Structural Performance of Wood Diaphragms with Thick Panels

Project Leader:	Ciprian Pirvu, Building Systems, Wood Engineering Group, Vancouver Laboratory		
Program Area:	Building Systems	Start Date:	April 2005
Program Goal:	BS	Completion Date:	March 2008
Project No.:	4636	Date of Last Update:	March 26, 2007
Project Liaison(s):	Peggy Lepper, Canadian Wood Council; Steward Garden, Canadian Forest Products Ltd.; Paul Jaehrlich, CertiWood Technical Centre; Darian Wentland, Jager Building Systems Inc.; Bob Rosebrugh, Grant Forest Products Inc.		

Long Term Goals / Strategies

To expand the use of wood in non-residential applications by developing structural systems that are cost-effective while spanning long distances and carrying higher loads than systems made of dimension lumber and traditional sheathing thickness.

Key Objectives

- Provide research information suitable for implementing design procedures for diaphragms with thick sheathing in the Canadian Standard for Engineering Design in Wood (CAN/CSA O86.1).
- Make the information available to other markets by publishing the results and recommended procedures in a journal article.

Key Actions and Deliverables

Deliverables	Expected Delivery Date Completed Item ✓
Report on cost analysis and feasibility/competitiveness of a diaphragm system with thick panels, and recommendation from project liaisons on whether or not to proceed with project.	October 2005 ✓
Report on the mechanical behaviour of connections between thick wood-based panels and studs. Provide a set of data results from the nail connection tests using thick panels.	March 2006**
Report on the structural behaviour of diaphragms with thick wood-based panels. Provide a set of data and analysis resulting from tests of diaphragms.	March 2007 ✓
Develop analytical models that utilize the connection test data and validate the model with the full-size diaphragm tests.	October 2007
Develop a simplified design method for calculating shear load capacity and deflection of wood diaphragms using thick panels.	March 2008
Produce a final report presenting project findings and the simplified design method.	March 2008
Present research findings at appropriate national and international conferences, seminars and forums. Write technical papers in recognized journals.	March 2008

** The working outline for the lateral nail resistance tests was developed and testing will take place at the end of the fourth quarter of fiscal 2006/07 and beginning of the first quarter of 2007/08. Findings will be incorporated in the final report.

Status

Status 2005-06

The first step of the project was a cost analysis to determine if the diaphragm with thick panel concept is economically feasible. The systems considered in the cost analysis were originally designed as tall walls (each 16 ft long by 16 ft high). They were considered adequate for cost analysis purposes given: (i) the similarity in construction between diaphragms and shear walls, and (ii) the fact that the systems were already tested and experimental data was available. The main conclusion of the cost analysis was that if wood diaphragms with thick panels are appropriately designed, the increase in capacity may prevail over the increase in total cost involved in purchasing materials, and building the diaphragms.

The cost analysis draft was circulated among project liaisons and the feedback was positive, supporting continuation of the project.

Status 2006-07
In the second year of the project, work commenced with designing full-scale diaphragms and a test frame set-up that could be accommodated in Forintek's Wood Engineering Pilot Plant. Suggestions from project liaisons and the engineering community were considered and accommodated in the test matrix where feasible. The test matrix included construction details of fifteen 24 feet long by 8 feet wide diaphragms, made of 2×8 or 2×10 solid sawn lumber or laminated strand lumber for framing and plywood or oriented strand board for sheathing. Details of the diaphragm configurations and preliminary analysis are presented in the following chapters.

Partners
CertiWood Technical Centre
Structural Board Association
APA – The Engineered Wood Association

Rationale and Potential Impact
In the construction market, wood diaphragms with thick panels will be used mostly in non-residential construction, while a smaller percentage will be used in residential construction. When using thick panels, improved lateral resistance and deflection of diaphragms would generate better behaviour during earthquakes and high winds. Improved seismic and wind resistance of buildings using such diaphragms would also benefit building specifiers, their owners and insurance companies.

The CAN/CSA-O86-01 (CSA O86) currently provides shear resistance values for diaphragms made from panels with thickness ranging from 9.5 mm up to 18.5 mm. However, structural panels are now available in a wider range of thickness to accommodate specific customer demands. Since shear resistance values provided by CSA O86 for thin panels cannot be applied to thicker panels, new design values are needed for thicker panels. The project aims to provide designers and specifiers with a method to calculate shear resistance values for diaphragms using thick panels with thickness ranging from 18.5 mm to 31.5 mm. Ultimately, the new design values will be introduced into the CSA O86.

