periods) and damping ratios of the WIDC through ambient vibration testing of:

- the bare structure,
- the finished building upon completion of the construction, and
- the finished building in the 5th year.

The objective of the sound transmission tests was to determine the airborne sound insulation performance of selected wall assemblies and the impact sound insulation performance of selected floor assemblies.

The results of the performance tests will help validate calculation methods and tools/models of dynamic analyses, and help in the development of design values for damping ratios as inputs in the dynamic analyses of wood and hybrid wood buildings, with the eventual aim of improving designs in terms of wind and seismic issues. The results will also provide valuable feedback to the designers about the floor and building vibration performance. The information on floor stiffness will be useful for verifying the floor design and the method or numerical model used by the designers to determine the CLT panel thickness. The information on sound insulation of floors and walls will be useful to designers and builders to ensure not only that the design meets the minimum code requirements but also occupants' satisfaction. This in turn will improve our knowledge of the vibration and sound insulation behavior of such innovative CLT floors and walls as those in the WIDC and reinforce the designers' confidence in their design and in the method or model used for the floor and wall design. Such knowledge and understanding will be shared in the design community and will help in the development of vibration-controlled design methods and calculation models for innovative massive wood slab floors.

3 TECHNICAL TEAM

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Michael Green Architecture (Architectural Design):

Michael Green	Architect
Mingyuk Chen	Architect

Equilibrium Consulting (Structural Design):

Eric Karsh	Structural Engineer
Daniel Thomi	Structural Engineer

4 TESTING DURING BUILDING CONSTRUCTION

4.1 Site Description

4.1.1 Building

The WIDC is located in the city of Prince George in north-central British Columbia. At 6-storey and with its height being 29.5 meters, the WIDC building is the tallest modern wood building built to date in Canada. The Centre is showcasing the applications and capacities of many wood products and components. These include an innovative CLT floor assembly, a CLT elevator shaft, CLT staircases, laminated veneer lumber and glulam columns, an innovative mass timber roof, parallel strand lumber transfer beams, and structurally insulated panels in the exterior walls.

4.1.2 Floor Assembly

The CLT floors in the WIDC are very innovative. They are built with two layers of staggered CLT panels, thus creating gaps between the panels in each layer. The uppermost layer consists of 3-ply CLT panels. The bottom layer consists of 5-ply or 7-ply CLT panels (Figure 1). Each top CLT panel is connected to the two CLT panels below with self-tapping screws and HSK shear connectors, which are perforated steel plates glued into sawcuts over 2/3 of the joint length. The gaps between the top panels are covered on the top by plywood panels. The floors are supported on CLT walls, glulam beams, and LVL columns.

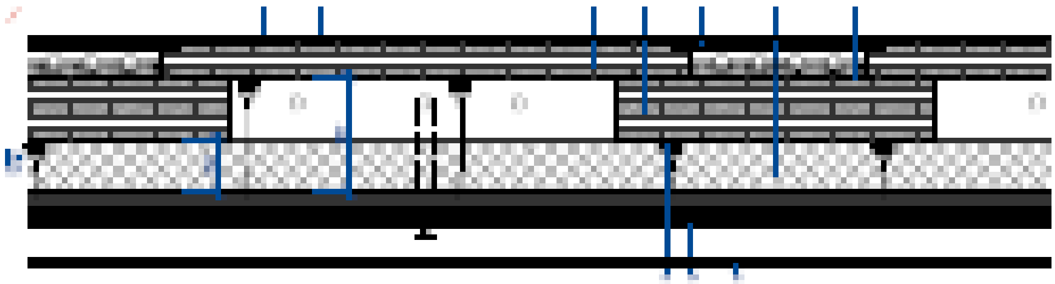

Figure 1 – Cross-section of the innovative CLT floor design in the WIDC. The floors are constructed of staggered 3-ply and 5-ply CLT panels. (Drawing courtesy of Michael Green Architecture)

4.1.3 Status of Construction during Testing

The vibration tests at the WIDC were conducted on April 15 and 16, 2014, at which time the building was under construction but the entire structural frame was erected. The scaffolds were around the building (Figure 2). The building was enclosed by the curtain walls and the roof, but no siding or other exterior finishing was yet installed. The partitions were being installed on the floors on the ground level, and on levels 1 and 2, and some gypsum boards, acoustic hangers, metal channels, and sound absorption materials were being installed under the CLT floors on levels 2 and 3 (Figures 3 and 4). The floors on levels 4 to 6 were open, without any partitions or ceilings yet installed, but some construction materials were presented.

Figure 2 – The WIDC building was surrounded by scaffolding during testing.


Figure 3 – Examples of the construction status of the CLT floors on level 2, with partitions.


Figure 4 – Examples of the construction status of the CLT floors on level 3, where some gypsum boards, acoustic hangers, and sound absorption materials were installed.

4.2 Methods: Vibration Performance Testing

There is no established design method for determining the appropriate vibration-controlled spans for such innovative CLT floors as those in the WIDC, and we do not have any knowledge of the vibration behaviour of such floors where the stiffness is not uniform throughout. Therefore testing is useful according to draft ISO standard method for timber floor vibration (Hu and Chui 2013).

4.2.1 Selection of the Floor Test Sections

FPInnovations conferred with Equilibrium Consulting Inc. regarding the selection of typical floors for the vibration performance tests. Equilibrium Consulting Inc. recommended that the floors on levels 3 to 6 would be the most relevant. There are two typical types of floor systems: 1) floors have exterior single spans, 5.7-m grid B to C and E to F; 2) floors have interior double spans, 6.0-m grids C to E. (See the grid numbers on the floor plan of level 6 in Figure 5). Equilibrium Consulting Inc. also recommended that other conditions should be measured if we have time, especially the penthouse floor, which is wood-concrete composite floor.

When the floor construction status was inspected on April 15, 2014, just prior to commencing the floor vibration test, it was found that the CLT floors on levels 4 to 6 were the base structure floors without partitions and dropped ceilings. But, most of the floor space was loaded with various construction materials (Figure 6). It was also found that the penthouse floor was too full to access for the floor vibration tests and too stiff to vibrate. The floor was very solid and did not move at all when heels were dropped on the floor. FPInnovations' current test equipment is not sensitive enough to detect the vibration signals of such stiff floor. Therefore, the penthouse floor was excluded from our floor testing list.

Eventually, we found some sections of the CLT floors in level 6 which were less loaded, and had more open space than on the other levels. Therefore, two floor sections were selected on level 6 for inclusion in the vibration testing: test section L6F1 and test section L6F2 (Figure 5).

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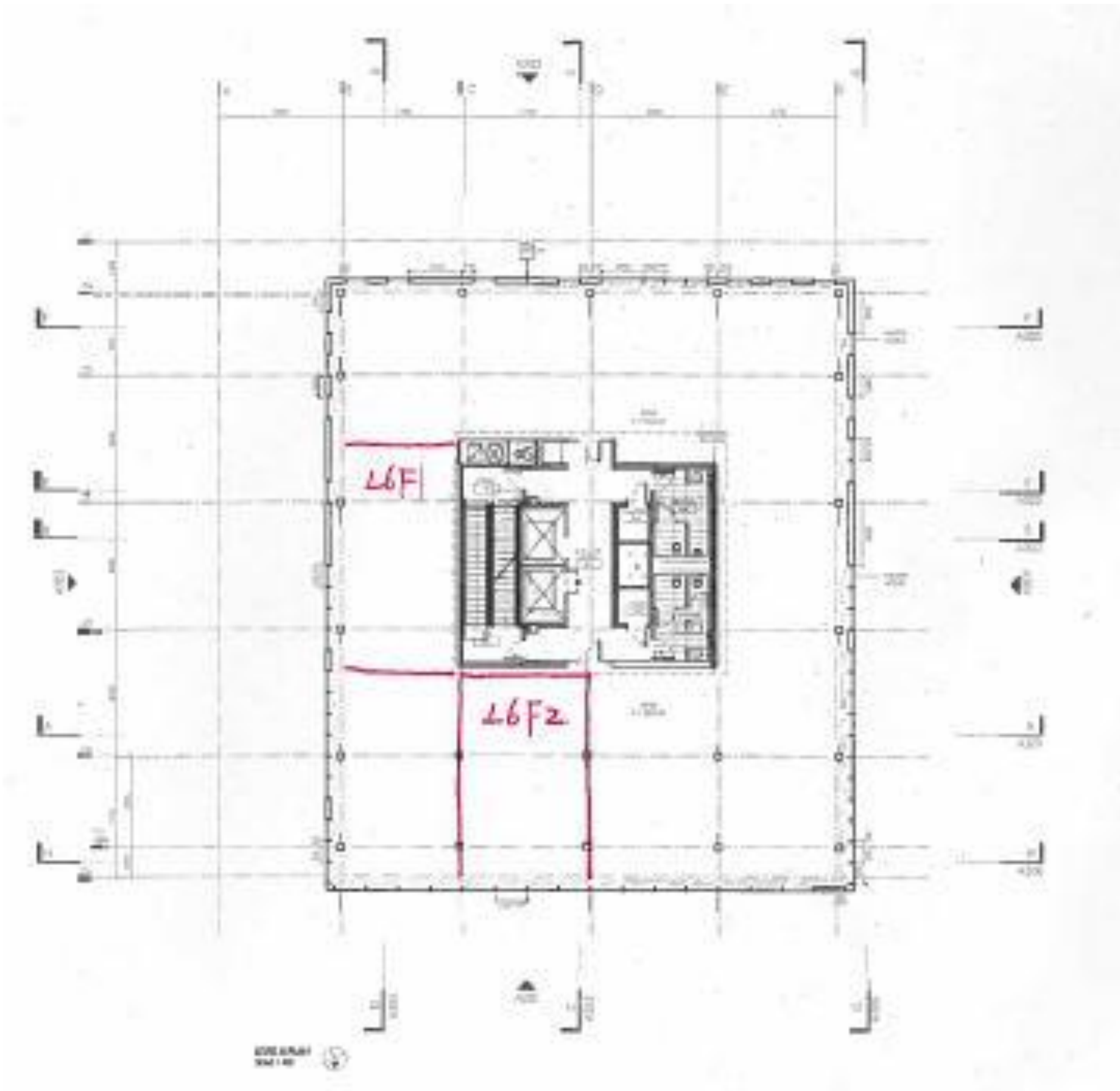

Figure 5 – Floor plan of level 6, showing the two test sections, L6F1 and L6F2. (Drawing courtesy of Michael Green Architecture)

Figure 6 – On levels 4 to 6, the CLT base floor was loaded with some construction materials.

