STATIC LOAD TEST OF A LOW RISE WOOD BUILDING

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Summary
This paper describes structural monitoring experiments on a single storey wood light frame residential building located in Fredericton, NB, Canada. The test structure was used as a means to develop broad based understanding of the load paths and load sharing mechanisms in wood light frame structures, especially the non-structural components. The building was equipped with weather station, pressure sensors on roof and walls, and load cells at roof-wall and wall-foundation interfaces to monitor the behavior of the structure under various static loading scenarios and wind loading variations that can be difficult to reproduce under controlled conditions. The structure was statically loaded and monitored during its progressive construction to determine the effects of sequential partial modifications to the building on its stiffness: OSB sheathing panels, rigid insulation, plasterboard on interior walls, plasterboard on ceiling, partitions and wall panels with perforations were added to the structure. A rigorously verified numerical SAP2000 model will be created that incorporates the contributions of structural and nominally non-structural parts along with other architectural additions to the stiffness response of the experimental building. The model will be capable of predicting the static failure mechanisms. Verification of the stiffness response would be based on ability to replicate deformations and point observations of internal forces obtained during natural wind and artificial point static loadings.

1. Introduction
Wood light-frame structures are widely used in North America and have become the dominant construction method for residential and other purposes when low-rise construction is appropriate, mainly because of its economy. The use of minimal structural materials allows builders to enclose a large area with minimal cost, while achieving a wide variety of architectural styles. Platform framing and the older balloon framing are the two different light frame construction systems used in North America. They are highly indeterminate structures and can be most vulnerable to extreme wind, snow and seismic loads depending on the geographic location and addressing all those loading scenarios is important. It has been estimated that between 1983 and 1995, worldwide economic losses due to wind and earthquake events were US$ 230 billion [1]. Some other figures of the economic losses due to recent hurricanes damages are: Charley, Frances, Ivan and Jeanne (2004): $20 billion. Forceful winds in 2005 were the cause of most hurricane damages, such as Katrina and Wilma. Further historical and climatologically predictions imply that hydro-meteorological disasters will be the main concern and mitigating damage to wood light frame buildings by cyclonic winds will, as in the past, be an important structural engineering issue.

Low-rise buildings are defined as structures with low aspect ratios (ratios of their overall height to their plan dimensions), shallow foundations, generally flexible horizontal diaphragms, and are frequently constructed from several different materials of dissimilar stiffness, strength and mass properties. Low-rise light frame buildings depend on composite action and load sharing behavior within and between wall, roof and floor subsystems for stiffness, stability and strength. Practical experience proves that traditional light frame systems can be extremely strong and robust under
strong winds, provided that interfaces between subsystems are properly constructed. Most small light frame construction enters the category of non-engineered buildings for which prescriptive (proven by experience) construction details are given, embodying high degrees of structural redundancy. However, the engineering community is questioning this especially in the case of buildings constructed with modern (non-lumber) wood based products and when building shapes are irregular, with large openings in walls [2]. An aim of this project is verification and improvement of structural performance of non-engineered wood buildings.

Component failures as roof sheathings, tiles, rafters, cladding and building failures still occur in high winds despite improvements to building codes. According to Part 4 of the National Building Code of Canada wind loads can be represented using tributary areas. This simplified approach is reasonable in situations where subsystems are statistically determinate, but this is rarely the case in light frame construction. Effort is made to incorporate load sharing and composite action effects on the material resistance side of the design equation when designing components but in general, there is no systematic design method for wood systems. Other important issues are the current arbitrary nature of decision about how roof and floor subsystems distribute load horizontally to shear walls and certainty about contributions of non-structural elements to building responses to loading. Uncertainty and presumably inaccurate expectations about how loads flows through buildings are common mistakes, but tend to only become apparent during hurricanes, tornadoes and earthquakes [2]. Consideration of continuity within connections, attention to eccentricities and continuity of load paths are most vital design issue. The weakest links in the design process are the lack of proper understanding of load paths and uncertainty about the integrity of the interfaces between subsystems (wall-to-roof, wall-to-floor and wall-to-foundation connections).

The knowledge to date obtained about the structural behavior of light frame structures is mainly derived from construction practices and a few experimental studies on major structural elements or shear wall assemblies, load sharing or the overall system effects. Current design procedures and analysis of light frame structures do not give considerations to the complex three-dimensional structural responses of the buildings to wind gusts approaching it from different directions, nor does it consider the effects of non-structural elements. Design is based on design code that overestimates the peak structural load effect [3].

Building performance against wind loads can only be addressed using full-scale tests [4,5]. Implicit in this is the acceptance that element-by-element design strategies are unsatisfactory. Most tests have been conducted on isolated members or connections or on subsystems isolated from their systematic context. Evidence of whole building behavior is largely lacking and as yet improved design procedures cannot be devised.

The focus of this project is to monitor the effect of wind loading and the load path created within the structure. Full scale whole house testing is needed to properly understand the system behavior and prove the validity of isolated component test results and their interpretations [6,2].

2. General Research Statement

Efforts were focused on understanding load paths through both, the structural and nonstructural components of the light frame structure exposed to natural environmental wind loads and on performing structural analysis and laboratory studies that supplemented to the understanding and creation of techniques that can be extrapolated to the behavior of load paths in other buildings. This involved:

i. Continuous field monitoring of wind for an experimental building

ii. Artificial static loading

iii. Creating a numerical analytical model of the entire structure

iv. Comparison of field observations of external wind pressures with wind tunnel observations from a parallel project at Concordia University (collaborative activity)
v. Ancillary laboratory studies necessary to develop and validate the numerical analytical model of the entire structure.

Related work by professors and students at UNB and collaborators elsewhere, mainly the Canadian Wood Council, Forintek Canada Corp., Concordia University, University of Western Ontario, University of Manitoba and Penn State University, will contextualize the findings toward achieving the broad goal of improved structural analysis methods for wood light-frame buildings in general. This research is a continual of previous studies [7] and work accomplished in this field at UNB. To date, the test structure has been constructed, instrumented and various static load tests and wind tunnel tests completed for the structure.

This paper will address only the static loading test on the full-scale structure.

3. In-Situ UNB Full-Scale Test Structure

The test building is a single-storey timber framed house like structure 'bungalow' style located in Fredericton. NB. This existing building was specially constructed for the purposes of wind and load-path experiments, and is a reference for validation of numerical models and wind tunnel tests, Figure 1. The building has a construction typical of bungalows in Canada and the USA designed using the so-called 2x4 system. It is a platform-type framework constructed using panellized wall segments with a length of approximately 3.6 m. The building dimension is 26’x 51’ (8.5m x 17m). The building had only two openings in the form of pedestrian doors and no trapdoor ventilation. The floor platform sits on a frost wall with a concrete foundation 10” (254mm) thick and having an outside wall height 16” (406mm) above grade. A crawlspace is beneath the floor is 4’ (1.3 m). The floor consists of 42 free-span wood I-joists spaced at 16” (0.406m) on centre. The floor sheathing is composed of 4 x 8 ft (1.22 x 2.44m) OSB sheets with 5/8” (15.9mm) thickness. No floor finishing had been installed. The roof consists of 29 pre-manufactured free-span gable roof trusses spaced at 2’ (0.61m) on centre. All walls of the building have nominal 2x4 (38mm x 89mm finished) Spruce-Pine-Fir (S-P-F) framing for studs, and sole and header plates, with nailed on OSB sheathing. The studs are spaced at 2 ft (0.61m) on centre. Three of the walls were assembled based using open prefab panellized wall segments (wall panels) and employing a 12 ft (3.66m) module. The fourth wall was stick built. Construction details are simple throughout, including vertical joints between adjacent wall panels. For walls that are panellized panels are butt-jointed and fastened together with nails. These practices are typical of construction practices in Canada. Following erection of the walls fibreglass insulation was installed in cavities between studs, air and vapour barriers installed, plasterboard lining installed on a selective basis, and external rigid insulation and drop siding applied externally everywhere.

Fig. 1 Full-Scale UNB test structure

Fig. 2 Load cell at foundation level

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Materials within the walls of the test building are:
- Framing: planed stud-grade S-P-F,
- Sheathing: 4 x 8 ft (1.22 x 2.44m) OSB panels 7/16 in (11.1mm) thick,
- Interior lining: 4 x 8 ft (1.22 x 2.44m) drywall sheets 0.5 in (12.7mm) thick,
- Sheathing-to-framing connection: 2.25 in (57.2mm) long common nails spaced at 6 in (152.4mm) along panel edge connections and 12 in (304.8mm) along interior connections.
- Stud-to-plate connection: 3.5 in (88.9mm) spiral nails (2 per joint).
- Plasterboard-to-framing connection: drywall screws spaced at 300 on centre.
- Integral insulation: fibreglass matt in framing compartments.
- Exterior insulation: Styrofoam panels 24in x 96in (600mmx2400mm) attached to outside the OSB sheathing using nails spaced 300 on centre.
- Siding: drop siding with stained wood nailed on vertical wood strapping spaced at 2 ft (0.61m) of the centre.

3.1 Instrumentation

The approach was to measure load distributions and resulting deflected shapes and discrete observations of internal forces under static load tests and normal wind load conditions. The responses were expected to be in the elastic regime. The building was monitored during its sequential modifications from its construction stage to investigate effect of adding:

a) OSB sheathing panels
b) Rigid insulation panels
c) Wood siding
d) Interior - Gypsum plasterboard to shear walls
e) Interior - Gypsum plasterboard to ceiling
f) Window openings
g) Wall partitions

Instrumentation included a set of 27 load cells at wall-foundation interface (Figure 3), that carried the entire weight of the structure for instantaneous measurements of resultant applied forces, which was important to interpretation of collected static load test data. Another set of 16 load cells under the roof truss (Figure 4), at roof-shear wall interface were installed to verify how the finite element model as an aid would help in deciding its reliability. Each of the load cells were calibrated individually, and it was ensured that they carried no moment in the direction of loading by providing pinned connections between the steel channel and the load cells. Each load cell measured in x, y and z directions. Calibration were performed by a simple equilibrium check at various stages during their installation and also verified during the preliminary static load cell tests.
A weather station was installed near the building to record wind speeds and directions at 10m and at the roof height of 5.5m. Nineteen pressure taps on roof surface and 9 on the wall were installed to monitor the incoming wind loads. The atmospheric pressure was measured using a barometric pressure sensor (Young Model# 61202V). Internal house pressures were measured which allowed the calculation of the net pressure acting on the wall. This method ensured that any fluctuation in pressures internally or externally would be accounted for.

3.2 Data Collection, Verification and Interpretation

All the pressure taps and load cells were assigned channel numbers for the logging device. Data collection, verification and interpretation proved to be a tremendous task as there was a bulk amount of data collected. A total of 220 channels were connected to the data-logging device with each taking 10 readings per second. The data was collected during static load testing, using STRAINSMART, a computer program that monitors the logging device and hence the load cells and pressure taps channel readings.

4. Static Load Test

For better understanding of load paths, verification and prediction of the house model response (SAP finite element model), static loads were applied at different locations of the house and experimental response was compared to the model. The loads applied were within the elastic range using a loading apparatus that was designed and built to facilitate the gravity and lateral load application on the exterior walls of the test house, