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TESTING OF WOOD DIAPHRAGMS STRENGHTENED WITH QUAKE LOCK SYSTEM[TH]

Project Report
(Phase I)

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EXECUTIVE SUMMARY

An experimental study was conducted on wood deck diaphragms at the Wood Science Laboratory of the University of British Columbia in collaboration with International Structure Lock System Inc. The test program was designed to evaluate the effectiveness of Quake Lock™ system for strengthening wood deck diaphragms.

Six test specimens were constructed, delivered to the laboratory and tested. Each deck was composed of plywood sheeting panels with a supporting frame. The supporting frame consisted of the perimeter members and intermediate longitudinal joists. The panels were connected to the perimeter frame members with nails, as well as to the joist beams. Two types of wood deck diaphragms were constructed and investigated: Deck with lumber joists; and deck with I-joists. Quake Lock™ was installed underneath the deck and was employed to connect the joists together in perpendicular direction. Two decks without Quake Lock™ were used as benchmark specimens.

The testing program included in-plane inelastic shear tests, deflection tests and vibration tests. The in-plane shear tests included monotonic and quasi-static reversed cyclic inelastic deformation and were used for seismic evaluation of the decks. A loading protocol was developed for performing the reversed cyclic tests. Monotonic load-deformation response was used to determine the deformation parameter required for defining the amplitudes of the loading sequences. The deflection tests were used to assess the performance of the decks under gravity loads and vibration tests were conducted to determine the dynamic characteristics of the diaphragms.

The results from this series of tests showed that deck specimens strengthened with Quake Lock™ were stronger and stiffer than those without such a system. This system increased the ultimate shear strength and in-plane initial stiffness of the deck 25% and 30%, respectively. The deflection tests showed that the out-of plane vertical deflection decreased 35% for lumber joist and 22% for I-joist decks. Also, the specimens with Quake Lock™ showed a lower period of vibration, indicating a higher stiffness than the specimens without Quake Lock™. Although it is recognized that additional testing is required to confirm the observed behavior for other types of decking systems, it is clear from these tests that adding the Quake Lock™ System to the wood deck diaphragm improves the performance of the deck.

PROJECT REPORT

1. Introduction

A series of tests on wood deck diaphragms was conducted at the University of British Columbia (UBC) in collaboration with International Structure Lock System Inc. The tests including monotonic and cyclic in-plane shear tests, deflection tests and vibration tests, took place at the UBC Wood Science Laboratory between July 8th and July 23th of 2010.

This test program was designed for evaluation of the effect of Quake Lock™ system on the seismic inelastic response and gravity load bearing performance of wood deck diaphragms. For simplicity, the Quake Lock™ is referred to as "QL" in the text, tables and figures. The QL system has been suggested as an alternative strengthening strategy for wood decks with two different types of joist; lumber joist and I-joist. The expected and reported inelastic deformation of the diaphragms in typical single-storey structures during an earthquake is illustrated in Figure 1. As it is shown, the severe deformation zones are concentrated on the end edges of the deck. Therefore, the test program was designed to represent a half portion of the overall deck diaphragm. The objectives of this test program were the following:

- to evaluate the effectiveness of using QL for strengthening of wood deck diaphragms with two types of joist; lumber joist and I- joist;
- to determine the in-plane shear performance and failure mode of the wood deck diaphragms strengthened with QL;
- to compare the out-of-plane stiffness of strengthened decks with conventional decks when subjected to static gravity loads and impact loads;

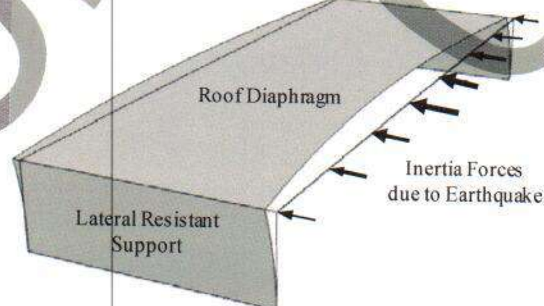


Figure 1: Inelastic deformation of deck diaphragms in typical single-story structures during a severe earthquake

2. Test Specimens Description

Six specimens with dimension of 4.839m x 2.438m were constructed by International Structure Lock System Inc. and delivered to the Wood Science Lab at UBC.

Each deck was composed of four sheeting panels and a supporting frame. The sheeting panels, each 1.209m wide and 2.438m long, were made up of a layer of 19mm (¾") D Fir plywood connected to the frame members with 63.5mm (2.5") nails at 200mm with center to center spacing at panel edge and joist locations. The supporting frame consisted of two transverse members at the end edges of the deck, and seven longitudinal joists with 406mm spacing running perpendicular to the sheeting panels. The transverse members were made up of a 304.8mm x 31.8mm (12" x 1 ¼") dimensional lumber. Two joist types were used for the deck specimens: 304.8mm x 31.8mm (12" x 1 ¼") lumber joist and NJH 12"-Nascor I-joist. The I-Joists consisted of two 30.5mm x 55.9mm (1 1/5" x 2 1/5") SPF lumber flanges graded and glued (edgewise) to a 9.5 mm (3/8") thick oriented strand board (OSB) web. Ends of the I-joists were secured using 28.6mm (1 1/8") OSB rim board and attached to the transverse lumbers using 2 – 82.6mm (3 1/4") nails into the end of the top and bottom flange.

Each QL assembly consisted of an 1.2mm (18 gage) thick steel beam with a U-channel cross section having two brackets, one on each end. One bracket hooked over the top chord of a joist, and the other bracket hooked under the bottom chord of an adjacent joist, connecting the two joists diagonally across the space between them. Each member had a hole in the middle of the U-channel, and holes in both brackets to allow it to be connected to adjoining members by screws. A QL system assembled for three joists is illustrated in Figure 2.

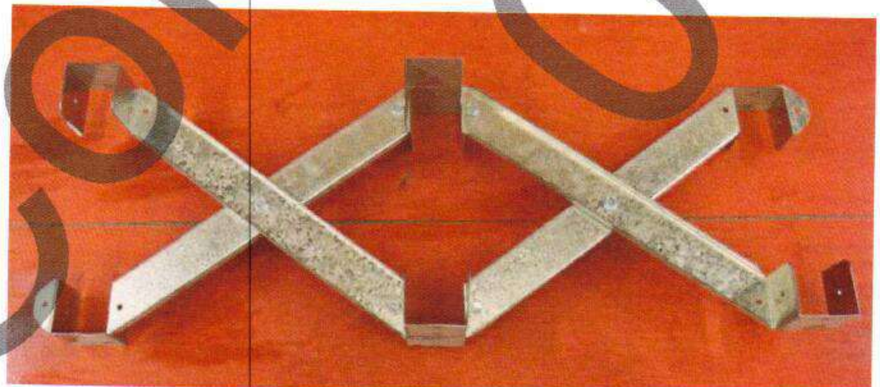


Figure 2: QL system fabricated for three joists of the wooden diaphragm

The QL system consisted of individual members arranged in four parallel rows with 1.588m spacing each spanning the gaps between the joists. At each location, two members were installed between the joists to form an X, bracing the gap between the joists along both diagonals. These two members were screwed to the joists through holes in their brackets, and to each other through the hole in the middle of the central U-channel section. Additionally, the brackets on the members spanning the gap on one side of a joist were screwed to the brackets on the members on the opposite side of the joist so that the QL members were interconnected across the entire width of the floor (in the direction perpendicular to the joists).