4.2.2 Description of the Floor Test Sections

As indicated in the floor plan (Figure 5), test section L6F1 comprised the center portion of the entire CLT single span floor of 5.7 m. The tested portion of the floor included five 3-ply CLT panels of 1.45 m wide and 5 gaps of 0.5 m between two CLT panels. This portion of the floor was loaded with only a package of glass, which was located close to the end of the floor where the elevator walls were located (see Figure 7).

As indicated in the floor plan in Figure 5, section L6F2 comprised the half span of the double equal continuous span floor of 12 m. The edges of the floor were bounded by the curtain wall and the CLT wall of the elevator. The floor was empty and had no load on it at all. Figure 8 shows the condition of section L6F2. This section included five 3-ply CLT panels and six gaps as counted from the edge at the curtain wall to the edge at the elevator wall.

Figure 7 – Condition of test section L6F1.

Figure 8 – Condition of section L6F2.

4.2.3 Ambient Vibration Test to Determine Natural Frequencies and Damping Ratios of the Building without Finish

Ambient vibration testing uses natural excitations, such as wind, heavy traffic, etc., as means to induce vibrations in the structure. From the vibration signals, the natural frequencies, damping ratios and mode shapes of the structure are extracted. This test is simple, easy to conduct, and reliable. Therefore, ambient vibration tests have been widely used to determine the natural frequencies and damping ratios of heavy structures, such as steel–concrete buildings, towers, bridges, etc., as related to wind and seismic designs.

Ambient vibration testing has also been used successfully to determine the natural frequencies and damping ratios of wood frame buildings (Camelo *et al.* 2002; Kang 2009; Van de Lindt *et al.* 2010). Therefore, ambient vibration testing was conducted on the WIDC during construction on April 15–16, 2014 to determine the building natural frequencies and damping ratios.

The system used to conduct the ambient vibration testing at the WIDC consisted of a four-channel LMS data acquisition device, an eight-channel LMS data acquisition device, eight accelerometers of sensitivity around 500 mv/g, and LMS operational modal analysis software loaded on a laptop computer (Figure 9). The accelerometers had an operating range of 0.2 to 1000 Hz.

Figure 9 – At left, data acquisition devices for ambient vibration testing: master on top and slave on the bottom.

The four-channel LMS data acquisition device was used as the master device (Figure 9). It was located on level 5 and was connected to the computer equipped with the software for acquiring the signals and for post processing of the signals to obtain the natural frequencies, mode shapes, and damping ratios. The eight-channel LMS data acquisition device was used as the slave device (Figure 9). It was connected to the master device, but it was roving from one floor to other. Therefore, the two devices together formed a 12-channel data acquisition system. The master and the slave data acquisition devices and the laptop computer formed the working station.

Two accelerometers were fixed horizontally on the surface of the corner of level 5 floor through a fixture (Figure 10). The axis of one accelerometer was oriented along the long axis (y axis) of the building, while the axis of the other accelerometer was placed along the direction perpendicular to the long axis of the building (x axis). The x and y axis was indicated in the floor plane, see Figure 11. These two accelerometers were used as references and were connected to the master LMS data acquisition device. The reference accelerometers were placed on the floor of level 5 to avoid the node of the second cantilever mode of the building along its height because this node was most likely positioned close to the floor of level 6. Figure 11 describes the definitions of the x and y axes, and the locations of the reference accelerometers, A1 and A2. This arrangement allows the measurement of the signals for the horizontal vibrations of the building in the x and y axes. During the ambient vibration test, these two accelerometers were fixed on the floor at the same location on level 5.

Figure 10 – Reference accelerometers in position on level 5 floor.

The other six accelerometers, numbered A3 to A8 (Figure 11), were successively moved (roved) from the floor on level 2 to the floor on level 6 to measure the building's lateral vibrations at each level. They were placed along the symmetric axis of the building plane in the x and y directions at three different locations on the floor of each level, i.e., one in the edge near the outer perimeter of the floor, one in the other edge near the outer perimeter of the floor, and one in the centre of the entire floor (Figures 11 and 12). At each location, two accelerometers were placed in the same way as the two reference accelerometers (Figure 11). Such a setup allows the identification of the two translations and the torsion modes in the building plane, and of the second cantilever mode of the building along its height. These six roving accelerometers were connected to the slave LMS data acquisition device, therefore the slave device was also roving from the floor on level 2 to the floor on level 6. The duration of data acquisition time window was 2 minutes. LMS operational modal analysis software was used to extract the vibration modes, and the associated natural frequencies and damping ratios, from the signals measured by the roving accelerometers at each level along with the signals measured by the reference accelerometers for the building.

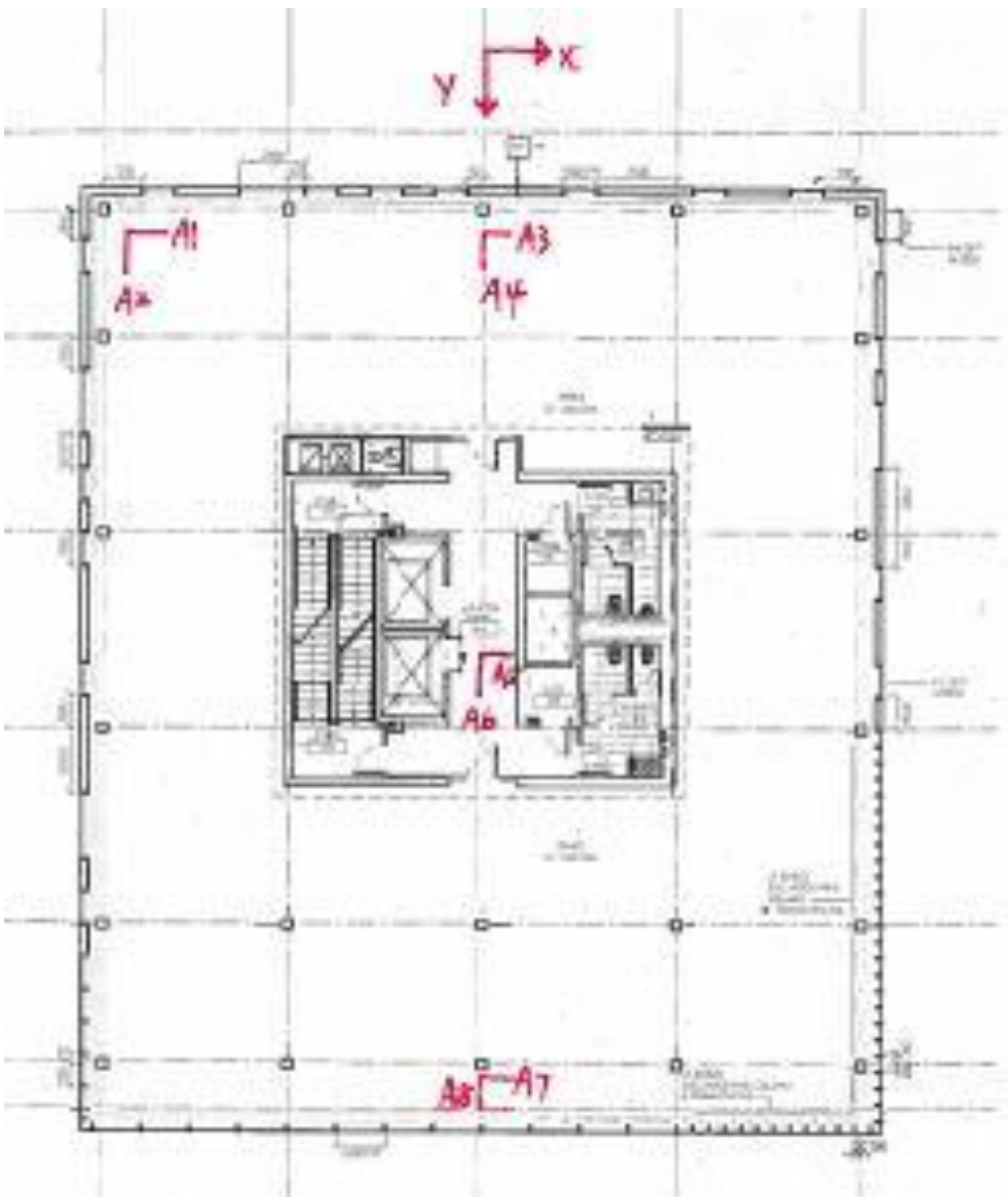

Figure 11 – Locations of the reference and roving accelerometers (A1 to A8) on level 5 floor. (Drawing courtesy of Michael Green Architecture)

Figure 12 – Roving accelerometer setup. Left: Two roving accelerometers, A3 and A4, were positioned at the floor edge near the curtain wall. Right: Two roving accelerometers, A5 and A6, were positioned at the floor centre.

4.2.4 Hammer Impact Test to Determine Floor Fundamental Natural Frequencies

The classical impact-response test, which is also called the modal test, was conducted to determine the natural frequencies, modal damping ratios, and vibration modes of floor sections L6F1 and L6F2 on level 6. Modal testing followed a standard procedure specified in the draft ISO standard proposed by Hu and Chui (2013). Hammer excitation was selected because of its simplicity and reliability.

The hammer impact was applied at the top of the floor by a person sitting on a supported beam such that the tester's weight was not added to the floor. The hammer impact was located on the panel next to the center panel, and was offset from the mid-span of the panel of the test floor areas. At such a location, it was unlikely that a nodal point of the first three modes would occur. The floor acceleration was measured on each panel of the five top CLT panels at the middle span of the test floor areas. Figure 13 shows the typical modal test setup and the locations for the hammer and accelerometers in test sections L6F1 and L6F2.