According to a recent study on non-residential wood product usage, only 1.2 billion square feet (Bsf) of structural panels were used in new non-residential construction in the United States in 1995 (McKeever and Adair, 1998). This is approximately equivalent to 10% of the total wood usage in the new residential construction sector and has been in decline since 1985. One of the major impediments to the use of wood in non-residential buildings is the lack of design data for wood systems other than those used in houses.

The value to the Canadian wood products industry of this missed market is potentially large. Using data from the McKeever and Adair study, and assuming 50% of the non-residential market is accessible for wood (Goetzl and McKeever, 1999), we can derive a missed market in the U.S. for structural panels of 4.8 Bsf, given a potential market of 6.0 Bsf (3/8" basis) and an actual use of 1.2 Bsf in 1995. In 2002 dollars, this translates to CAD$1.7 billion (using an average price of $350 Canadian per thousand square feet of plywood and OSB). Ultimately, if thick panel diaphragms were only 10% of the missed market, this would represent an annual market share of CAD$170 million.

Proposed Approach

The long-term goal of the project is to expand the use of wood in non-residential construction by developing cost-effective systems that could span longer distances and could carry higher loads than systems made of dimension lumber and regular sheathing thickness. This will be accomplished by evaluation of structural performance of diaphragms with thick panels subjected to lateral loads such as those generated by high winds and earthquakes. On the analytical side, the project aims to develop a design method to calculate shear resistance values for diaphragms with panels up to 31.5-mm in thickness. Research findings will provide considerations for implementing the new design method into the CSA O86.

Research activities proposed for the third year of the project (2007-08) include: i) completion of the nail slip connection tests; ii) development of a non-linear analytical model that would characterize structural behaviour of diaphragms with thick panels, iii) validate the model against experimental test data of full-scale diaphragms, collected during the second year of the project, and iv) report the findings at year-end. Research findings will be shared with the CSA O86 Committee at their annual meeting.

Work Completed this Fiscal Year

1. Full-Scale Diaphragm Tests

Test Matrix

A considerable amount of thought was put into the initial planning of the full-scale diaphragm tests. This included developing a test matrix with fifteen diaphragm configurations and designing the testing set-up. The test matrix was planned as to:

1. Reflect potential end-uses of the diaphragms with thick panels. Applications include large residential or non-residential buildings with longer spans that are able to resist higher loads.
2. Provide a linkage with the shear strength values for diaphragms published in CSA O86 (i.e., Table 9.5.2). The current values were developed for light frame structures and expanding the table will allow engineers to design diaphragms for larger structures using the same table.
3. Establish a link with the 1966 and 1978 APA diaphragm tests (Tissell, 1966; and, Tissell and Elliott, 1978). It is assumed that the current shear strength values specified in the CSA O86 are based on the APA tests. These tests are described in the APA Reports No. 106 and No. 138. The test matrix includes a couple of diaphragms in the test matrix have similar characteristics to the configurations tested by the APA.
4. Use wood products that are currently used in practice such as solid sawn lumber for framing and plywood for sheathing. However, given the potential end-use of the diaphragms, engineered wood products, such as laminated veneer lumber or laminated strand lumber for framing and oriented strand board (OSB) for sheathing, may be more suitable for achieving longer spans. Therefore, some configurations were built with such engineered materials.
5. Use a nail type that is extensively used in practice, such as spiral nails, which are known to have better performance that common nails.
6. Include adhesive in addition to nails for the sheathing-to-framing connections in some diaphragms.
7. Current Code for residential construction limits joist spacing in diaphragms to 2 ft on centre (oc) (Clause 9.5.3.2 in CSA O86). It is presumed that this limit was introduced in the code for shearwalls and then adopted for diaphragms. While restricting joist spacing might make sense for shearwalls sheathed with thinner panels to prevent bucking, a thick panel is very unlikely to buckle under load in a diaphragm configuration, therefore wider joist spacings were also considered.
8. Many factors influence the overall behaviour of diaphragms. We tried to focus on certain parameters, and when feasible, varied only one key parameter between configurations to allow for accurate comparison.

Diaphragm Construction

To start with, all the diaphragms were constructed as part of a larger diaphragm system. They were 24 ft long by 8 ft wide, because this is the largest diaphragm size that can be accommodated in Forintek's Wood Engineering Pilot Plant.

Table 1 shows a few construction characteristics of the diaphragms tested in this study. Several parameters were varied between configurations, such as: panel thickness, panel arrangement within diaphragm, nail size, nail spacing, joist spacing, etc. All material used for diaphragm construction was stored in the pilot plant at approximately 20±3ºC and 60±10%RH for at least two weeks.