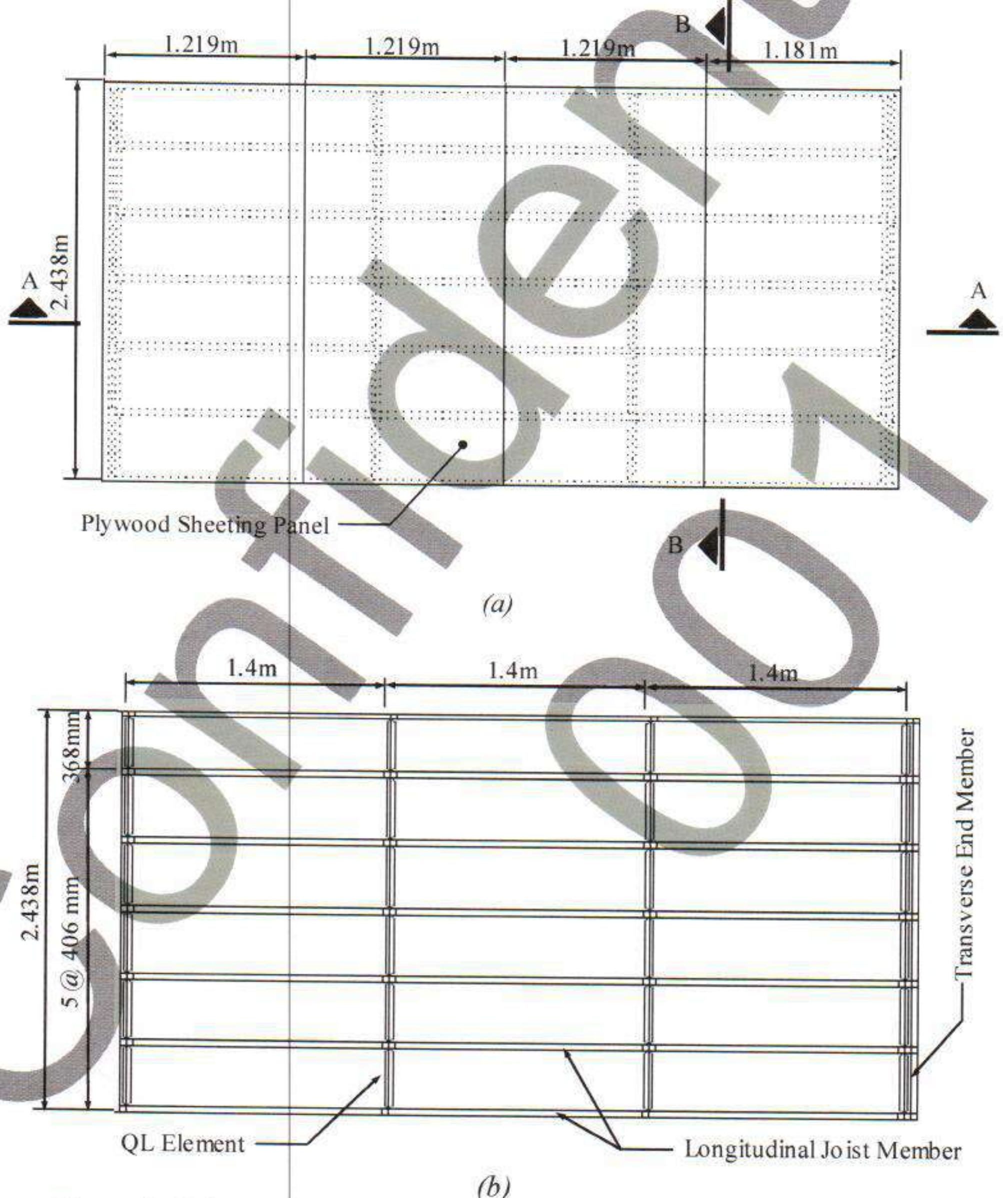


Figure 3: Schematic plan view of the specimens: a) Top view; b) Bottom view

Two decks without QL were used as benchmark specimens and represented a typical conventional deck. The schematic layout of deck specimens, top and bottom views, are illustrated in Figure 3 and cross sections are shown in Figure 4. Table 1 gives the characteristics of all the test specimens. Damage was observed during testing of specimen 1 and it was localized in the perimeter members. This was caused by a weak connection between the hold down and the joist. The damaged specimen was repaired and the test was repeated. The repaired specimen is referred to as "specimen 7" in this report.

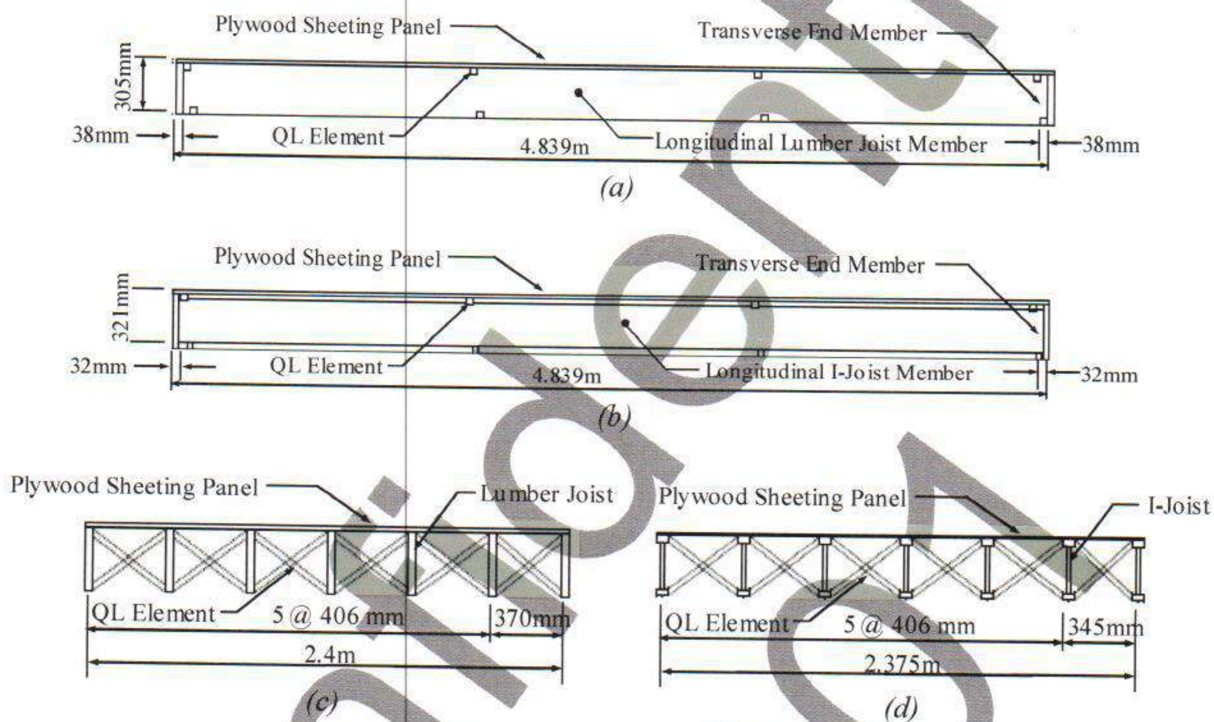


Figure 4: Schematic section view of the specimens: a) Section A-A (lumber joist specimen); b) Section A-A (I-joist specimen); c) Section B-B (lumber joist specimen); d) Section B-B (I-joist specimen)