The force and acceleration signals were recorded by the same LMS master and slave data acquisition devices as those used for ambient vibration testing. Five accelerometers were used for the modal tests. The accelerometers were the same as those used for the ambient vibration testing. The 2.5-kg Kistler model no. 9278A instrumented hammer was used for the tests. The load cell in the hammer has a sensitivity of 0.23 mv/N. The soft tip was used for the hammer so that the impact force would have a long duration and the impact force energy would be concentrated in the low frequency range of 2 to 50 Hz. Such an impact force would excite the fundamental natural frequency of such massive timber slab floors, for which the fundamental natural frequency would be expected to be around 10 Hz. The signals were post-processed to determine the natural frequencies, modal damping ratios, and mode shapes using LMS impact–response modal analysis software.

Figure 13 – Hammer impact tests, showing the tester sitting on a supported beam, the hammer, and the accelerometers. Left: test section L6F1, the single-span floor. Right: test section L6F2, the double-span continuous floor.

4.2.5 1-kN Static Deflection Test to Determine Floor Stiffness

1-kN static tests were conducted on sections L6F1 and L6F2 to determine the maximum static deflections of the floors under a 1-kN concentrated static load and to determine deflection profiles across the floor widths. Knowing the deflection profiles was especially important because the stiffness in the across-floor width direction is highly un-uniform of these innovative CLT floors and difficult to estimate. The 1-kN static deflection is a measure of the stiffness of the floor.

The basic elements needed to measure static deflection under a concentrated load are: 1) a stable reference from which to measure floor movement, 2) an accurate and sensitive deflection-measuring device, and 3) a mobile loading system. In this study, a supported beam was used as the reference. An electronic gauge having a resolution of 0.001 mm was fixed to the reference beam and used as the deflection-measuring device (Figure 14). In order to measure the static deflection of the floor centre, the tip of the deflection gage was attached to the top of the middle point of the centre joint between the top 3-ply and bottom 5-ply CLT panel. The concentrated static load was applied by a person standing still over each centre of the joints that are located between the top and bottom CLT panels (Figure 14), from one side of the floor to the other in turn, while recording the measurement at the gauge location (Figure 14).

The deflection profiles of the floors were generated from the complete set of measurements. Three measurements were taken at each loading location to ensure that stable results were obtained. The average of three sets of the deflection profiles were used to plot the deflection profile of the test floor under the person's weight. The deflection measurements were normalized to a 1-kN load.

Figure 14 – 1-kN static deflection tests showing the reference beam, the deflection gauge, and the tester applying his weight on the floor. Left: Test section L6F1, the single-span floor. Right: Test section L6F2, the double-span continuous floor.

4.2.6 Informal Subjective Evaluation

An informal subjective evaluation was conducted by the FPInnovations testing team, and some visitors on April 16, 2014. One testing team member, the evaluator, stood in the center of the floor area, and gauged the floor movement as the other people walked on the floor.

4.3 Results

4.3.1 Building Vibration Performance

Table 1 provides the natural frequencies, damping ratios, and the vibration modes of the floor of the WIDC, as tested on April 15 and 16, 2014 while the building was under construction. The vibration modes in the floor plane were associated with the first cantilever mode of the building along its height. Figure 15 demonstrates the time history signal of the acceleration response of the building along the x-direction to ambient excitation including wind, interior and exterior traffic, and the activities of the construction workers. Figure 16 plots a typical cross-power function. From the cross-power functions, the natural frequencies, the modal damping ratios associated with the natural frequencies and vibration modes, and the vibration mode of the floor plan were extracted.

One member of the construction team, who was responsible for checking the straightness of the columns during construction, reported to us that when he used a laser beam to check the columns on level 5 a few days before our testing, he found that the vibration displacement of the tops of the columns reached 10 mm (3/8 of an inch) due to ambient excitation. He also noticed that when the laser beam was pointed on the roof it “danced” like waves in the ocean due to the ambient excitation. He felt that the building vibration was noticeable, and that it was not the same as that in high-rise concrete buildings in which the construction team normally work. What this member of the construction team observed is normal because it is the natural responses of light weight buildings to ambient excitations as long as the vibration responses do not affect the occupants’ comfort.

Table 1 – Summary of the first three natural frequencies, damping ratios, and vibration modes of the building

Natural frequency (Hz)	Modal damping ratio (%)	Vibration mode of floor plane
1.1	3	Translation vibration in the x-direction
1.5	2	Translation vibration in the y-direction
3.4	4	Torsion

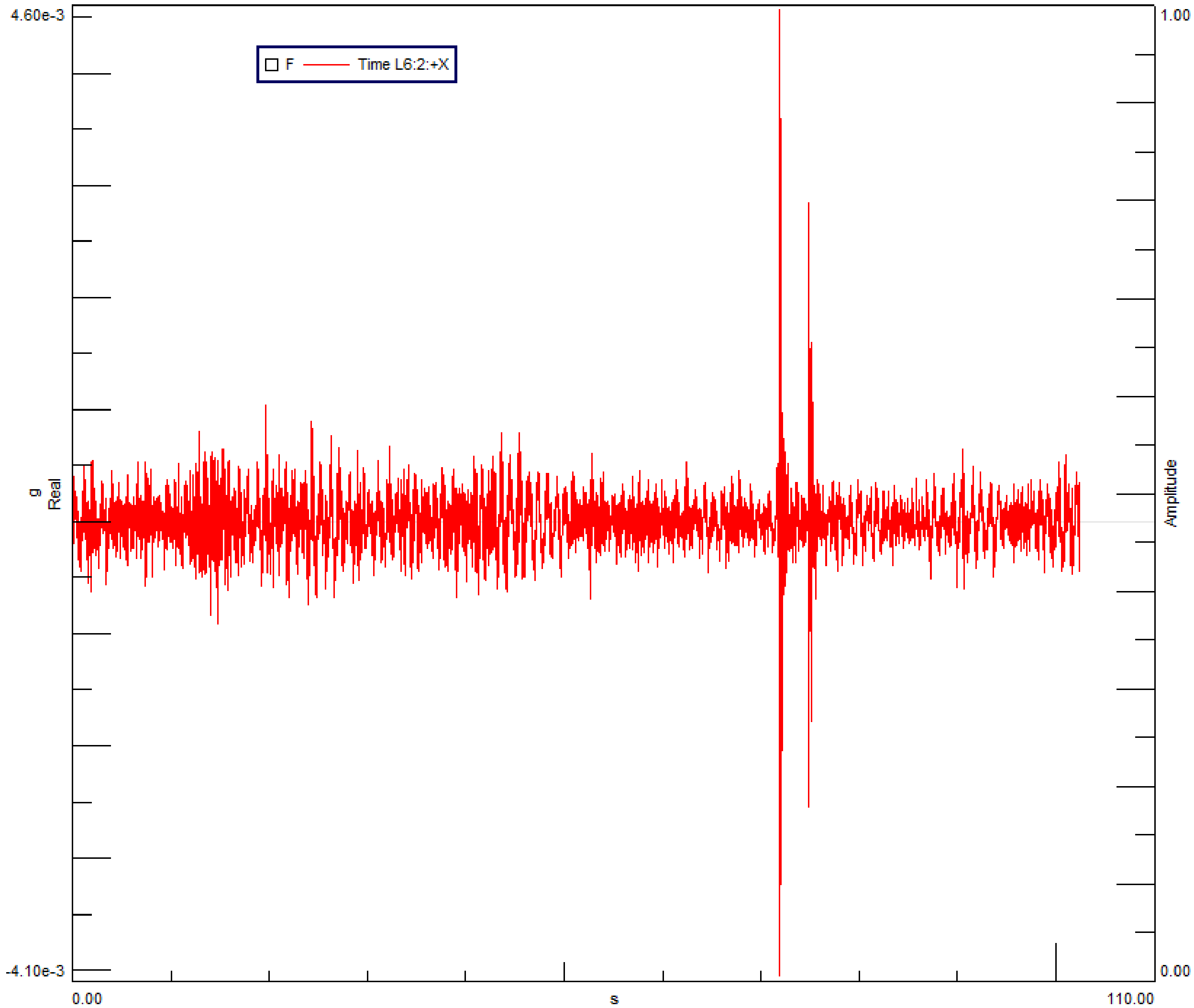

Figure 15 – A typical time history of acceleration response of the building translate to ambient excitation: edge of level 6 in the x-direction.

