Project Code (if known) : **T1 – 3 – C1**	Project Title : **Innovative CLT Building Systems – Localized Rolling Shear Reinforcement**
Network Theme : **Theme 1 : Cross laminated timber – material characterization and structural performance**	
Start Date : Month/Year : **01 / 2013**	Completion Date: Month/Year : **12 / 2015**
Lead Investigator / Institution : **Dr. Frank Lam / University of British Columbia**	
University Co-Investigator(s) / Institution(s) : **Dr. Terje Haukaas / University of British Columbia**	
FPInnovations Co-Investigator(s) **Dr. Marjan Popovski / FPInnovations**	
Industrial collaborator(s) / organization(s) : CST Innovations, Structurlam Products	
HQP (HQP code if known) : **MSC?-T1 (Y4-5)**	

1. Background *(1/2 - 1 page, problem statement, brief review of past and current relevant research, degree of consultation with stakeholders)*

Cross laminated timber (CLT) panels are vulnerable to situations of high shear forces, because such forces can invoke some of the weak properties of wood, particularly rolling shear and compression perpendicular to grain. High shear forces can arise at point-loaded support conditions, as well as at supports of beam with low span-to-depth ratios. Recently, a few research studies have explored the reinforcement of CLT panels against rolling shear failures. Colling et al. (2007), in an unpublished report, observed that the installation of inclined self-tapping wood screw can substantially enhance the load carrying capacity of CLT panels against rolling shear failures. Mestek et al. (2011) studied this problem in detail and investigated the use of self-tapping wood screws as a means to reinforce vacuum-formed CLT with stress relief grooves against rolling shear failures.

Mestek et al. (2011) observed that the confining effects from compression perpendicular to grain can enhance the rolling shear strength by around 20%, conservatively estimated. Furthermore, it was observed that the smaller the ratio between the width of the gap between laminae or relieve groove and the thickness of the laminae, the smaller the rolling shear capacity. Results further indicate that significant improvements in load carrying capacity against rolling shear failures can be observed in CLT panels reinforced with 8 mm diameter self-tapping wood screws. The amount of improvement depends on number of screws, screw spacing, screw diameter and type, and screw installation angle. For a variety of beam cases, up to 64% increase in load carrying capacity was observed. Under two-way load-carrying action, an even more significant increase in load carrying capacity of the plates was observed. These increases cannot be explained by stress calculations from FEM approaches. Instead, the differences were attributed to stress dispersion, redistribution, and dowelling effects by the activation of normally less stressed areas of the panel.

In Canada, CLT products are typically made with thicker laminae compared to European CLT products. This may have a negative influence on their rolling shear strength properties. Therefore, there is a need to further study reinforcement techniques against rolling shear failures in Canadian CLT products, such that the benefits of reinforcement observed in earlier studies can be examined. Furthermore, design approach suggested by Mestak et al. (2011) needs to be evaluated with Canadian-made CLT, particularly in the context of reliability-based design, before such techniques can be widely adapted in practice.

FPInnovations has identified industrial buildings as a potential market for application of CLT. We will consult Dr. Popovski of FPInnovations on this project and we will also work with Canadian CLT producers to develop technical knowledge to address the identified research gap.

2. Objectives *(1/4 page, long-term goals of research, project objectives and, if appropriate, specific objectives of each sub-project)*

The long-term goal of research is to develop fundamental understanding of how to improve the rolling shear capacity of Canadian made CLT products, by:

- Developing a database on rolling shear capacity of reinforced CLT panels.
- Establishing reliability-based design provisions on rolling shear reinforcement of CLT panels.

3. Research Method *(1/2 – 1 1/2 page, proposed approach highlighting areas of innovation, roles of graduate students and PDF, relationship to on-going and other proposed research (if appropriate), and key deliverables)*

Full scale testing will be conducted to establish the rolling shear capacity of Canadian made CLT panels, with and without reinforcements where such failure modes are expected. The panels will be considered as beam elements as well as plate elements, where different boundary conditions will be studied. In the beam elements the boundary conditions will include cases with simple supports, support conditions induced by typical fixity methods, and intermediate support over multi-span panels. In two-way plate elements, the boundary condition to be considered will include point supports from columns, represented by simple supports, as well as support conditions induced by typical fixity methods. The new database will also include the evaluation of different arrangements of reinforcements.

Based the experimental data from this study and UBC's existing database on the withdrawal behavior of self-tapping screws, probabilistic models will be developed so that reliability-based design procedures can be established in consistent with the design principles of CSA-086. Here the random characteristics of the rolling strength properties of the CLT panels as well as the reinforcements must be considered to establish the reliability index versus performance factor relationship for various conditions under the stochastic loadings.

4. Training of HQP, and interaction with FPInnovations scientists and practitioners/industry *(1/4 - 1/2 page, nature of involvement of FPInnovations and other scientists and training of HQP, highlight nature and frequency of contacts)*

This project will engage one MASc student. The student will be responsible for the experimental and analytical components of the work.

Dr. M. Popovski of FPInnovations, A. Ceccotti of IVALSA Italy, and G. Schickhofer of TU Graz will be research collaborators. Face-to-face project meetings will be scheduled whenever convenient given the logistics of involving the participation of our international collaborators. Teleconference can also be arranged.

It is also noted that the student enrollment takes place in September of each year in the University system. Thus, the proposed project start date in January is awkward. It is therefore emphasized that the student might possibly commence the studies in September following the January start date.

5. Schedule, Milestones and Deliverables *(Describe the work schedule and provide milestones for completion of major project components and list deliverables. This information will be used to evaluate progress when progress reports are considered. Note if the project contains more than 1 HQP, milestones and deliverables should be provided for each.)*

Year	Milestone/Deliverable	Month due
2013	Student recruitment Conduct Literature review Student complete course work component of their studies. Plan full scale testing.	End of Year 1
2014	Complete full scale testing Conduct reliability analysis for rolling shear reinforcement of CLT walls Make rational design recommendations based on reliability design approach	End of Year 2

6. Funding

Note that funding will be allocated based on the table shown below.

HQP	Stipends	Research expenses	Travel
Master student (2 yr max)	$16500	$4000	$3000

Funding is requested for one Master student for two years Y4 to Y5 ($23,500 per year for two years).

7. References

Mestek P., H. Kreuzinger, and S. Winter (2011) Design concept for CLT - Reinforced with self-tapping screws. In proceedings of the 44th Meeting International Council for Research and Innovation in Building and Construction Working Commission W18 - Timber Structures CIB W18 Alghero, Italy. Paper 44 - 7 – 6. 14 pp.

Colling, F. and S. Bedö (2007) Prüfbericht Nr.: H06-01/1-ZE-PB; Kompetenzzentrum Konstruktiver Ingenieurbau, Abteilung Holzbau, Fachhochschule Augsburg, unpublished.

8. Dissemination and implementation of research results

Dissemination :-

Format (fill in those that apply)	Target audience / level	No.
Thesis	Students, academic colleagues	1
Journal article	Peers in the field	1
Conference proceedings	Students, colleagues, and peers in the field	1
Research report		0
Others (specify)		N/A

Implementation:-

Implementation process (fill in those that apply)	Brief description of technical information to be implemented	Additional technical work required that will facilitate implementation
Design guideline document		
Production guideline document		
Technical note		
Information leading to change proposal for building code	Reliability based factors and provision for rolling shear reinforcement of CLT panels	
Information leading to change proposal for design standard		
Information leading to change proposal for test or product standard		

Computer program		
Others (specify)		

Project Code (if known) : **T1-4-C1**	*Project Title :* **Development of Non-destructive (NDT) Technique for CLT Grading and Quality Control**
Network Theme : **Theme 1 : Cross laminated timber – material characterization and structural performance**	
Start Date : Month/Year : **01 / 2013**	*Completion Date: Month/Year :* **12 / 2014**
Lead Investigator / Institution : **Dr. Ying-Hei Chui / University of New Brunswick**	
University Co-Investigator(s) / Institution(s) :	
FPInnovations Co-Investigator(s) **Dr. Lin Hu / FPInnovations**	
Industrial collaborator(s) / organization(s) : **Nordic Engineered Wood**	
HQP (HQP code if known) : **MSc3-T1 (Y4-5)**	

1. Background *(1/2 - 1 page, problem statement, brief review of past and current relevant research, degree of consultation with stakeholders)*

CLT is an engineered wood product that is highly orthotropic. Determination of its key elastic stiffness properties, such as pure elastic moduli and shear moduli, is critical in its application. Some of these properties can be estimated from component properties, but a reliable test method is required to verify the calculated values and for experimental characterization of these properties. Measurement of elastic properties using traditional static test procedures is tedious and in some cases practically impossible due to the difficulties in inducing a pure bending or shear. Vibration test technique offers an alternative in determining these elastic properties. A major benefit of vibration test is that a number of elastic properties can be measured from a single test. It also eliminates the need to use heavy loading equipment which is necessary for testing full-size CLT panels. This type of testing technique has been successfully applied to beam-like products such as dimension lumber and wood I-joists to provide flexural stiffness and shear rigidity (Chui 1991, Tardif 2000).