Table 1: Testing Program and Description of specimens

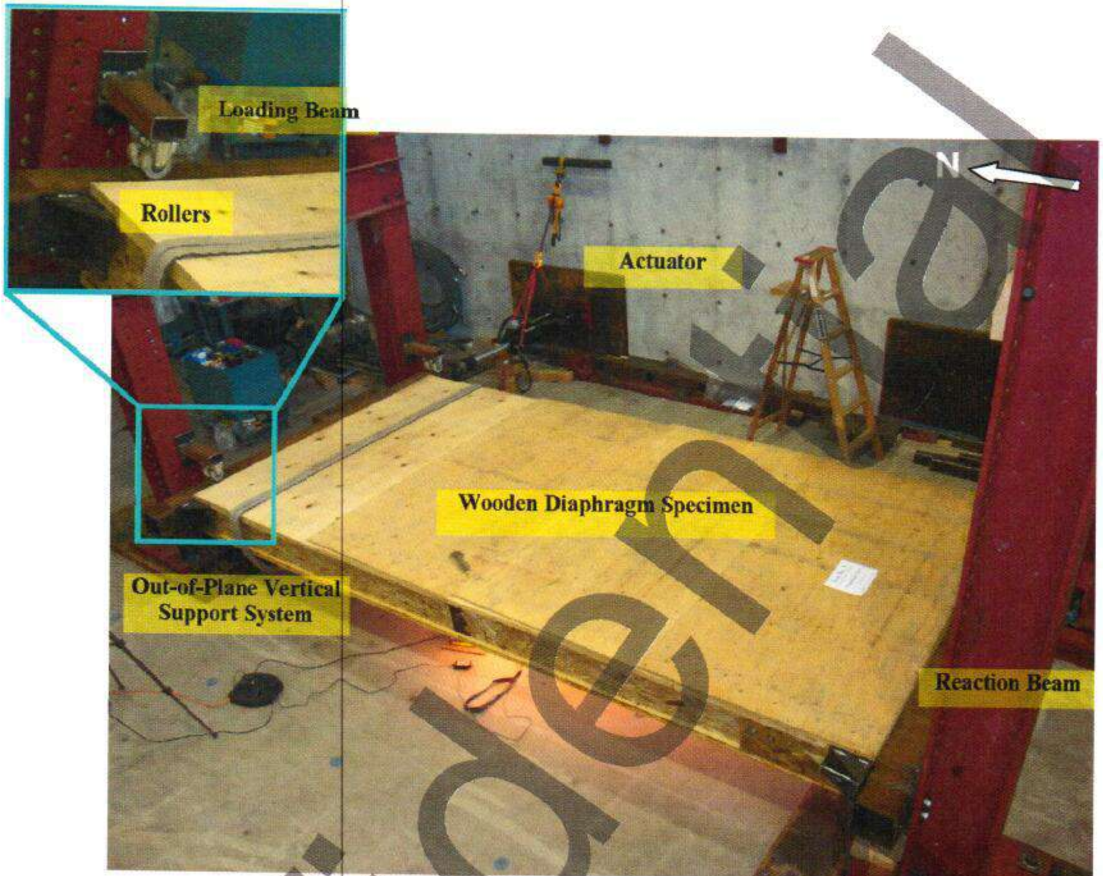
Test Specimens	Description	Loading Type	Date of Test
Specimen 1	Lumber Joist (Benchmark)	Monotonic	8/ Jul./2010
Specimen 2	Lumber Joist + QL	Monotonic	19/Jul./2010
Specimen 3	I-Joist (Benchmark)	Monotonic	21/Jul./2010
Specimen 4	I-Joist + QL	Monotonic	21/Jul./2010
Specimen 5	Lumber Joist + QL	Cyclic	22/Jul./2010
Specimen 6	I-Joist + QL	Cyclic	23/Jul./2010
Specimen 7	Repaired Specimen 1	Monotonic	23/Jul./2010

3. Test Setup

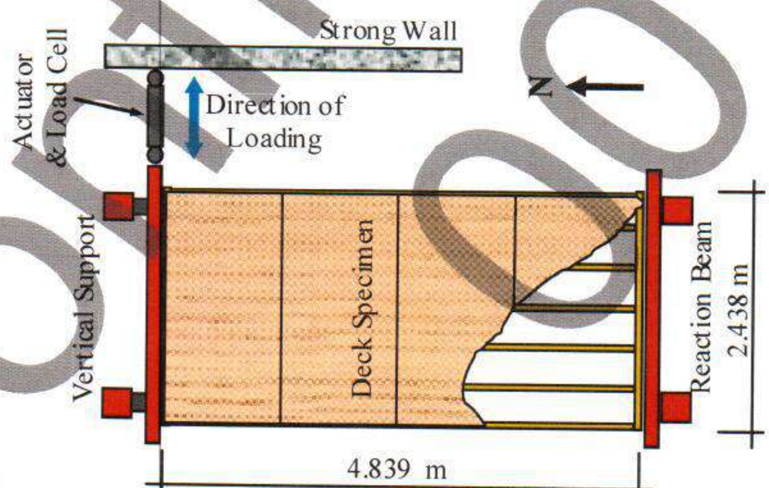
A large-scale test setup was built to represent a half portion of a 10m span deck diaphragm. The setup consisted of a fixed reaction steel beam in one end (south side) and a loading steel beam in the other end of the specimen (north side). The loading beam was vertically supported to avoid any eventual out-of-plane movement. The support system consisted of two beams attached to the rigid floor each equipped with four rollers located on both top and bottom sides of the loading beam. The loading beam could freely move between the rollers in the west-east direction. The reaction beam attached to two strong supports was used to connect the south side of the test frame to the rigid floor and prevent any movement. HSS 203 x 203 x13mm profile was used for both reaction and loading beams. The specimen was connected to the reaction and loading beams firmly by eight steel bolts prior to testing, and two steel brackets were used to fix the specimen laterally to the beams to avoid sliding.

The load was applied by a hydraulic actuator with a two-way capacity of ±100 kN force and a stroke limit of ±250 mm. The actuator was connected to a strong reaction wall and applied the load to the reaction beam. It was pinned at both ends to rotate freely in the horizontal direction. A load cell was mounted on the actuator to measure the applied load signal. The displacement was measured by the internal displacement sensor of the actuator directly.

For the deflection test, an LVDT (Linear Variable Differential Transformer) with a capacity of ±50 mm was installed on the strong floor to capture the vertical displacement in the center of the specimens. For the vibration test, an accelerometer was mounted on the deck specimens at the center point to measure the acceleration signals created by a controlled impact produced with a hammer. The location of the sensor and impact load are shown in Figure 14. A general view of the test setup, a test specimen during testing and the schematic plan view of the set up are illustrated in Figure 5.