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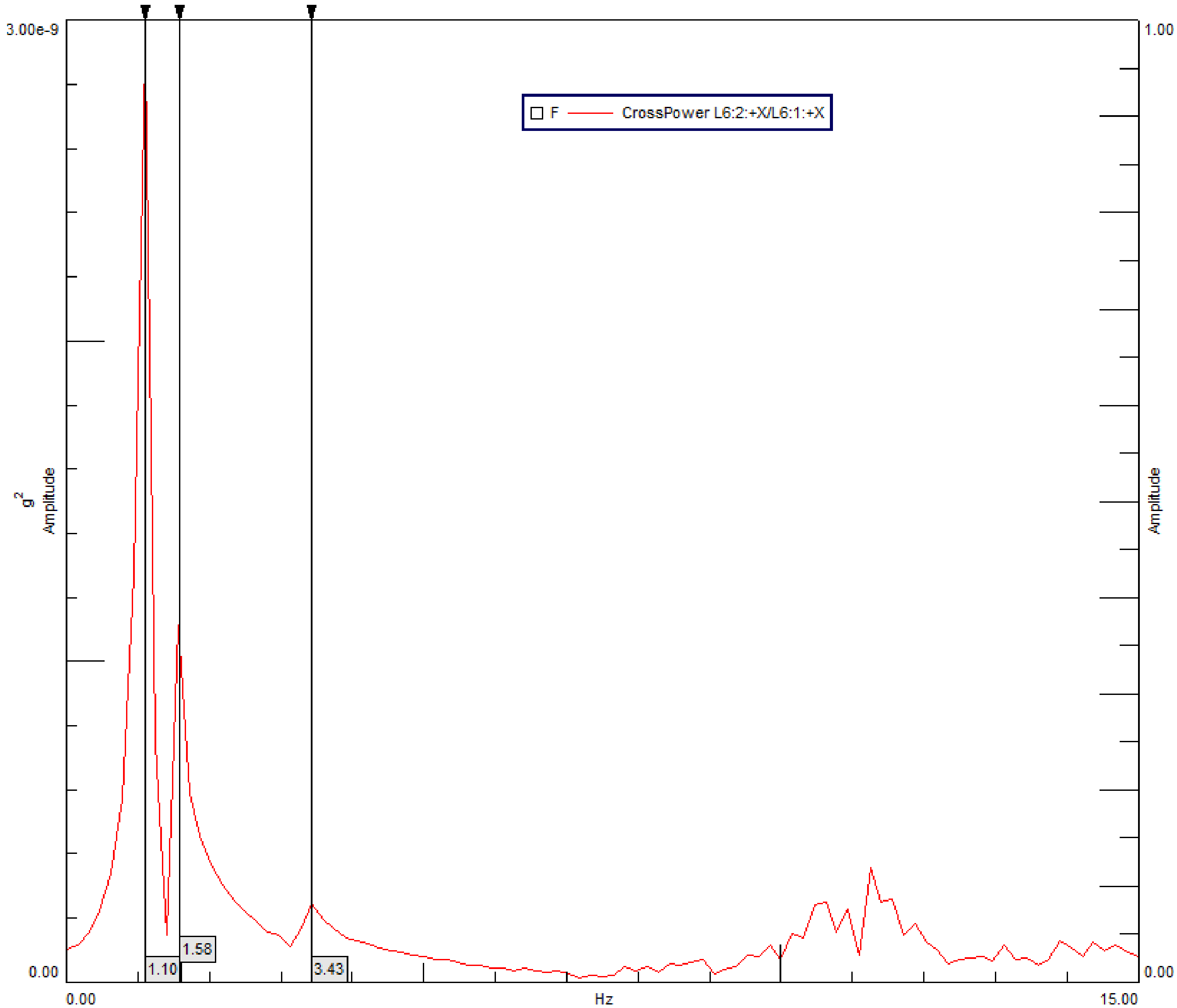

Figure 16 – A typical cross-power function between the signals of reference point and the point at the edge of the floor, on level 6.

4.3.2 Floor Vibration Performance

Table 2 summarizes the attributes of floor vibration performance, including the comments from the informal subjective evaluation.

Figures 17 and 18 show the typical frequency response functions generated from the measured hammer impact signals and the acceleration signals using the LMS impact-response modal analysis software. The fundamental natural frequencies, the damping ratios, and the mode shapes of the floors were extracted from a set of the frequency response functions. Figures 19 and 20 illustrate the measured deflection profiles of the two test sections.

In comparing the deflection profile of floor section L6F1 with that of floor section L6F2, we found that the deflection of L6F1 did not return to zero at the end of the static deflection test, but section L6F2 did, perhaps because section L6F2 had a clear boundary at both edges, but section L6F1 was a central portion of the entire floor (Figure 5). L6F2 was a plate with four edges supported. L6F1 floor was more like a plate with two edges free, and two ends were supported on walls. Besides, there were heavy loads on the left and right sides of the center portion of the floor that was tested.

Table 2 – Summary of attributes of floor vibration performance

Floor test section	Span (m)	Fundamental natural frequency (Hz)	Modal damping ratio (%)	Maximum 1-kN static deflection (mm)	Informal subjective evaluation
L6F1	5.7 (single span)	11.3	2	0.64 (0.51 if the 0.13-mm unrecovered deflection at the edge of the floor section is subtracted, see Figure 18)	Felt the vibration, marginal to acceptable
L6F2	6.0 (double span)	11.4	2	0.36	Less vibration than L6F1, acceptable

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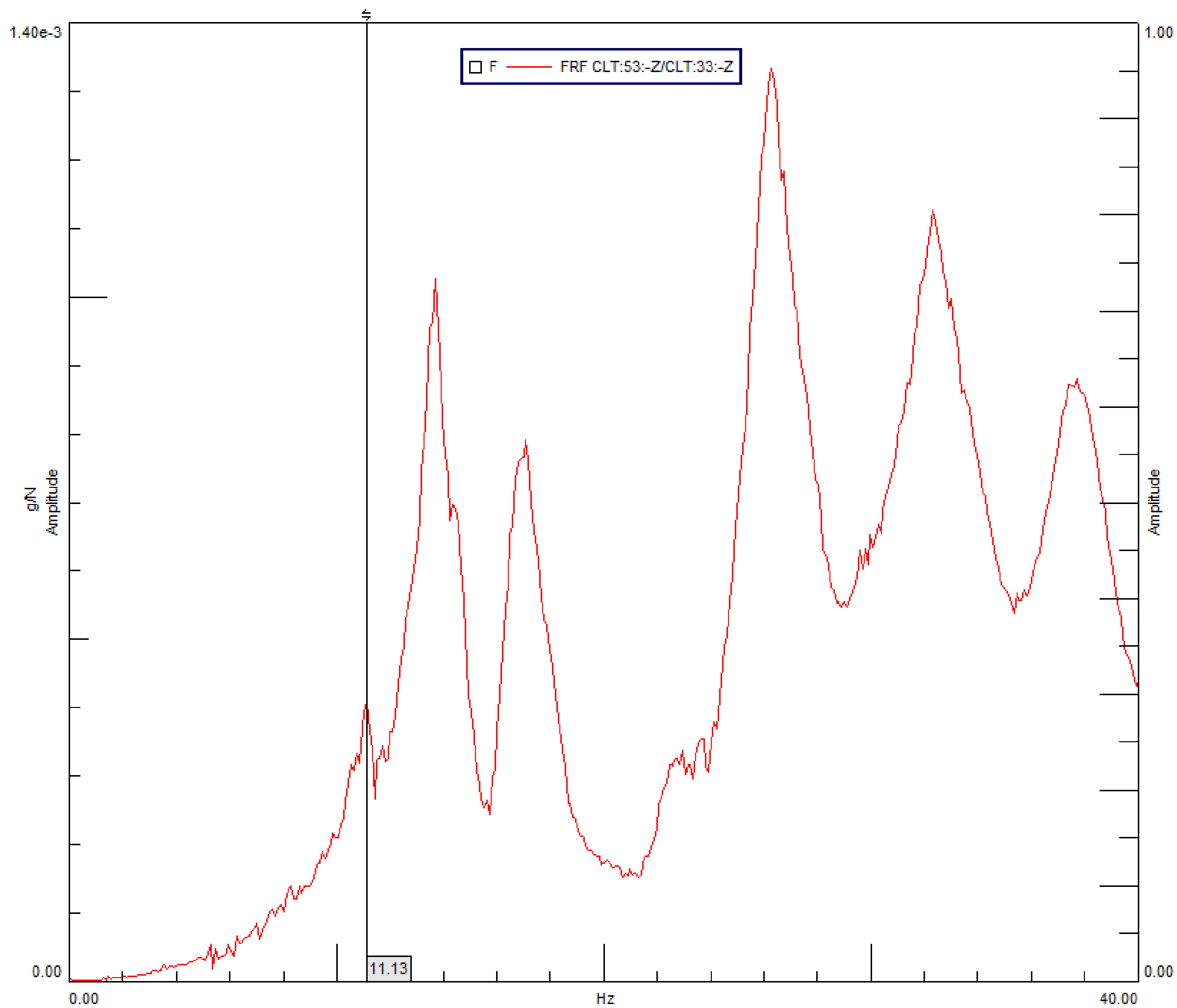

Figure 17 – Typical frequency response function obtained from the measured signals: test section L6F1.

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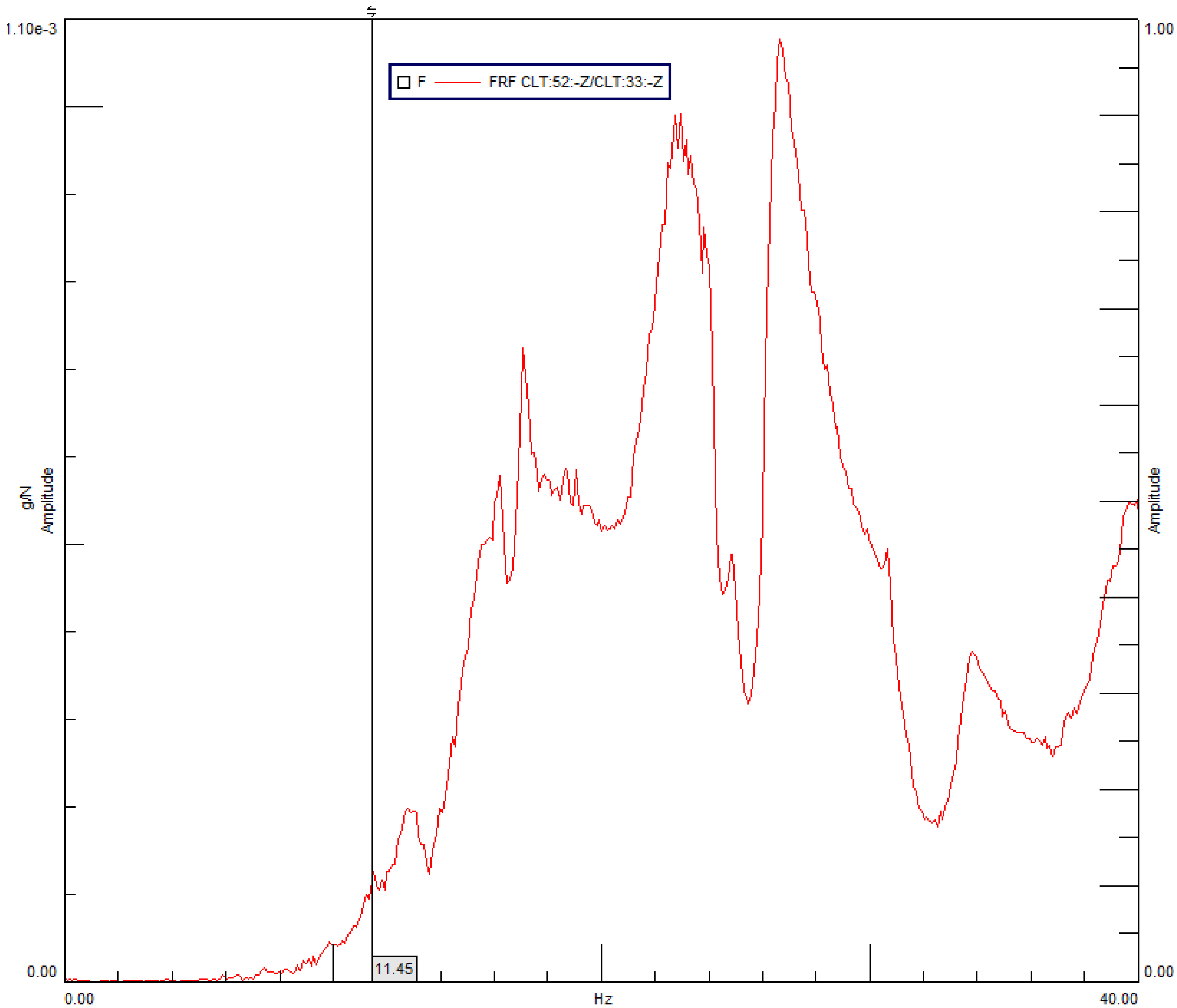

Figure 18 – Typical frequency response function obtained from the measured signals: test section L6F2.