The same vibration test concept can be extended to determine elastic properties of plate-like products such as CLT. The orthotropic plate vibration theory shows that the natural frequencies of an orthotropic plate are a function of the plate mass and its elastic constants. In theory, all 9 elastic constants (3 Young's moduli, 3 shear moduli and 3 Poisson's ratios) can be estimated from vibration test based on 9 measured natural frequencies, and the use of mechanics models that relate the elastic constants to these natural frequencies. The mathematics involved often requires the iterative solution of these mechanics-based equations which are often complex and non-linear. Therefore in practice only a few elastic properties can feasibly be determined experimentally using this approach.

Lau and Tardif (1996) and Larsson (1997) were among the first researchers to measure wood-based panels using vibration test method. Lau and Tardif (1996) used a cantilever support arrangement to test thin oriented strand board (OSB) panels under torsional vibration. Their machine, known as TorBend, provides E_{xx} and G_{xy} only. One weakness of TorBend is that a clamped support condition is difficult to achieve in practice for wood-based material due to wood's natural softness. Larsson's method (Larsson 1997) uses free-free support condition that provides the elastic properties of thin orthotropic plates, namely the moduli E_{xx}, E_{yy} and G_{xy} and the Poisson's ratio, v_{yx}. Larsson's method is based on vibration (modal) tests and the use of a finite element (FE) model. An iterative process was used in which the elastic properties of the FE model were changed until the numerical natural frequencies matched the measured values from the vibration test. OSB was used as test panel to demonstrate his method. The elastic properties measured from static tests were compared with results from vibration tests on the same specimens. The results showed some deviations which Larsson attributed to the small dimensions of the test specimens and creep, since the static tests on the small specimens were carried out before the vibration tests were undertaken. The use of finite element model and the need for iterative calculation make the application of this approach difficult.

Sobue and Katoh (1992) present a paper on the determination of the orthotropic elastic constants of plywood boards by use of a plate vibration method. The elastic moduli E_{xx} and E_{yy}, and the in-plane shear modulus G_{xy} are determined simultaneously by the determination of three natural frequencies. In the proposed test method, the test panel is supported at one edge and tested in a vertical orientation. This test arrangement allows 3 simple equations to be derived based on orthotropic plate theory. No iterative calculation is required. The elastic properties determined by the vibration method match well with those measured by static bending and twisting tests.

The most recent work on this topic was by Gsell and his co-workers (Gsell et al. 2007). They present a vibration testing method developed for the simultaneous evaluation of two Young's moduli (E_x and E_y) and three shear moduli (G_{xy}, G_{yz} and G_{xz}) of a CLT panel. The evaluation procedure works as follows. First, the overall stiffness properties of CLT panels were calculated by composite theory based on assumed material characteristics. In the next step natural frequencies and mode shapes of the plate specimen were evaluated by experimental modal analysis in free-free boundary conditions followed by a theoretical modal analysis based on Reddy's plate theory (Reddy 1984) and the initially calculated elastic properties. The resulting natural frequencies and mode shapes of experimental and theoretical modal analysis were compared. The calculated elastic properties were adjusted within an optimization process until natural frequencies and mode shapes of experimental and theoretical analysis match. The method was able to determine 4 of the 5 elastic constants for all tested specimens. It was also found that calculations based on commonly used elastic properties could lead to over-estimated results. A significant drawback of this method is that solution is difficult to achieve and is subjected to the choice of initial estimates. The implementation of the Reddy's plate theory requires the use of a computer and a significant level of user intervention appears necessary. Based on a review of literature and the work conducted to-date at UNB under projects T1-1-C1, T1-2-C1 and T3-5-C2 which used the Sobue and Katoh (1992) method to characterize CLT properties, it appears that the Sobue and Katoh method provides a fairly accurate estimate of the three elastic properties. This method also has the best potential to be implemented as an in-plant testing technique for grading or quality control purposes due to its simplicity. Although a drawback of this method is the smaller number of properties that can be measured, it provides the 3 most important elastic properties required for design purposes.

2. Objectives *(1/4 page, long-term goals of research, project objectives and, if appropriate, specific objectives of each sub-project)*

The long-term goal of this project is to lead to the development of a device that can be used as testing tool for evaluating the 2 elastic and shear moduli of cross laminated timber panel. However, prior to that a number of technical issues need to be addressed. These will be studied in this project. The specific objectives of this project are:

- To evaluate the influence of support condition on the measured natural frequencies, and propose a clamping system for testing CLT panel.
- To compare the elastic properties measured using the proposed vibration test technique and those measured using conventional static methods.
- To develop an algorithm that allows identification of the three correct natural frequencies from measured spectrum signals.