Diaphragms D0 to D7 were built using double joists and chords of grade stamped No. 2 SPF lumber, while diaphragms D8 to D12-A were built with single joists and chords of 1.7E TimberStrand® LSL. The double joists were nailed together using a staggered nailing pattern alternating on both sides. The continuous double chords had bolted and nailed lap splices using a similar nailing pattern as the joists. Diaphragms D0 to D7 were blocked using 2×6 SPF flat blocking spaced at 4 ft oc, and supported by Strong-Tie® Z clips or using tongue and groove sheathing (i.e. diaphragms D1 and D2), while one configuration was completely unblocked (i.e. diaphragm D10). Flat blocking between the joists is a common practice to provide a wider support for all the panel edges and significantly reduce the likelihood of nails missing or splitting the blocking, which is frequently seen in the case of vertical blocking.

Diaphragms D8 to D12-A were built with end-nailed or toe-nailed vertical blocking. Most of the diaphragms had joists spaced at 4 ft oc, except one with joists spaced at 2 ft oc (i.e. diaphragm D9). One diaphragm configuration used an construction adhesive (i.e. elastomer) in addition to mechanical fasteners for sheathing-to-framing connections (i.e. diaphragm D12-A). In practice, construction adhesives are used for floor diaphragms.

Table 1: Construction details of diaphragms

Diaphragm Number	FRAMING			SHEATHING			
	Joists		Blocking	Panel		Nail Length & Diameter (in)	Adhesive
	Type	Spacing		Type	Orientation		
D0	2x8 #2 or better SPF	48" oc	Y	5/8" OSB	PER	2-1/2 x 0.131	N
D1	2x8 #2 or better SPF	48" oc	N	1-1/8" PLY-T&G	PER	2-1/2 x 0.131	N
D2	2x8 #2 or better SPF	48" oc	N	1-1/8" PLY-T&G	PER	2-1/2 x 0.131	N
D3	2x8 #2 or better SPF	48" oc	Y	1-1/8" PLY	PER	3-1/4 x 0.131	N
D4	2x10 #2 or better SPF	48" oc	Y	1-1/8" PLY	PER	3-1/4 x 0.131	N
D5	2x10 #2 or better SPF	48" oc	Y	1-1/8" PLY	PER	3-1/4 x 0.131	N
D6	2x10 #2 or better SPF	48" oc	Y	3/4" PLY	PER	3-1/4 x 0.131	N
D7	2x10 #2 or better SPF	48" oc	Y	3/4" PLY	PER	2-1/4 x 0.131	N
D8	1.7E LSL	48" oc	Y	1" OSB	PER	3-1/4 x 0.131	N
D9	1.7E LSL	24" oc	Y	1" OSB	PER	3-1/4 x 0.131	N
D10	1.7E LSL	48" oc	N	1" OSB	PAR	3-1/4 x 0.131	N
D10-A	1.7E LSL	48" oc	Y	1" OSB	PAR	3-1/4 x 0.131	N
D11	1.7E LSL	48" oc	Y	7/8" OSB	PER	3-1/4 x 0.131	N
D12	1.7E LSL	48" oc	Y	1-1/8" OSB	PER	3-1/4 x 0.131	N
D12-A	1.7E LSL	48" oc	Y	1-1/8" OSB	PER	3-1/4 x 0.131	Y

Note: All nails for sheathing to framing connections were 15 degree angle coil nails (i.e., spiral).

Two diaphragms (i.e. D10 and D10-A) were constructed with the panels' major axes (i.e. long dimension) parallel to the direction of loading (and to the direction of the joists), while the other diaphragms had the sheathing oriented perpendicular to the direction of loading (and to the direction of the joists). All the diaphragms were constructed with joists supported by hangers. In terms of nail spacing, all diaphragms had nails spaced 6" on intermediate supports, 6" spacing at panel edges (except diaphragm D7 with 4" nail spacing), and 6" spacing on diaphragm boundary (except diaphragms D5, D6 and D7 with 4", 4" and 3" nail spacing, respectively). The spiral nails were driven using a pneumatic coil nail gun. There were no openings in the diaphragms tested in this study.

Diaphragm Testing
All diaphragms were tested within 24 hours of construction. They were supported on rollers that allowed free movement in the direction of loading; movement in vertical direction was restricted at midpoint on tension chord and at both ends of the compression chord.