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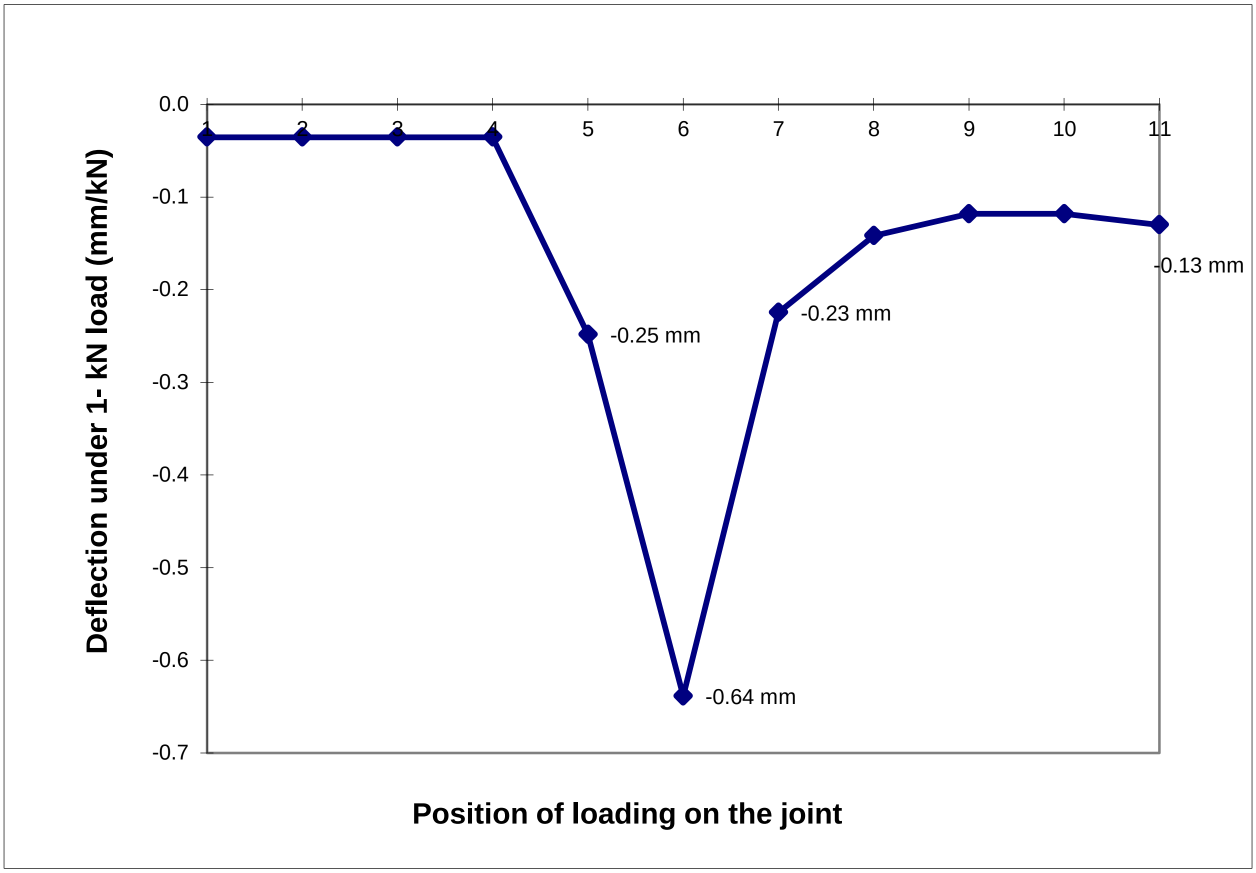

Figure 19 – Static deflection profile: test section L6F1.

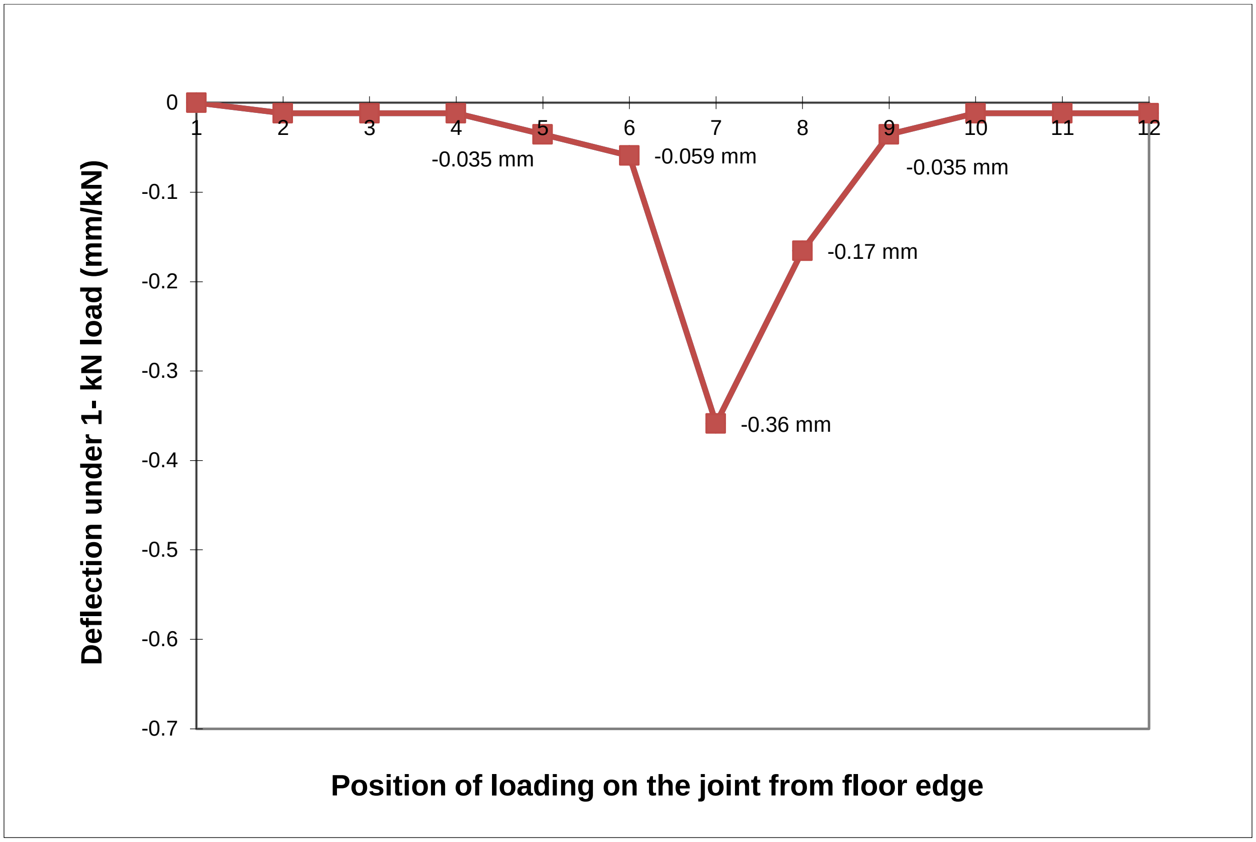

Figure 20 – Static deflection profile: test section L6F2.

5 TESTING AFTER BUILDING COMPLETION

The WIDC building was commissioned and occupied with tenants before the second round of building vibration tests and the sound insulation tests.

5.1 Building Description

The WIDC is a 6-storey post and beam system showcasing glulam and LVL members, and innovative CLT floors and walls. The lower floors of the WIDC building accommodate the University of Northern British Columbia and include a lecture hall on the main level and laboratories, classrooms, and faculty offices on floors 1 through 3. The upper floors of the building include offices for other tenants. During the testing, the floors on 6th and 5th levels were open without any partitions and finishes as shown in Figure 21(a). Half of the floor on 4th level had partitions under construction and the floor did not have any finish as shown in Figure 21(b). The floors on the first 3 levels had finished partitions and occupants.

(a) 5th floor view

(b) 4th floor view

Figure 21 - View of floors on 4th to 6th levels

Structural wall assemblies were constructed with 5-layer CLT panels, wood frames cavities filled with fiberglass batt insulation, and 5/8 in (16 mm) gypsum boards. Some of the structural walls had a 1.0 in (25 mm) air gap between the CLT panels and wood frames, and a double layer of gypsum boards. Interior partition wall assemblies were typically built with 2x4 in (38x89 mm) wood studs at 24 in (610 mm) o.c. filled with fiberglass batt insulation, and a double layer of gypsum boards. Some of the interior partition walls were constructed with a double wood frame with an air gap in between, and other partition walls had only one layer of gypsum boards on one side.

Description of the innovative CLT floor assembly is given in Section 4.2.2.