3. Research Method *(1/2 – 1 1/2 page, proposed approach highlighting areas of innovation, roles of graduate students and PDF, relationship to on-going and other proposed research (if appropriate), and key deliverables)*

In the first instance, single layer and 3-layer scaled CLT panels will be fabricated and tested using the proposed test methods to identify the appropriate natural frequencies. Prior to panel fabrication, the laminates that are used for making the scaled CLT panels will be tested for elastic and shear moduli using the beam vibration method developed by Chui (1990). The panel vibration tests will be conducted using different clamping pressure levels at the supported edge. The test panel will be clamping at one edge and impacted by an instrumented hammer. The response at 3 locations will be measured simultaneously using accelerometers. Although only 3 natural frequencies are required for the calculation, the first 8 natural frequencies will be obtained to allow the most appropriate 3 natural frequencies to be identified. This work is necessary because not all natural frequencies have the same sensitivity to changes in elastic properties. From the perspective of ensuring the best accuracy of the calculated values, it is desirable to identify the three natural frequencies that are most sensitive to the elastic properties that are of interest. A few clamping details, including a steel angle and round pipe, will also be studied. The clamping pressure will be controlled by a hydraulic jack. After the vibration tests, static bending and torsional tests will be conducted to measure the two elastic and in-plane shear moduli. The measured properties from vibration test at different clamping details will be compared with the static test results, which will be treated as the reference values for identifying the appropriate frequencies for calculation purposes and the clamping details and pressure.

The measured spectrum data from the above vibration tests will be used in the development of an algorithm that can identify the 3 appropriate natural frequencies for calculation of elastic properties. A key challenge is to identify the correct mode shapes from the three accelerometer responses. It is expected that the algorithm will extract the 3 correct natural frequencies from the vibration spectra of each panel.

Once the above work is complete which will allow the project team to fulfill the 3 objectives above, the final work will be expanding the test technique to full-size CLT panels. A portable device for clamping a panel edge will be fabricated. The clamping device will be brought to a CLT producer for testing of panels after they are produced. This will provide an initial assessment of the application of the proposed test technique in grading or controlling quality of CLT panels in a manufacturing facility.

4. Training of HQP, and interaction with FPInnovations scientists and practitioners/industry *(1/4 - 1/2 page, nature of involvement of FPInnovations and other scientists and training of HQP, highlight nature and frequency of contacts)*

This project will be undertaken in years 4-5 by a MSc student (MSc3-T1) under the supervision of Dr. Ying-Hei Chui at UNB. FPInnovations collaborator will be Dr. Lin Hu. Dr. Hu has substantial NDT experience and she will act as an advisor to the graduate student. The graduate student will interact with graduate students, MSc1-T1, PhD1-T1 and PhD3-T3, who are working in projects T1-1-C1, T1-2-C1 and T3-5-C2 respectively at UNB. A student with an appropriate technical background has been recruited to work in this project, and he will commence in January 2013.

5. Schedule, Milestones and Deliverables *(Describe the work schedule and provide milestones for completion of major project components and list deliverables. This information will be used to evaluate progress when progress reports are considered).*

Year	Milestone/Deliverable	Month due
2013	Fabrication of scaled CLT panels Vibration testing of scaled CLT panels with different clamping details	July November

2014	Development of algorithm Static testing of scaled CLT panels Development of clamping device Mill trial	January April July December

6. Special request *(If there is any special funding request provide details and justification. See notes for allocated funds for stipends, research expenses and travel.)*

Notes:

1/ Allocated cost per MSc student/yr (2 years max): stipends = $16,500, Research cost = $4,000, Travel = $3,000
2/ Allocated cost per PhD student/yr (3 years max): stipends = $19,000, Research cost = $4,000, Travel = $3,000
3/ Allocated cost per PDF per year (2 years max): stipends = $40,000, Research cost = $5,000, Travel = $4,000

7. References

Chui, Y. H. 1991. Simultaneous evaluation of bending and shear moduli of wood and the influence of knots on these parameters. Wood and Fibre Science. 25, 125-134

Gsell, D., Feltrin, G., Schubert, S., Steiger, R., and Motavalli, M. 2007. Cross-laminated timber plates: Evaluation and verification of homogenized elastic properties. J. Structural Engineering 133(1): 132-138.

Lau, P.W.C. and Tardif, Y. 1996. Evaluation of moduli of elasticity and rigidity of panel products by torsional-bending vibration". Report of project No. 3110M464 to Canadian Forest Service, Forintek Canada Corp. Ottawa.

Larsson, D. 1997. Using modal analysis for estimation of anisotropic material constants. Journal of Engineering Mechanics. 123(3), p.222-229.

Sobue, N. and Katoh, A. 1992. Simultaneous Determination of Orthotropic Elastic Constants of Standard Full-Size Plywoods by Vibration Method. 895-902. Journal of Japan Wood Research Society (*Mokuzai Gakkais*). 38(10), p. 895-902

Tardif, Y. 2000. Validation of transverse vibration dynamic test method for solid beams and engineered wood joists. Report #2392 to Canadian Forest Service, FPInnovations – Forintek Division, Quebec City, QC.

8. Dissemination and implementation of research results

Dissemination:-

Format (fill in those that apply)	Target audience / level	No.
Thesis	Scientific community	1

Journal article	Wood product journal Engineering mechanics journal	2
Conference proceedings	Non-destructive testing conference Word Conference in Timber Engineering (2014)	2
Research report		
Others (specify)		

Implementation:-

Implementation process (fill in those that apply)	**Brief description of technical information to be implemented**	**Additional technical work required that will facilitate implementation**
Design guideline document		
Production guideline document		
Technical note		
Change proposal for building code		
Change proposal for design standard		
Change proposal for test or product standard	A potential vibration test method for any wood-based panel product, such as CLT, plywood, OSB and SCL.	
Computer program	A computer program to extract vibration mode and natural frequencies from spectrum data	
Others (specify)	Technology that can be licensed to the industry for commercialization.	Implementation of the technology in a prototype device

Project Code (if known) : **T1 – ~~2~~ 10 – C4**	*Project Title :* **Innovative post-tensioned CLT walls**
Network Theme : **Theme 1 : Cross laminated timber** **– material characterization and structural performance**	
Start Date : Month/Year : **01 / 2013**	*Completion Date: Month/Year :* **12 / 2015**
Lead Investigator / Institution : **Dr. Frank Lam / University of British Columbia**	
University Co-Investigator(s) / Institution(s) : **Dr. Terje Haukaas / University of British Columbia**	
FPInnovations Co-Investigator(s) **Dr. Marjan Popovski / FPInnovations**	
Industrial collaborator(s) / organization(s) : CST Innovations, Structurlam Products	
HQP (HQP code if known) : **PDF?-T1 (Y4-5); MSC?-T1 (Y4-5)**	

1. Background *(1/2 - 1 page, problem statement, brief review of past and current relevant research, degree of consultation with stakeholders)*

Cross laminated timber (CLT) can be manufactured in lengths of 16 m. Panels up to this length can be used to form vertical elements in buildings to resist seismic action. However, typically these panels are cut into small sizes to form wall elements. They are then further connected to each other via self-tapping wood screws or commercially available steel angle brackets or slotted in T beams to transfer the shear forces between each other and into the foundation. Because of the high rigidity of the panels in comparisons with the connections, hold-downs are also provided to prevent uplifts. Nevertheless observations from shaking table tests of a full scale CLT building indicate a degree of racking motion as the rigid panels slipped relative each other under high lateral loads. If CLT elements, regardless of size, were used to build elevator or stair shaft to form a shear core in midrise construction to resist lateral loads, the high aspect ratio (height to width) of this type of structure can also result in significant uplift and rocking type behaviour during strong motion earthquakes.

University of Canterbury has adapted a post-tensioning technology, originally developed for post-tensioning of concrete members in high-rise buildings, to glue-laminated timber and laminated veneer lumber moment resisting frame structure (Buchanan et al. 2011, Newcombe et al. 2010, Palermo et al. 2010, Pampanin et al. 2006 and Van Beerschoten et al. 2011). The main advantages of this type of system are the use of cost effective energy dissipation fuse devices and self-centering features of the post-tensioning. So even under strong motion shaking the building would return to its original undamaged position and the damaged energy dissipating devices can be replaced at a low cost. This technology can significantly improve seismic safety of buildings and control damage induced by earthquake. Post-tensioning technology has not been applied to CLT systems as tall walls. There is a unique opportunity to marry the stiff CLT tall wall system with a form of the post-tensioning systems with self-centering and energy dissipating features.

CLT is recognized as an important engineered wood product that can help expand the application of structural wood products in mid-rise to tall buildings. We will be in consultation with Dr. Popovski of FPInnovations on this project. We will also work with Canadian CLT producers to develop technical knowledge to address this issue and relate the CLT performance to the manufacturing parameters of Canadian CLT products.

2. Objectives *(1/4 page, long-term goals of research, project objectives and, if appropriate, specific objectives of each sub-project)*

The long-term goal of research is to develop fundamental understanding of the performance of post tensioned CLT walls in the context of reliability based design. The project objectives are:

- Develop a database to study the behavior of post tensioned CLT walls.
- Develop verified computer models to predict the performance of post tensioned CLT walls.
- Develop reliability based design code provisions to address post tensioned CLT wall systems.

3. Research Method *(1/2 – 1 1/2 page, proposed approach highlighting areas of innovation, roles of graduate students and PDF, relationship to on-going and other proposed research (if appropriate), and key deliverables)*

Post-tensioning of tall CLT walls will be studied by combined experimental and modeling approaches. Monotonic and reverse cyclic tests will be performed in CLT shear walls with and without application of the post-tensioning tendon to obtain their monotonic load deformation and hysteresis behaviour. Energy dissipating mechanisms will also be introduced at the bottom corners of the wall. It is anticipated a flag-like hysteresis behaviour will be obtained with the post-tensioning and energy dissipation techniques. The properties of the tendon and energy dissipation devices will be established in small specimen tests. A mechanistic model will be developed to consider this behaviour and calibrated against the test results. The model will be coupled with CLT shear wall analysis program to allow prediction of reverse cyclic behaviour of the walls. Full scale wall test results will be used to verify the program predictions. The verified model will be expanded to consider dynamic analysis. It will be used to study the performance of post-tensioning of tall CLT walls with energy dissipation devices against earthquake excitation in nonlinear time step analysis using reliability approaches. The probability of failure of these systems as a function of peak ground acceleration and carried mass will be established. This information will lead to establishing the design parameters such as force modification and ductility factors in design and building codes.

4. Training of HQP, and interaction with FPInnovations scientists and practitioners/industry *(1/4 - 1/2 page, nature of involvement of FPInnovations and other scientists and training of HQP, highlight nature and frequency of contacts)*

This project will train a PDF (PDF?-T1) and a MSc (MSc?-T1) student under the supervision of the proponents for years 4 and 5. The PDF will develop expertise in the topic of reliability analysis and model development of post tensioned CLT walls. The MSc student will be responsible for the experimental component of the work.

Dr. M. Popovski of FPInnovations, A. Ceccotti of IVALSA Italy and A. Buchanan University of Canterbury will be research collaborators. If possible face to face project meetings will be scheduled whenever convenient given the logistics of involving the participation of our international collaborators. Teleconference can also be arranged.

It is also noted that the student enrollment takes place in September of each year in the University system. Thus, the proposed project start date in January is awkward. It is therefore emphasized that the student might possibly commence the studies in September following the January start date.

5. Schedule, Milestones and Deliverables *(Describe the work schedule and provide milestones for completion of major project components and list deliverables. This information will be used to evaluate progress when progress reports are considered. Note if the project contains more than 1 HQP, milestones and deliverables should be provided for each.)*

Year	Milestone/Deliverable	Month due
2013	Recruitment of student and PDF Conduct Literature review (MASc and PDF) Student complete course work component of their studies. Initiate model development of detailed mechanistic model (PDF)	End of Year 1
2014	Completed experimental component of the study (MASc) Completed model development and verify model (PDF) Conduct reliability analysis (PDF) Make rational design recommendations based on reliability design approach (PDF)	End of Year 2

6. Funding

Note that funding will be allocated based on the table shown below.

HQP	Stipends	Research expenses	Travel
MSc student (2 yr max)	$16500	$4000	$3000

PDF (2 yr max)	$44000	$5000	$4000

Funding is requested for one MSc student for two years Y4-5 ($23,500 per year for two years) and one PDF for two years Y4-5 ($53,000 per year for two years).

7. References

Buchanan, A.H., A. Palermo, D. Carradine, and S. Pampanin. (2011). Post-tensioned timber frame buildings". The Structural Engineer 89(17): 24-30.

Newcombe, M., M. Cursiel, S. Pampanin, A. Palermo, A. and A. Buchanan. (2010). Simplified design of post-tensioned timber frames. In proceedings of the 43rd Meeting International Council for Research and Innovation in Building and Construction Working Commission W18 - Timber Structures CIB W18, Nelson, New Zealand.

Palermo, A., S. Pampanin, D. Carradine, A. Buchanan, B. Lago, C. Dibenedetto, S. Giorgini, and P. Ronca. (2010). Enhanced performance of longitudinally posttensioned long-span LVL beams. In proceedings of 11th World Conference on Timber Engineering, Trentino, Italy. CD ROM Proceedings.

Pampanin, S., A. Palermo, A. Buchanan, M. Fragiacomo, M. and B. Deam. (2006). CodeProvisions for Seismic Design of Multi-Storey Post-Tensioned Timber Buildings. In proceedings of the 39th Meeting International Council for Research and Innovation in Building and Construction Working Commission W18 - Timber Structures CIB W18, Florence, Italy.

Van Beerschoten, W., T. Smith, A. Palermo, S. Pampanin, F.C. Ponzo. (2011). The Stiffness of Beam-Column Connections in Post-Tensioned Timber Frames". In proceedings of the 43rd Meeting International Council for Research and Innovation in Building and Construction Working Commission W18 - Timber Structures CIB W18, Nelson, New Zealand.

8. Dissemination and implementation of research results

Dissemination :-

Format (fill in those that apply)	**Target audience / level**	**No.**
Thesis	Students, academic colleagues	1
Journal article	Peers in the field	2
Conference proceedings	Students, colleagues, and peers in the field	2
Research report		0
Others (specify)		N/A

Implementation:-

Implementation process (fill in those that apply)	**Brief description of technical information to be implemented**	**Additional technical work required that will facilitate implementation**

Design guideline document		
Production guideline document		
Technical note		
Information leading to change proposal for building code	Reliability based design procedures for Post tensioned CLT walls	
Information leading to change proposal for design standard		
Information leading to change proposal for test or product standard		
Computer program		
Others (specify)		

Project Code (if known) : **T3-?C2**	*Project Title :* **INNOVATIVE WAYS TO MAKE CLT PANELS SOUND-ABSORPTIVE**
Network Theme : **Theme 3 – Building systems: fire performance, acoustic and vibration serviceability**	
Start Date : Month/Year : **09 / 2013**	*Completion Date: Month/Year :* **08 / 2015**
Lead Investigator / Institution : **Dr. Murray Hodgson / University of British Columbia**	
University Co-Investigator(s) / Institution(s) : **Dr. Frank Lam / University of British Columbia**	
FPInnovations Co-Investigator(s) **Dr. Ciprian Pirvu / FPInnovations**	
Industrial collaborator(s) / organization(s) :	
HQP (HQP code if known) : **MSc11-T3 (Y4-5)**	

1. Background

Internal building surfaces–for example, walls and floor-ceiling slabs–made of materials like cross-laminated timber (CLT) are highly sound-reflective. This can lead to highly reverberant and ’noisy’ acoustical conditions and occupant dissatisfaction in the building’s spaces [1]. In the case of sound-reflective ceiling slabs, sound absorption is usually added by way of a suspended acoustical ceiling, ceiling ‘clouds’ or, in some cases, acoustical baffles [2]. However, when the ceiling is part of the aesthetic design, or is a thermal slab, these options may not be acceptable–innovative ways must be found to introduce sound absorption. While the sound-transmission characteristics of CLT panels have been the focus of much research [3], their sound-absorption characteristics and how to improve them have not.

This project will investigate one option for improving the sound absorption–based on integrating an array of Helmholtz-resonator (HR) absorbers into the CLT panels. An HR absorber consists of a cavity of some volume in a solid medium, optionally filled with a porous sound absorber, connected to the external sound field by a neck of some shape, cross-sectional area and length. It provides high sound absorption at and near its resonance frequency, which depends on the HR dimensions.

The work will build on the results of a recent investigation for FPInnovations into the use of HR absorbers to solve a similar problem, in the case of profiled, wooden architectural panels [4]. The new project will be conducted by a Masters student in the UBC Acoustics & Noise Research Group at UBC, under the direction of Professor Murray Hodgson, in collaboration with Dr. Frank Lam (UBC Wood Science) and the Wood Science Lab, and Dr. Ciprian Pirvu of FPInnovations.

They will provide on-going support with respect to wood science and CLT construction and performance, as well as access to facilities for constructing and testing CLT test panels.

2. Objectives

Following are the main objectives of the proposed research:

a. review current methods for measuring the random-incidence absorption coefficient (RIAC) of architectural panels, the theory for predicting HR absorption, and the current design/ construction specifications for CLT panels
b. establish sound-absorption performance targets and design criteria
c. develop two or three prototype designs for the target applications
d. create test panels and measure their sound absorption
e. refine designs, retest to establish commercially-viable designs
f. consider the practicalities of commercial production of the prototype designs
g. investigate other aspects of performance of the prototype designs.

3. Research Method

Following are details of how the research phases will be achieved:

a. Current methods for measuring the random-incidence absorption coefficient (RIAC) of architectural panels will be consolidated. Work will focus on three methods for which experimental facilities are available to UBC: 1. the impedance-tube method, whereby the normal-incidence absorption of a 10-cm-diameter sample is measured; we will investigate whether measurements on a single HR absorber are representative of the RAIC performance and useful at the design stage; 2. the spherical-decoupling method, whereby the angularly-varying normal acoustical impedance of a minimum 5-m^2 sample, from which the RIAC can be calculated, is measured in an anechoic chamber, and; 3. the reverberation-room method, whereby the RAIC of a minimum 5-m^2 sample is found from the change in reverberation time due to the absorber in a reverberation chamber (i.e., a squash court).