Figure 1: Example of a diaphragm constructed with double SPF framing and plywood sheathing (diaphragm D2)

The diaphragms were loaded parallel-to-framing under unidirectional (static) loading using a 50 kip capacity actuator. Loading was uniformly distributed and continuously applied in four points along the compression chord until failure. Two 20 kip load cells each were used at the reaction points to verify the load applied by the actuator. Displacement transducers were used to measure in-plane horizontal deflections, out-of-plane displacement, displacements between double members due to shear forces that develop in joists during loading, gap at lap splice in tension chord, etc. Also, selected gaps between panels at the diaphragm boundary were continuously monitored during loading. Two photos of diaphragm set-up are shown in Figures 1 and 2.

Figure 2: Example of a diaphragm constructed with TimberStrand® LSL framing and OSB sheathing (diaphragm D8)

Preliminary Data Analysis

Given the limited number of configurations tested, general observations and conclusions on the structural behaviour of diaphragms with thick panels can be made; however, no statistical analysis can be made since only one diaphragm was tested per configuration. The maximum loads recorded on diaphragms ranged between 14,000 lbs and 36,000 lbs at midspan lateral deflections of approximately 2 to 4 inches respectively. Figure 3 shows the response of the diaphragms tested under static loading.

Three distinct structural behaviours could be identified in Figure 3. The shortest nails used for sheathing-to-framing connections generated the lowest loads and displacements (i.e. diaphragms D0 to D2), while longer nails accounted for higher capacities (i.e. diaphragms D3 to D12). Therefore, the first observation is that nail length (i.e. the length of nail penetrating into framing) has a significant effect on overall performance. The steepest slope was obtained for the diaphragm that used construction adhesive in addition to nails for sheathing-to-framing connections (i.e. diaphragm D12-A), which increased significantly the stiffness of the system. The LVL-OSB diaphragms were generally stiffer than the lumber-plywood configurations, allowing for less deformation of the system and less potential energy dissipation during a seismic event.

Higher maximum loads and deflections resulted from reducing the nail spacing on the diaphragm boundary and at panel edges. For example, by reducing the nail spacing on the diaphragm boundary from 6” to 4”, a 17.5% increase in maximum load and 22% higher displacement was obtained. Basically, more nails generate higher capacity in the system. Other findings include:

- A difference of 4% in maximum loads was obtained between the diaphragm with joists and blocking spaced at 2 ft oc (i.e. diaphragm D9), and that with joists and blocking spaced at 4 ft oc (i.e. diaphragm D8). This confirms that wider joist spacing may be used in the case of diaphragms with thick panels.
- A low effect (3%) of the panel orientation within diaphragm relative to the direction of loading was found (diaphragms D8 vs. D10-A).
- A minimum effect (8%) of blocking was observed (diaphragms D10 vs. D10-A). However, this finding is not particularly relevant because both diaphragms were constructed with the panels major axis parallel to the direction of the joists, and the only difference between the two configurations was the absence of the nail connections within the panel (i.e. diaphragm D10), which are not as critical as the connections on the

diaphragm boundary and at panel edges. It is worth mentioning that if these two diaphragms would have been constructed with the panels' major axes perpendicular to the direction of the joists, the absence of blocking would have had a more dramatic effect on the maximum load.