5.2 Ambient Vibration Test to Determine Natural Frequencies and Damping Ratios of the Completed Building

Ambient vibration test described in Section 4.2.3 was repeated on the completed building with finishes. The two reference accelerometers were located on the 5th floor. Other six accelerometers were roved from 6th floor to 4th floor to measure the building vibrations. The measurements were taken only on 6th – 4th floors because the floors on other levels were occupied and not accessible for the cables that had to be run from 5th floor to these floors. Besides, the cables also had to be run through the entire floors in levels 3 and 2. The measured frequencies and damping ratios of the building determined from the data measure on each floor were repeatable, the final results were the average of the data measured from each floor, so excluding the data of the building vibration measured from the 3rd and second floors will not affect the final results. Figure 22 shows the roving accelerometers at the center of 4th floor. The natural frequencies and damping ratios of the completed building were extracted from the series of the cross-power functions.

Figure 22 – Roving accelerometer setup on the floor of 4th level

Figure 23 shows a typical cross-power function between the signals of reference point and the point at the edge of the floor, on level 6. Table 3 summarizes the measured first three natural frequencies of the three vibration modes of the building in the floor plan and the associated modal damping ratios.

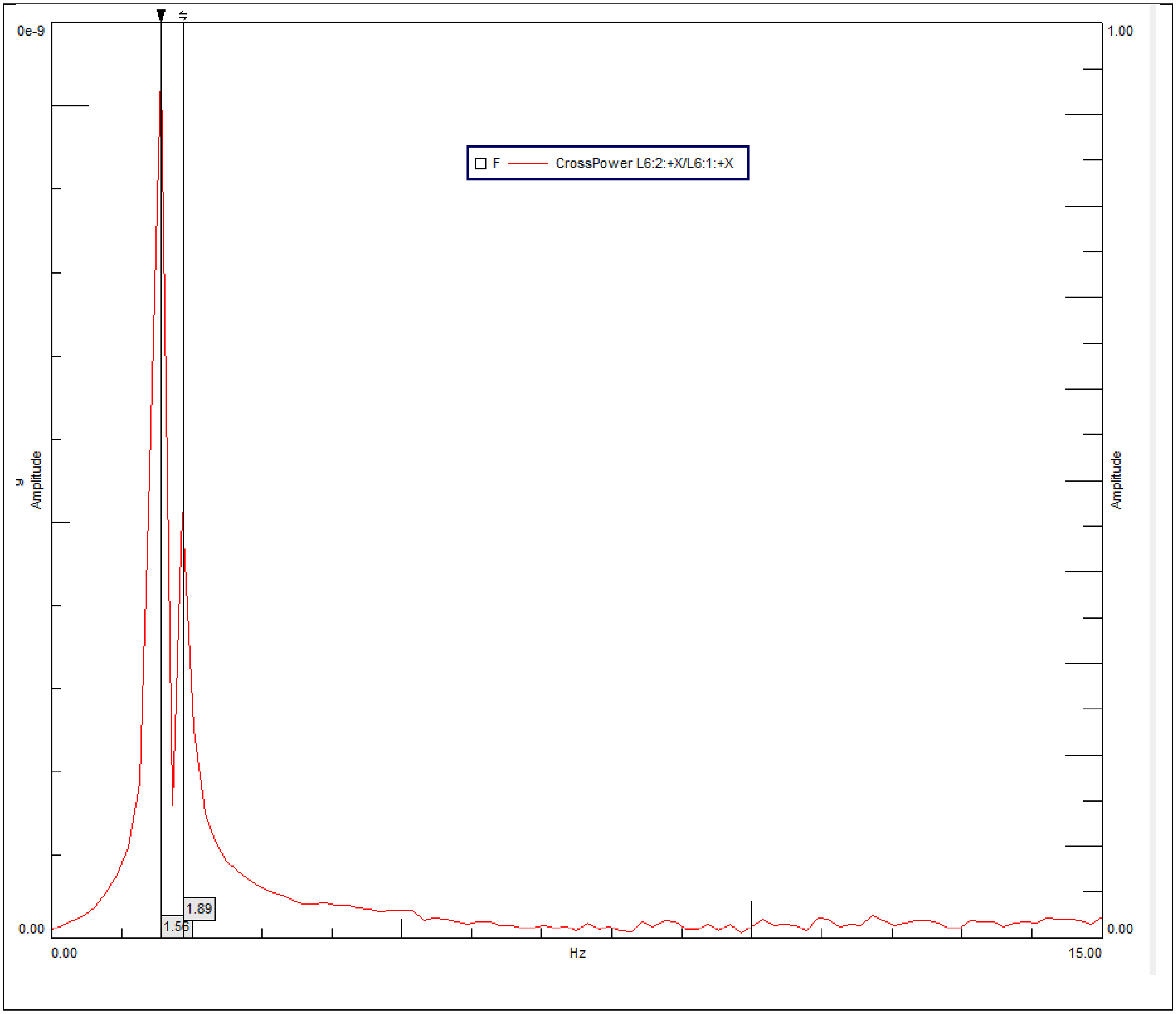

Figure 23 – A typical cross-power function between the signals of reference point and the point at the edge of the floor, on level 6.

Table 3 – Summary of the first three natural frequencies, damping ratios, and vibration modes of the completed building

Natural frequency (Hz)	Modal damping ratio (%)	Vibration mode of floor plane
1.6	2	Translation vibration in the x-direction
1.9	2	Translation vibration in the y-direction
N.A.	N.A.	Torsion

In comparison with the natural frequencies and damping ratios of the building without finishes, partitions and occupancy (Table 1), the natural frequencies of the first two vibration modes increased by 45% and 27%, respectively. The damping ratios of the first two vibration modes of the completed building were almost the same as these measured on the building without any finishes, partitions and occupancy during the building construction.

5.3 Sound Insulation Performance

Airborne sound insulation performance of selected wall assemblies and the impact sound insulation performance of selected floor assemblies were assessed on-site in accordance to standard test methods.

5.3.1 Test Methods

Airborne sound insulation performance of a wall assembly between two adjacent rooms in the building was determined according to ASTM E336 (ASTM, 2014). This standard allows for field testing of a wall to determine its apparent sound transmission class (ASTC) rating due to the direct sound transmission through the wall and the flanking due to indirect sound transmission paths. The ASTC rating for the wall assembly tested was determined as per the classification in ASTM E413 (ASTM, 2010).

Decay rates were measured according to ASTM E2235 (ASTM, 2014). Fifteen decay rates were collected (3 microphone positions, 5 decays).

Impact sound insulation performance of a floor assembly between two adjacent levels in the building was tested according to ASTM E1007 (ASTM, 2013). This standard provides a method for assessing the impact sound transmission of a floor assembly by using a standard tapping machine on-site. The apparent impact insulation class (AIIC) rating derived by using this method takes into account the direct sound transmission through the floor assembly and the flanking due to indirect sound transmission paths. The AIIC ratings for the floors tested were determined as per the classification in ASTM E989 (ASTM, 2006). The tapping machine was placed in four positions in each of the two source rooms:

- Position 1: on 3-ply CLT floor section and parallel to CLT's strong axis.
- Position 2: same as Position 1 but perpendicular to CLT's strong axis.

- Position 3: on plywood floor trench and parallel to trench direction.
- Position 4: on 3-ply CLT floor section at 45° with respect to Position 1.

5.3.2 Test Equipment

For measurement of the airborne sound attenuation, the sound source generating pink noise was connected to a Yamaha DXR10 10-inch Bass-reflex type powered speaker (1100-Watt dynamic, 700-Watt continuous Power Rating). In the case of impact sound transmission, a standard EM50 Electromechanical Tapping Machine, manufactured by Look Line and built to ISO 140 standards (five hammers fall 40mm +/- 5%, at 10 Hz) was used to generate the noise. A single sound level meter Larson Davis Model 831 Type I was used to measure sound levels during the tests. Calibration of the sound level meter was in conformance with the standard requirements. The sound level meter underwent the annual calibration on November 13, 2014 and was found compliant to manufacturer specifications.

Data analysis was carried out with DNA software of Larson Davis that interfaces with the sound level meter.

5.3.3 Description of Tested Assemblies

A wall assembly and a floor assembly were tested for sound performance. The assemblies were selected as to allow for testing specific wall and floor designs that are critical from a sound insulation performance perspective for the building to fulfill its intended scope. Moreover, the source and receiving rooms were selected as to meet the volume requirement of less than 150 m^3 specified in ASTM E336.

5.3.3.1 Wall Assembly

The wall assembly between a meeting room and a teaching assistant office on the second floor was chosen for airborne sound attenuation testing. The approximate volumes of the source room (S) and the receiving room (R) were 83 m^3 and 53 m^3 respectively (Figure 24). The approximate area of the partition wall between the two rooms was 13.44 m^2.

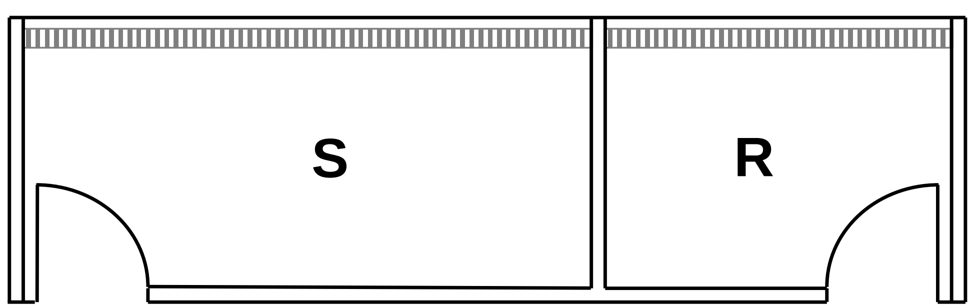

Figure 24 – Source and receiving rooms for airborne sound attenuation of selected wall assembly

Figure 25 – Details of source and receiving rooms

The source and receiving rooms were both furnished at the time of testing (Figure 25). The furniture in the source room included a large conference table, chairs, and a wall cabinet. The walls in the source room, other than the partition wall measured for sound insulation, were soundproofed with fabric wrapped acoustic panels placed at specific locations within the walls. The receiving room had three desks with chairs and metal cabinets. The entrance doors in both rooms had acoustic frames with an STC (Sound Transmission Class) rating of 45.

Details of the wall assembly selected for airborne sound attenuation testing are given in Table 4.