(a)



(b)

Figure 5: Wood Diaphragm test set-up: a) General view; b) Schematic plan view

4. Loading Protocol

A loading protocol was developed for performing reversed cyclic tests on the deck specimens. These tests were displacement-controlled using a gradually increasing displacement at 1 mm/sec, which allows for a good comparison of the results among the specimens. Figure 6 shows the loading history used for cyclic testing.

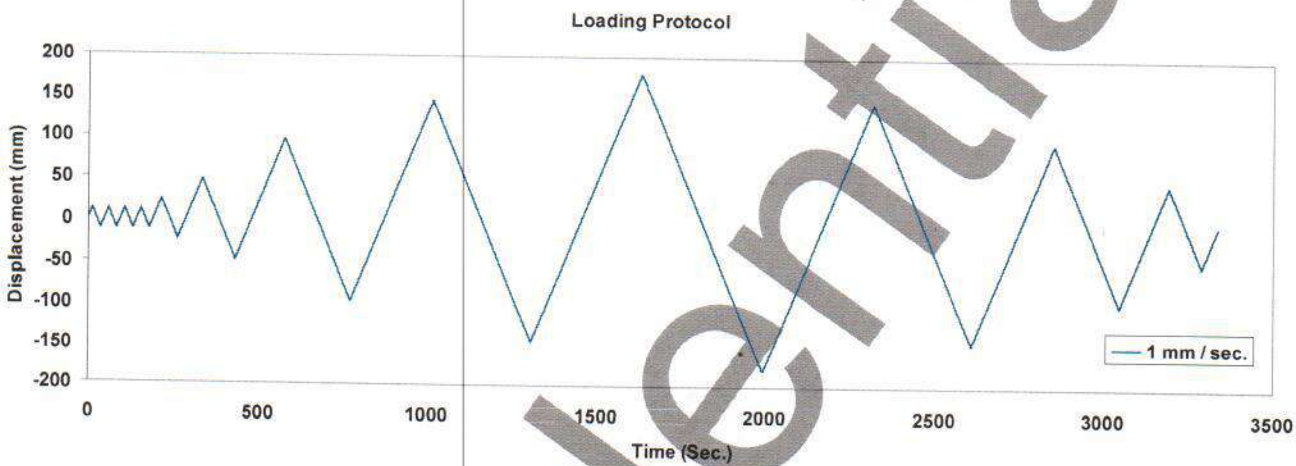


Figure 6: Loading protocol for cyclic tests

5. In-Plane Monotonic and Cyclic Tests

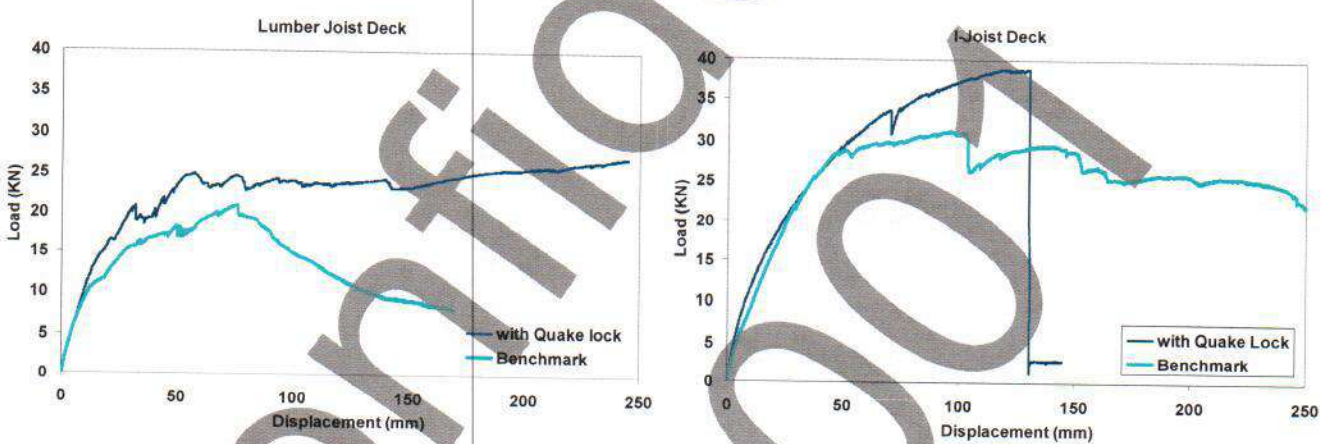
Monotonic tests were first performed to determine the shear performance and deformation parameters of the deck types studied. The inelastic behavior and failure modes were observed during these tests. The measured shear stiffness and ultimate shear strength of the specimens were recorded and summarized in Table 2. The load-displacement curves obtained from all monotonic tests performed for each of the specimens are illustrated in Figure 7.

Reversed cyclic tests were then performed on diaphragms strengthened with the QL system to observe the inelastic response and hysteretic behavior under large deformation conditions. Load-displacement responses of the specimens strengthened with the QL system under cyclic and monotonic loads are compared in Figure 8. The monotonic curves in both type of decks showed an acceptable agreement with the envelope of the reversed cyclic curves. Elastic stiffness and initial yielding drift of each specimen type were similar in the monotonic and cyclic tests. In the cyclic test of lumber joist deck a pinched hysteretic behavior was observed. This specimen sustained large inelastic deformation cycles with progressive strength degradation.

In contrast, the specimen with I-joist showed a very rapid strength reduction due to a sudden brittle failure that occurred in the web joist close to the fixed end.

Table 2: Measured response parameters of the specimens

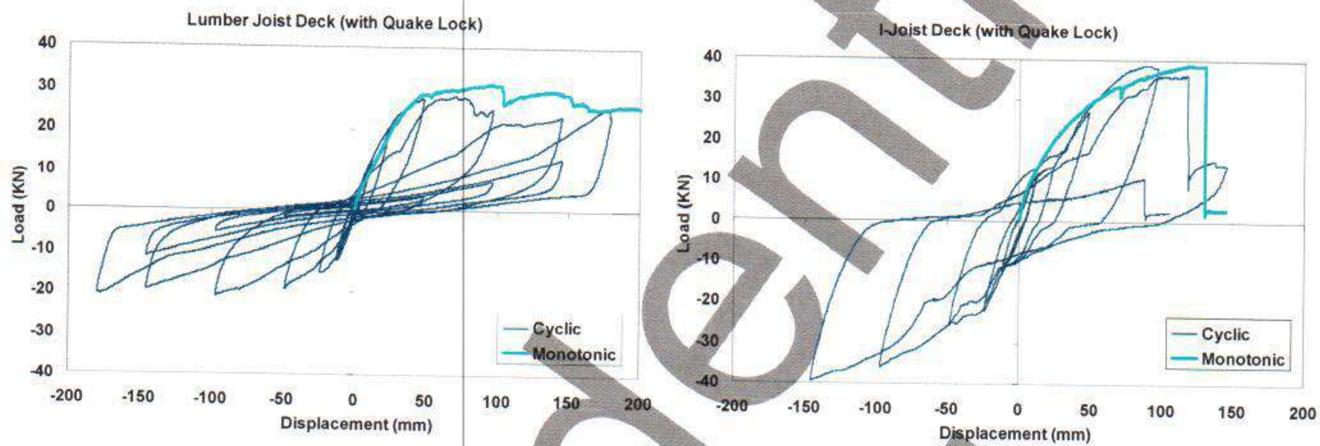
Test Specimens	Initial Shear Stiffness (G') (kN/mm)	Ultimate Shear Strength (kN/m)	
Specimen 1 Lumber Joist (Benchmark)	2.28	5.08	
Specimen 2 Lumber Joist + QL	2.3	10.25	
Specimen 3 I-Joist (Benchmark)	2.42	12.82	
Specimen 4 I-Joist + QL	3.19	15.94	
Specimen 5 Lumber Joist + QL	2.63	11.58 (in west direction)	8.67 (in east direction)
Specimen 6 I-Joist + QL	2.94	15.89 (in west direction)	14.75 (in east direction)
Specimen 7 Repaired Specimen 1	2.42	8.59	