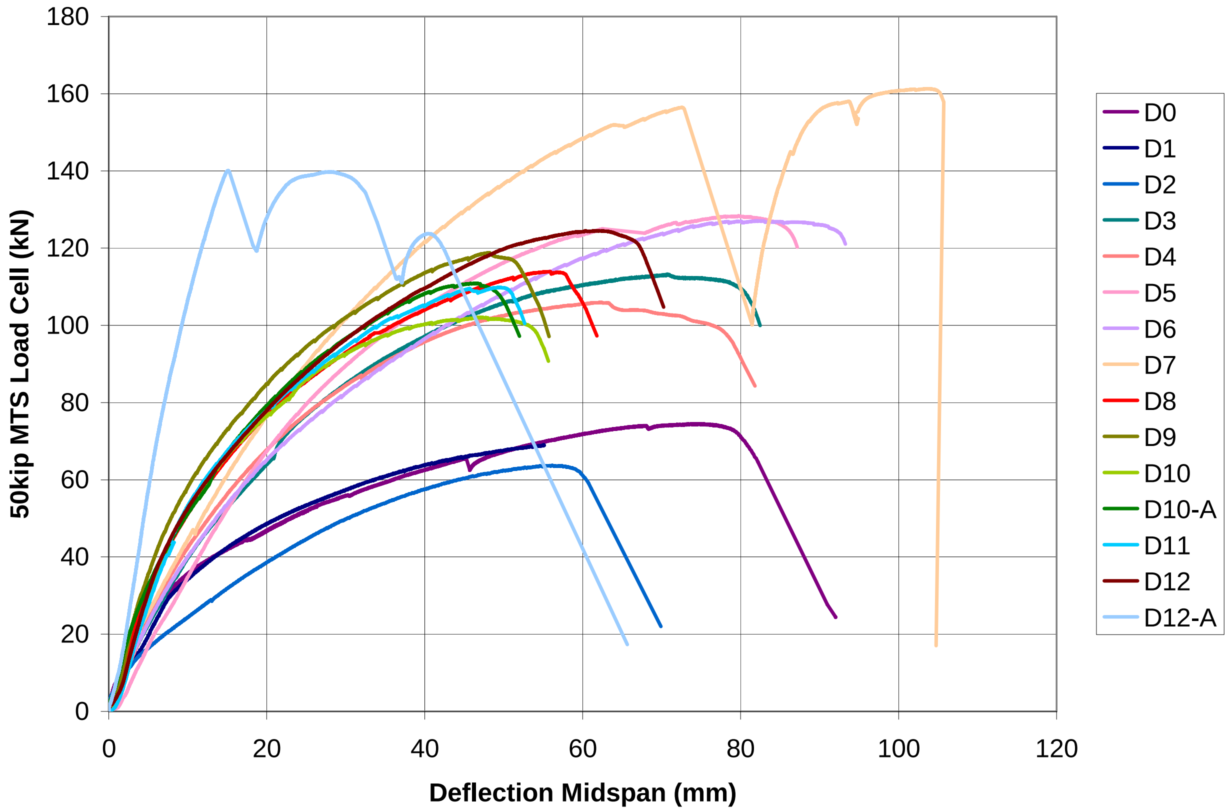

Figure 3: Load-deflection response of the diaphragms tested

The predominant failure mode of the diaphragms with thick panels was failure of the sheathing-to-framing nail connections on either one or the other side of the diaphragm. The failure never occurred simultaneously on both sides of the diaphragm.

Figure 4 shows the characteristic failure mode of a diaphragm with double SPF framing and plywood sheathing, while Figure 6 shows the failure mode of a diaphragm with single LSL framing and OSB sheathing.

The main failure mode of the sheathing-to-framing nailed connections was nail withdrawal from framing. This failure mode was observed, in particular, for the diaphragms with thick plywood sheathing and SPF framing, and was partly due to the lower densities of the SPF framing as compared to LSL framing.

Figure 4: Characteristic failure mode of a diaphragm constructed with double SPF framing and plywood sheathing (diaphragm D2)

Figure 5: Detail of the diaphragm side that failed due to nail withdrawal (diaphragm D2)

Figure 5 shows a detail of failed sheathing-to-framing nail connections mainly due to nail pull-out from framing. All the SPF frame members used for diaphragm construction were tested non-destructively to determine the transverse vibration modulus of elasticity (MOE) prior to construction. The boards with extreme MOE were discarded. The double joist members were produced by cutting in half a 16 ft long board and then nailing together the two boards, to eliminate the possibility of nails being pulled out of one member of the double joist because of low density compared to the other member of the double joist. Diaphragms were precisely constructed given that only one replicate was constructed per configuration.

Figure 6: Characteristic failure mode of a diaphragm constructed with LSL framing and OSB sheathing (diaphragm D9)

Figure 7: Detail of failed sheathing-to-framing connection in diaphragm D9 (Legend for shapes: diamond – nail pull through, circle – nail withdrawal, square – nail fatigue)

In the case of diaphragms with LSL framing and OSB sheathing, nail pull through the sheathing was more frequently observed in the failure of the sheathing-to-framing connections than for the SPF-plywood diaphragms (Figure 7). This was due to a combination of higher density of the frame members and possibly lower lateral nail resistance of OSB compared to plywood (however, this has to be confirmed by the lateral nail resistance tests).

2. Lateral Nail Resistance Tests

A test plan for the load-deformation (or load-slip) tests on nailed connections using thick sheathing was prepared and will be completed by the end of the first quarter of the third year. The load-slip tests will determine the lateral nail resistance of a nailed stud-to-sheathing connection, tested in accordance with ASTM D1761. Information from the nail-slip tests will be used in the finite-element model that will be developed during the third year of the project to characterize the non-linear behaviour of the diaphragms.

3. Introduction of project to the Code Committee

A presentation was made to introduce the project to the CSA O86 Technical Committee and the Subcommittee on System Design at their annual meeting in November 2006. Regular updates on this project will follow at future meetings of this Committee.

Publications/Patents

N/A

References

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