Table 4 – Details of wall assembly tested for airborne sound attenuation

Wall Type	Construction Details (Cross-Section)
Interior Partition Wall W3	• 2 layers of 16 mm (5/8 in) gypsum board[1] • 2x4 wood studs at 610 mm (24 in) o.c. • Fiberglass insulation in cavity (89 mm, 3.5 in) • Air gap (25 mm, 1 in) • 2x4 wood studs at 610 mm (24 in) o.c. • Fiberglass insulation in cavity (89 mm, 3.5 in) • 2 layers of 16 mm (5/8 in) gypsum board[1]

Note: 1Gypsum board sealed with acoustic caulk on backer rod

5.3.3.2 Floor Assemblies

The floor-ceiling assembly between the third and second levels in the building was chosen for impact sound transmission testing and for airborne sound attenuation testing. The source rooms located on the third floor were faculty offices with approximate volumes of 38.27 m^3 (S1) and 38.41 m^3 (S2) (Figure 26). The approximate floor area of these rooms was 11.35 m^2 (S1) and 11.39 m^2 (S2). These rooms were roughly aligned vertically with half of a design classroom on the second level with an approximate volume of 111.7 m^3 (R). The two halves of the design classroom were separated by a movable partition.

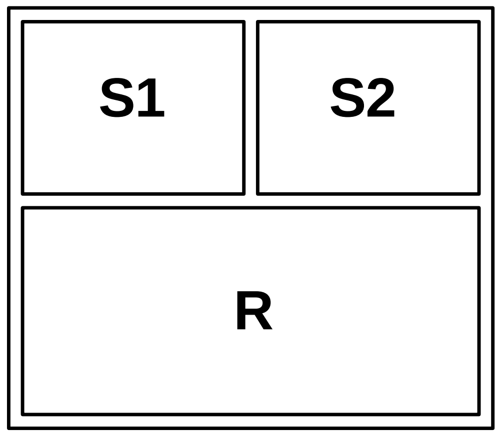

Figure 26 – Source and receiving rooms for impact sound transmission of selected floor assemblies

Figure 27 – Details of source rooms (above) and receiving room (below)

The source and receiving rooms were all furnished at the time of testing (Figure 27). The faculty offices on the third floors were furnished with desks, chairs, and cabinets, while the design classroom on the second floor was furnished with two hexagonal tables and chairs. The south-facing wall in the receiving room was soundproofed with fabric wrapped acoustic panels placed at specific locations within the wall. The entrance doors in all rooms had acoustic frames with an STC (Sound Transmission Class) rating of 45.

Details of the floor assembly selected for airborne sound transmission and impact sound transmission testing are given in Table 5.

Table 5 – Details of floor assembly tested for airborne and impact sound transmission

Floor Type	Construction Details (Cross-Section)

Floor F1-NB-2	• 5 mm (0.2 in) carpet
	• 4 mm (0.16 in) acoustic underlayment
	• 15 mm (0.6 in) mineral acoustic panel
	• 99 mm (3.9 in) 3-ply CLT sections staggered with 169 mm (6.6 in) 5-ply CLT sections or 239 mm (9.4 in) 7-ply CLT sections
	• Rubber pad between staggered CLT sections
	• Cavity under 3-ply CLT sections, i.e. dropped ceiling:
	  ○ Ceiling hangers and resilient channels
	  ○ 150 mm (6 in) air gap
	  ○ Fiberglass insulation to maintain max 150 mm (6 in) air gap
	  ○ 150 mm (6 in) fiberglass insulation
	  ○ 2 layers of 16 mm (5/8 in) gypsum board [1]
	• Cavity above 5-ply or 7-ply CLT sections and between the 3-ply CLT sections of the floor:
	  ○ 2 layers of 16 mm (5/8 in) plywood floor trench
	  ○ Air-gap for in-floor services
	  50 mm (2 in) semi-rigid fiberglass insulation

Note: 1 Gypsum board sealed with acoustic caulk on backer rod.

5.3.4 Test Results

The test results apply only to the specific wall and floor-ceiling assemblies measured for airborne sound attenuation and impact sound transmission, respectively. These results are specifically for the measured rooms described in the report which do not include all areas/volumes near the separating partitions and shall not be used to characterize performance in other areas. The results stated in this report represent only the specific construction and acoustical conditions present at the time of the test. Measurements performed in accordance with this test method on nominally identical constructions and acoustical conditions may produce different results.

5.3.4.1 Wall Assembly

ASTC rating for the wall assembly described in Section 5.3.3.1 was 51. Measured sound transmission loss through the wall assembly in 1/3 octave band for frequencies ranging from 125 Hz and 4000 Hz is shown in Figure 28. The blue lines in Figures 28, 29, and 30 represent measured sound transmission loss and the black lines show the reference contour fitted to the data as per ASTM E433 (ASTM 2010). The measured ASTC rating of 51 is above the proposed minimum ASTC rating of 47 in the 2015 NBCC (IRC, 2015).

Test specimen area S:	13.4 m^2
Source room volume:	83.0 m^3
Receiving room volume:	53.1 m^3

Sum of deficiencies: 25 dB

Frequency Hz	FTL dB
125	38
160	36
200	41
250	40
315	47
400	44
500	46
630	47
800	54
1000	51
1250	56
1600	56
2000	56
2500	57
3150	60
4000	61

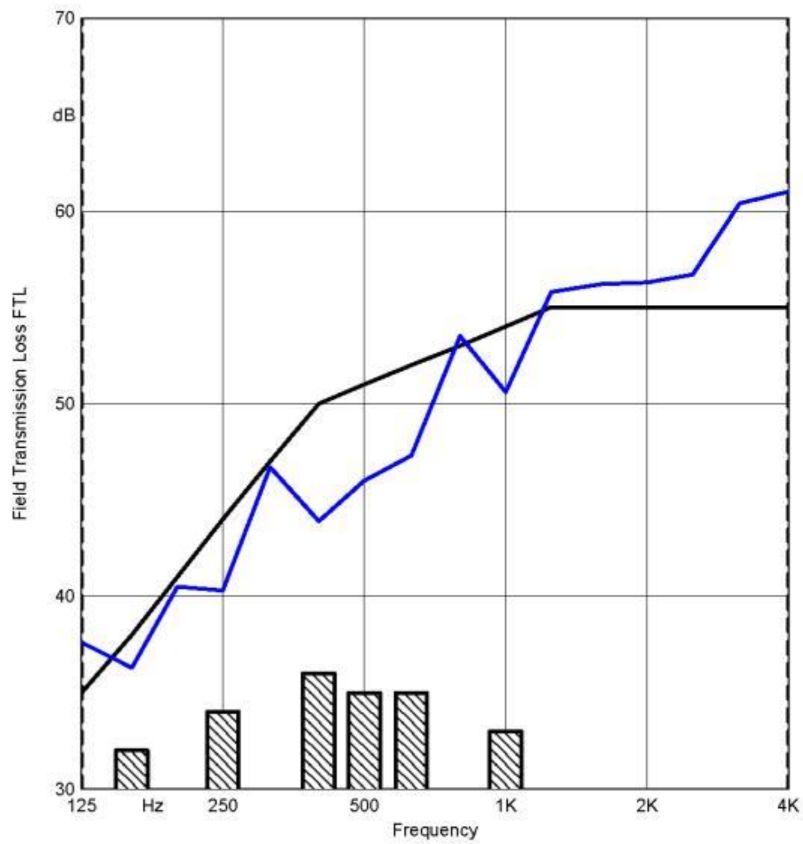

Figure 28 – Sound transmission loss in 1/3 octave frequency band spectrum measured through tested wall assembly

5.3.4.2 Floor Assemblies

The same ASTC rating of 53 was obtained for the floor assemblies in rooms S1 and S2 described in Section 5.3.3.2. The 1/3 octave band spectrums of the measured sound transmission loss through the floor assemblies in rooms S1 and S2 are shown in Figures 29 and 30, respectively, for frequencies ranging from 125 Hz and 4000 Hz. The ASTC rantings of 53 obtained for the floor assemblies are above the proposed minimum ASTC rating of 47 in the 2015 NBCC (IRC 2015).

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Test specimen area S: 11.4 m^2
Source room volume: 38.0 m^3
Receiving room volume: 111.7 m^3

Sum of deficiencies: 26 dB

Frequency Hz	FTL dB
125	37
160	37
200	43
250	44
315	47
400	46
500	49
630	53
800	47
1000	59
1250	62
1600	62
2000	60
2500	59
3150	62
4000	61

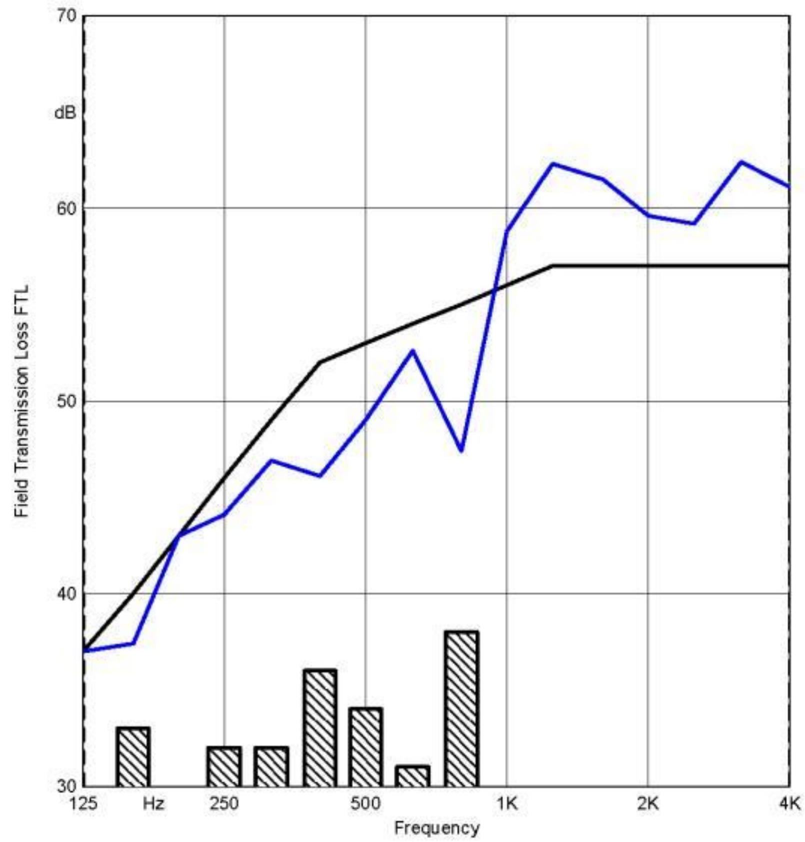

Figure 29 – Sound transmission loss in 1/3 octave frequency band spectrum measured through the floor-ceiling assembly in room S1