(a) (b)

Figure 7: Monotonic load-displacement response of strengthened specimens by Quake Lock™ versus benchmark specimens: a) Lumber joist deck; b) I-joist deck

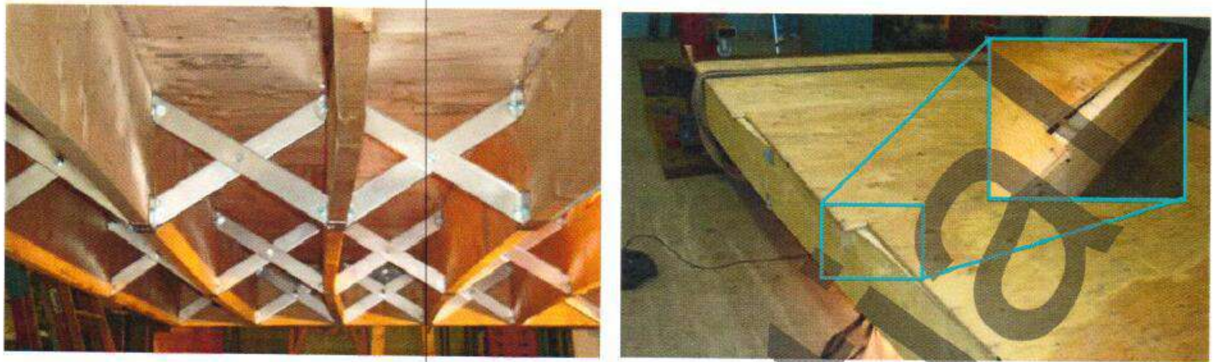
In the lumber joist deck without QL, the failure was localized at the end beam. It was developed by separation of the joists and panels from the end transverse beam. Adding the QL system to the deck resulted in uniform failure along the specimen. The failure happened by rotation of the panels, shear deformation of the nails and separation of the panels from the perimeter joists. Similar behavior was observed in the cyclic test. Figure 9 illustrates the general view of a lumber joist deck strengthened with QL system that deformed under monotonic loading. Deformation of the joists and a close up of a failed area of the panel at this specimen are shown in Figure 10. In the I-joist deck without QL the failure was distributed along the specimen with shear deformation of the nails, rotation of the panels and separation from the perimeter joists. In both monotonic and cyclic testing of a deck strengthened with QL local separation of the panels from the end beam occurred following a sudden brittle failure of the web joist closest to the fixed end.



(a) *(b)*

Figure 8: Cyclic Load-displacement response of the specimens versus monotonic response: a) Lumber joist deck; b) I-joist deck

Figure 9: Deformation of the lumber joist-deck with Quake Lock™ System (Specimen 2) under monotonic loading (general view)



(a) *(b)*

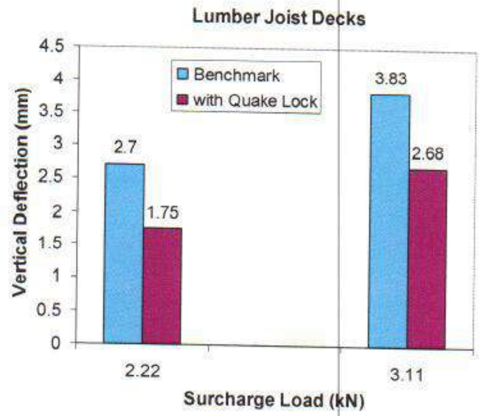
Figure 10: Deformation of the lumber joist deck with Quake Lock™ System (Specimen 2): a) Deformation of the lumber joists; b) Deformation of the panels and failure of the connections

6. Deflection Tests

Deflection tests were conducted on the specimens to determine the effect of the QL system in reducing the vertical deflection of a wood deck due to gravity loads. These tests were performed such that the system deformed in elastic range and on undamaged specimens prior to the in-plane shear test. The same setup as in-plane tests was used for deflection tests. Two steel blocks weighting 2.22 kN (500 lb) and 3.11 kN (700 lb) were placed on the middle of the deck, one after another, and the deflection at the centre of the deck was measured. Table 3 and Figure 11 show the vertical deflection measured for all the specimens when subjected to the surcharge weights. Each number presented in this Figure is the average of the measured deflection of different specimens for each type.

Table 3: Vertical deflection at center point of the specimens, (mm)

Test Specimen	Surcharge Load=2.22 kN (500 lb)	Surcharge Load=3.11 kN (700 lb)
Specimen 1 (Lumber Joist Benchmark)	2.7	3.83
Specimen 2 (Lumber Joist + QL)	1.69	2.66
Specimen 3 (I-Joist Benchmark)	1.95	2.75
Specimen 4 (I-Joist + QL)	1.5	2.17
Specimen 5 (Lumber Joist + QL)	1.82	2.69
Specimen 6 (I-Joist + QL)	1.47	2.12
Specimen 7 (Repaired Specimen 1)	2.82	3.95



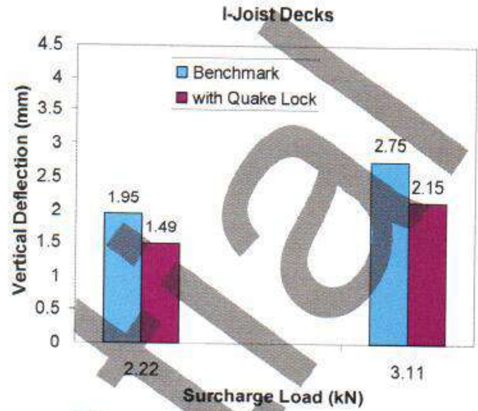
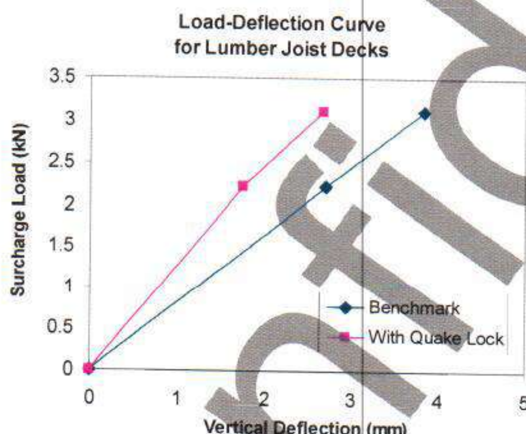


Figure 11: Average of vertical deflection at centre point of each specimen, (mm)

The out-of-plane stiffness of the lumber joist decks and I-joist decks are compared in Figure 12 for both conditions; wood decks without QL (benchmark specimen) and wood decks strengthened with QL. The schematic deflected shape of the specimens when subjected to surcharge weights is illustrated in Figure 13.



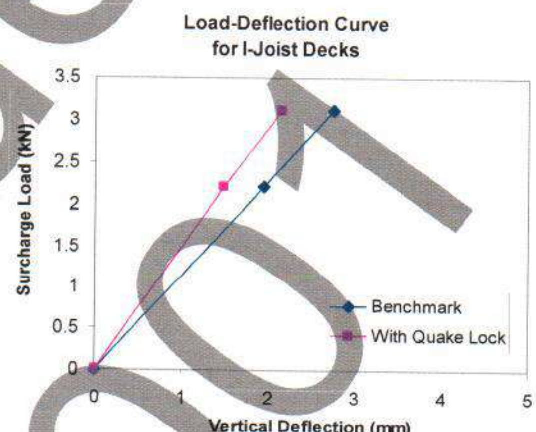
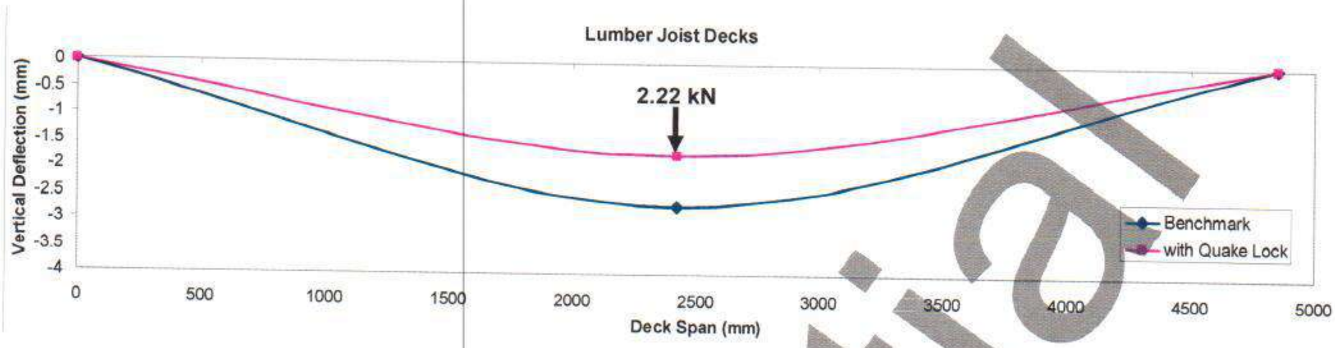
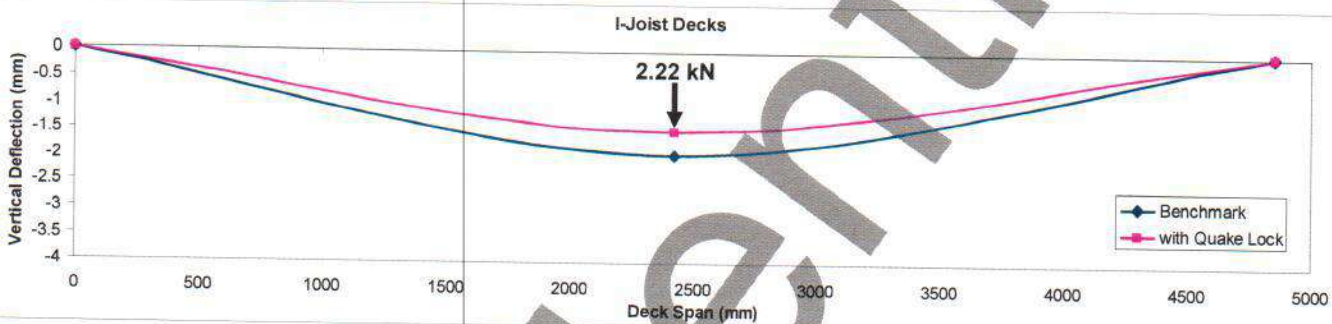
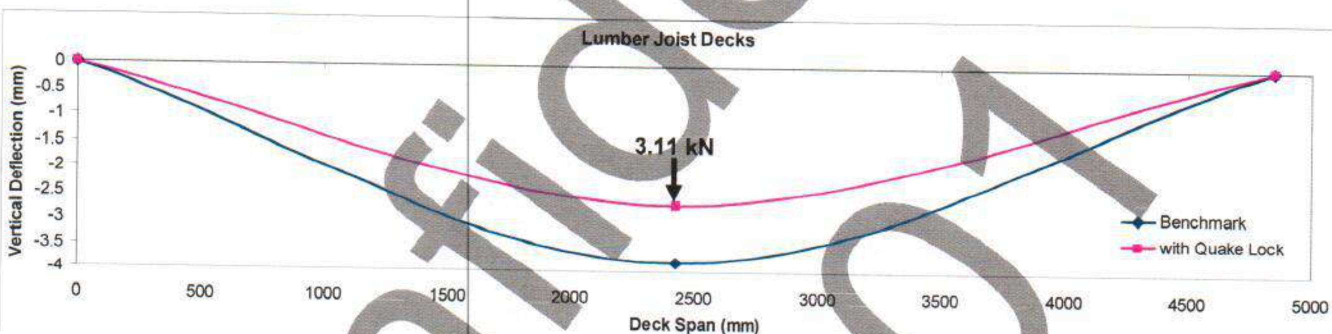


Figure 12: Vertical response of the specimens when subjected to surcharge load at the centre point







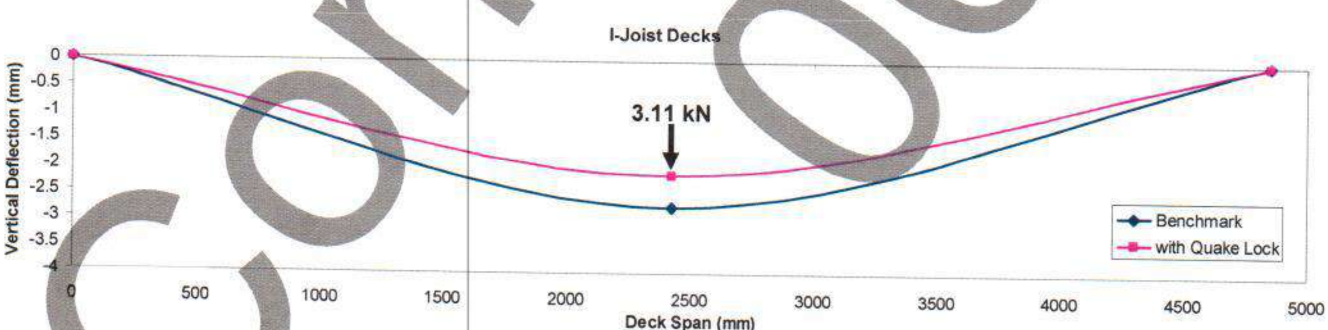


Figure 13: Deflection shape of the specimens when subjected to surcharge load at the centre point (2.22 kN=500 lb and 3.11 kN=700 lb)

7. Vibration Tests

Vibration tests (hammer tests) were performed on the specimens to evaluate the effect of QL system in reducing the vibration of the wood decks due to vertical dynamic loads. Hammer tests included recording the acceleration response of the specimens due to free vibration. Free vibration was generated by an impact load at the top of the specimens by hammer. These tests were performed in the elastic range of the deck and on undamaged specimens prior to in-plane shear test. The same setup as in-plane tests was used for these tests. Figure 14 shows the layout of the impact points and acceleration sensor. Two points were selected for impact load; Point "A" and Point "B". Only the data recorded from impact at "B" are presented in this report. Data recorded from impact at "A" is available in the companion DVD. The Seismosignal and Mathcad software packages were used for signal processing. Each recorded data was first filtered and corrected and then transformed to the spectral response functions. The acceleration time history obtained from specimen 1 is shown in Figure 15.