   Existing theoretical models for predicting the sound absorption of HR absorbers with various neck shapes (circular, rectangular, slot, etc.) [5] will be reviewed and coded.

   With the assistance of project collaborators, current design and construction specifications for CLT panels will be reviewed to determine the typical and feasible values of physical characteristics like board dimensions, number of layers, etc. [6].

b. Sound-absorption performance targets and design criteria and for various room-acoustical applications will be established with the help of acoustical consultants.

c. Based on these design criteria, two or three prototype designs of CLT HR absorbers will be established for the target applications. These will involve cavities and necks of various sizes and shapes; an array of HR absorbers will be created by leaving spaces of variable lengths between variable numbers of internal boards of a CLT panel, and/or drilling or milling holes or slots into them through the external boards to give the desired absorption characteristics.

d. Test panels of the prototype designs will be created in the UBC Wood Science Lab or at FPInnovations. These will be measured for sound absorption and evaluated with respect to the performance targets. The effect of introducing porous sound absorption into the internal HR cavities to increase damping and broaden the absorption frequency response will be tested and evaluated.

e. On the basis of the experimental results, the prototype designs will be refined and retested to establish commercially-viable designs.

f. The practicalities of producing the final designs commercially will be considered in discussion with the project collaborators.

g. Relevant aspects of the performance of the new CLT HR-absorber panel designs other than sound absorption, and in particular the effects of the presence of the HR cavities, will be investigated. If possible, this will be done with respect to airborne and flanking sound transmission in collaboration with NewBuildS partner Trevor Nightingale at the Institute for Research in Construction. It will also be done with respect to structural performance and mechanical vibration in the Wood Science Lab and/or at FPInnovations, in collaboration with the project collaborators. Fire resistance will also be considered, if possible.

4. Training of HQP, and interaction with FPInnovations scientists, practitioners/industry

Training of HQP

- This project will constitute the research project of an M.A.Sc. student in the Department of Mechanical Engineering at UBC
- An NSERC Undergraduate Summer Research Assistant will be employed from other funding to support the project.

Collaboration

- Project collaborators will provide on-going support with respect to wood science and CLT performance, as well as access to facilities for constructing and testing CLT test panels.
- Collaborators will support the project on an on-going, as needed basis; progress meetings will be held as required and at least every 6 months.

5. Schedule, Milestones and Deliverables.

Year	Milestone/Deliverable	Month due
2013	- review state of the art; establish performance targets	December
2014	- develop, create and test prototype designs - submit progress report	March
2014	- refine, retest prototype designs - consider practical construction	August
2015	- investigate other performance aspects	May
2015	- thesis preparation, defence - final report, publication preparation	August

6. Special request – n/a

7. References

[1] M. Hodgson, “Acoustical evaluation of six ‘green’ office buildings”, J. Green Build. Res., 3(4) 108-118 (2008).

[2] J. Higgins and C. Crocker, “Review of thermal slabs”, Technical Report, University of British Ccolumbia (2012).

[3] S. Gagnon and C. Pirvu, “CLT Handbook: Cross Laminated Timber”. FPInnovations (2011).

[4] C. Bibby and M. Hodgson, “Characterizing and Improving the Acoustical Performance of Profiled Architectural Surfaces”, Report to FPInnovations (2009).

[5] T. Cox and P. D'Antonio, “Acoustic absorbers and diffusers: Theory design and application”, 2nd ed. London and New York: Taylor and Francis (2009).

[6] APA/ANSI PRG 320 - 2011. “Standard for Performance-Rated Cross-Laminated Timber”. APA - The Engineered Wood Association, Tacoma, WA (2011).

8. Dissemination and implementation of research results

Dissemination:-

Format (fill in those that apply)	Target audience / level	No.
Thesis	University examining committee	1
Journal article	Acoustical and/or building scientific community	1
Conference proceedings	InterNoise; Int. Building Physics Conference	2
Research report	NewBuildS research team, NSERC	1
Others (specify)		

Implementation:-

Implementation process (fill in those that apply)	Brief description of technical information to be implemented	Additional technical work required that will facilitate implementation
Design guideline document	Guidelines to help designers, engineers, builders, etc. when using such specialty products as sound-absorptive CLT panels.	
Production guideline document		
Technical note	Description of the design and performance of sound-absorptive CLT panels based on HR absorbers.	
Change proposal for building code		
Change proposal for design standard	Design method for CLT panels containing HR absorbers.	
Change proposal for test or product standard	A potential sound-absorption test method for any wood-based panel product, such as CLT.	
Computer program	A computer program for predicting the sound-absorption characteristics of HR-absorber designs.	
Others (specify)	Technology that can be licensed to the industry for commercialization.	