Test specimen area S: 11.4 m^2
Source room volume: 38.4 m^3
Receiving room volume: 111.7 m^3

Frequency Hz	FTL dB
125	41
160	43
200	40
250	42
315	45
400	46
500	48
630	51
800	49
1000	59
1250	61
1600	61
2000	60
2500	60
3150	63
4000	61

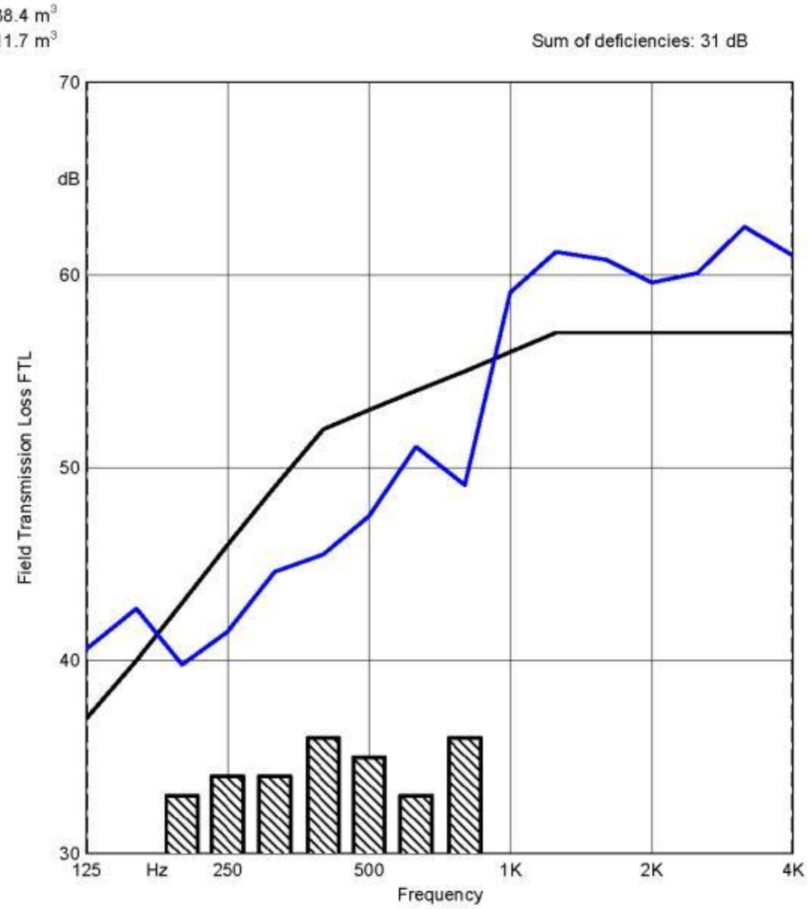

Figure 30 – Sound transmission loss in 1/3 octave frequency band spectrum measured through the floor-ceiling assembly in room S2

AIIC ratings for the floor assemblies in rooms S1 and S2 described in Section 5.3.3.2 were 59 and 57 respectively, averaging a rating of 58 for the tested floor. Normalized impact sound pressure levels of the floor-ceiling assemblies measured under the rooms S1 and S2 are shown in Figures 31 and 32, respectively, in 1/3 octave band spectrum for frequencies ranging from 125 Hz to 2000 Hz. The blue lines in Figures 31 and 32 represent measured impact sound pressure levels and the black lines show the reference contour fitted to the data as per ASTM E989 (ASTM 2006).

Currently, the 2010 NBCC (IRC, 2010) does not specify AIIC or IIC[2] (impact insulation class) ratings. The 2010 NBCC recommends a minimum IIC rating of 55 for bare floors tested without a carpet. It is expected that a carpeted floor has an IIC rating above 55. An AIIC rating based on field measurements is lower than an IIC rating measured in laboratory due to the flanking transmission.

Receiving room volume: 111.7 m³

Sum of deficiencies: 29 dB

Frequency Hz	L_n dB
100	60
125	61
160	61
200	58
250	52
315	45
400	37
500	35
630	36
800	34
1000	32
1250	31
1600	31
2000	32
2500	33
3150	34

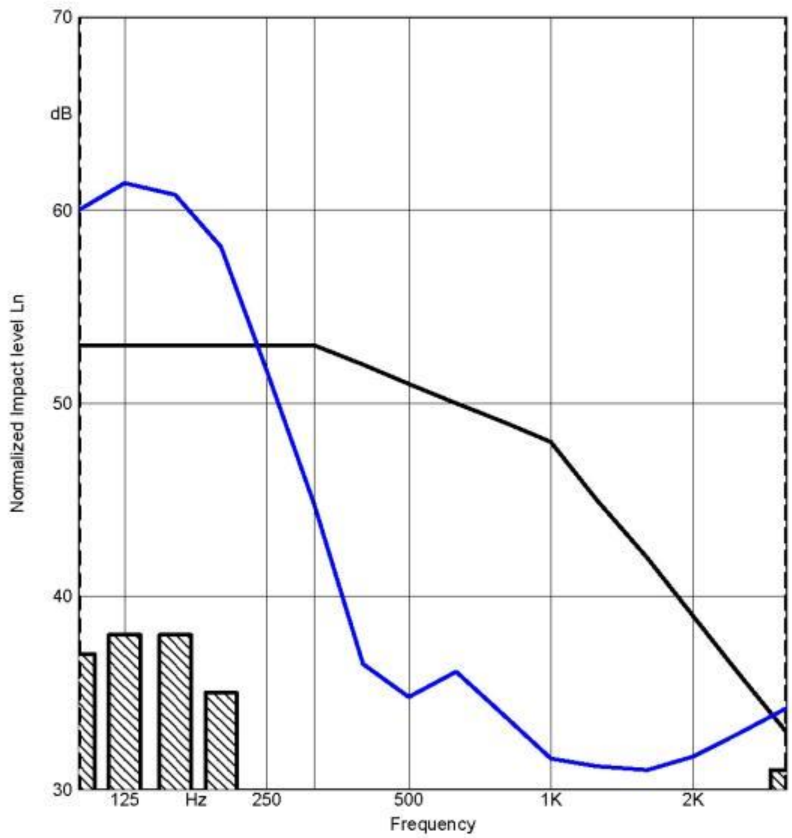

Figure 31 – Normalized impact sound pressure levels in 1/3 octave frequency band spectrum measured under the floor-ceiling assembly in room S1

[2] An IIC rating is calculated based on standard acoustic measurements carried out in an acoustic chamber with all flanking paths suppressed.

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Receiving room volume: 111.7 m^3

Sum of deficiencies: 18 dB

Frequency Hz	L_n dB
100	63
125	62
160	58
200	54
250	46
315	41
400	38
500	37
630	36
800	44
1000	35
1250	33
1600	33
2000	33
2500	33
3150	35

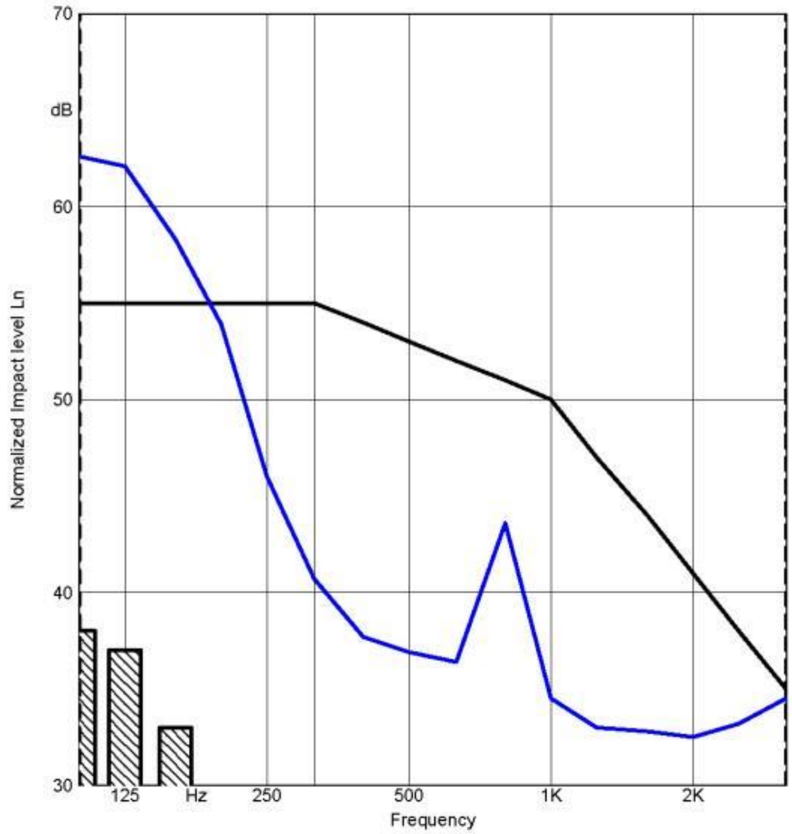

Figure 32 – Normalized impact sound pressure levels in 1/3 octave frequency band spectrum measured under the floor-ceiling assembly in room S2

6 CONCLUSION

The tests were performed in accordance to standard requirements and provided reliable data of the floor and building vibration performance, and on the sound insulation performance of the selected floor and wall assemblies. The findings of these tests will provide technical reference to architects and engineers for designs of mid-rise wood buildings.

7 PROPOSED FUTURE WORK

It is proposed that all the tests be repeated five years later to examine the potential change in performances caused by occupancy and service.

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