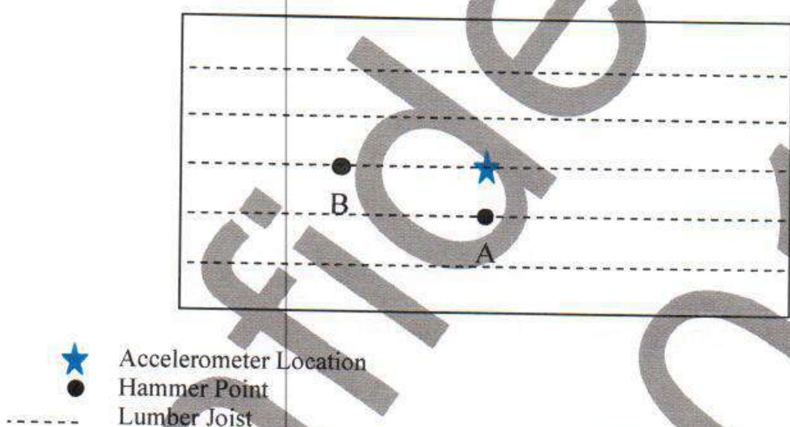


Figure 14: Layout of the impact points and accelerometer

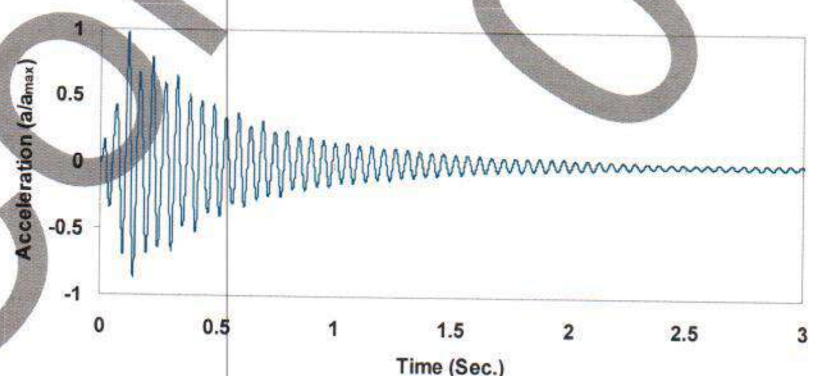


Figure 15: A recorded vertical acceleration for specimen 1,lumber joist-deck (benchmark) - impact at point B

Modal frequencies of the specimens 2, 3, 4 and 7, obtained from a Frequency Domain Analysis of the recorded acceleration time histories and viscous damping, determined from the decay of free motions, are presented in Table 4. The specimens with QL showed larger damping ratio than the specimens without QL. This means the QL system reduces vibration of the deck. Figures 16 and 17 show the Fourier Amplitude and Power Spectra of the response of these specimens, respectively. As these plots show, the first mode of vibration, which is related to the whole setup, does not show significant change whereas, adding QL system to a wood deck increases its natural frequencies in higher modes of vibration and increases the out-of-plane stiffness of deck.

Table 4: Damping and modal frequencies of the specimens obtained by hammer test - impact at Point B

Specimen	Damping (%)	Frequency (Hz)		
		Mode 1	Mode 2	Mode 3
Lumber Joist Benchmark (Test 7)	0.64	18.56	29.05	39.31
Lumber Joist + QL (Test 2)	2.45	18.56	36.62	74.95
I-Joist Benchmark (Test 3)	0.72	22.46	37.35	63.72
I-Joist + QL (Test 4)	1.75	21.48	38.82	72.51

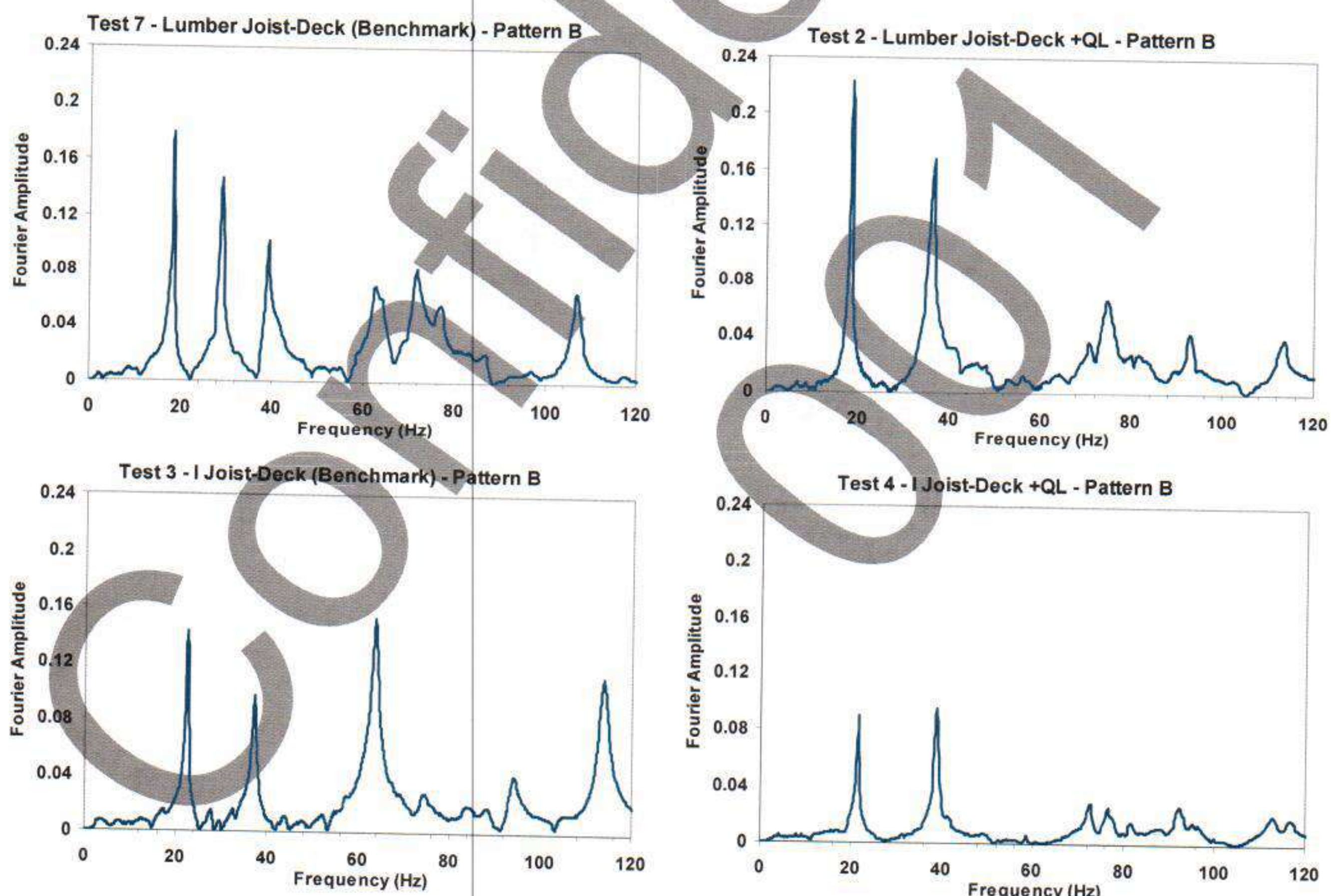
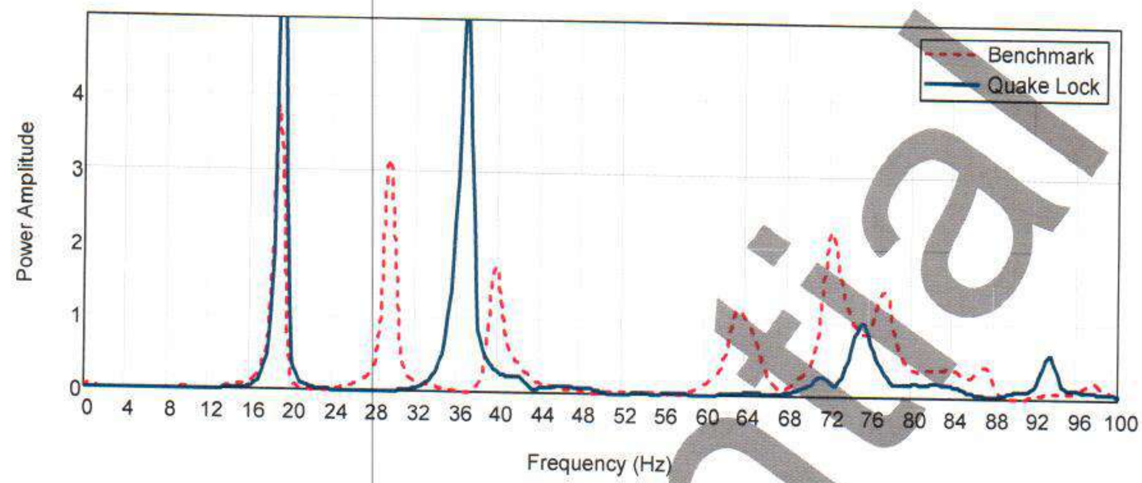
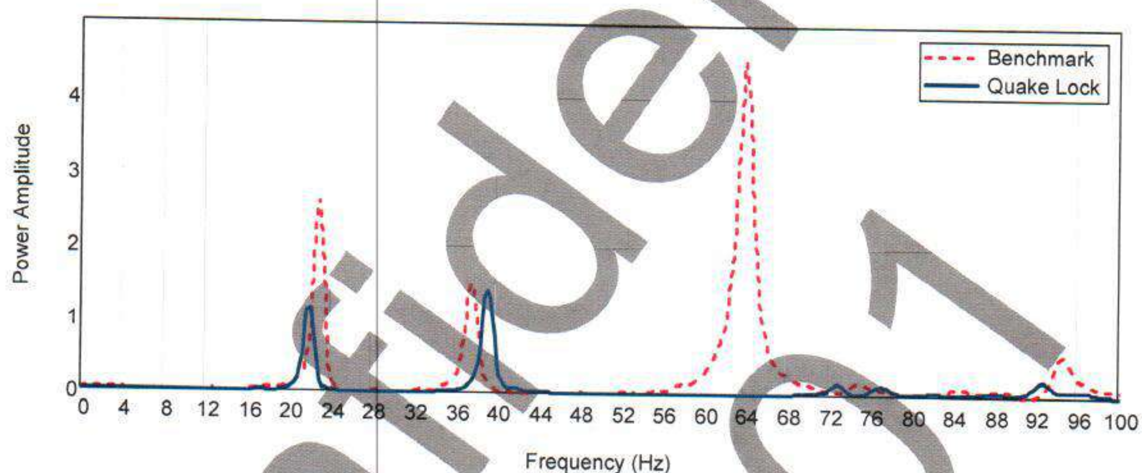


Figure 16: Fourier Amplitude of the response of the specimens – impact at point B



(a)



(b)

Figure 17: Power Spectra of the response of the specimens – impact at point B: a) Lumber joist deck; b) I-joist deck

8. Conclusions

Important observations from these tests include:

1. The results of in-plane shear tests showed that deck specimens strengthened with Quake Lock™ were stronger and stiffer than those without such a system. In monotonic tests, QL system increased the ultimate shear strength of the lumber joist deck and the I-joist deck 20% and 25%, respectively. The initial stiffness of the lumber joist deck was increased 30% while the stiffness of the I-joist deck did not show significant increase.

2. The monotonic tests on benchmark specimens showed that ultimate shear strength of the I-joist deck is 50% higher than the lumber joist deck. Both systems had a comparable initial stiffness but exhibited different post peak responses. The specimen with I-joist sustained large inelastic deformation with progressive strength degradation. In contrast, the specimen with lumber joist showed rapid strength reduction after the peak load was reached.

3. The monotonic curves of both type of decks agreed in general with the envelope of the reversed cyclic curves. Elastic stiffness and initial yielding drift of each type of specimens were similar in the monotonic and cyclic tests. The cyclic test of lumber joist deck showed a pinched hysteretic behavior. This specimen sustained large inelastic deformation cycles with progressive strength degradation. However, the specimen with I-joist showed a very rapid strength reduction due to sudden brittle failure which occurred in the web joist close to the fixed end.

4. Failure of the lumber joist deck without QL was localized at the end beam. It was developed by separation of the joists and panels from the end transverse beam. Adding QL system to the deck resulted in a uniform failure along the specimen. It happened by rotation of the panels, shear deformation of the nails and separation of the panels from the perimeter joists. Similar behavior was observed in the cyclic test.

5. Failure of the I- joist deck without QL was distributed along the specimen with shear deformation of the nails, rotation of the panels and separation from the perimeter joists. Local separation of the panels from the end beam occurred in both monotonic and cyclic testing following the brittle failure of the web joist close to the fixed end.

6. Deflection test results showed that the QL system increased the out-of-plane stiffness of the wood decks. Vertical deflection at the center of the decks due to surcharge loads in the middle of the deck was decreased 35% for lumber joist and 22% for I-joist decks.

7. In vibration tests the specimens with QL demonstrated higher damping ratio and stiffness under impact loads than the specimens without QL. The natural frequencies of the specimens for 2nd and 3rd modes of vibration were increased by the QL. This difference was not observed for the 1st mode of vibration which was related to the whole setup.

Although it is recognized that additional testing is required to confirm this same kind of observed behavior for other types of decking systems, it is clear from these tests that adding QL system to the wood deck diaphragm improves the performance of the deck.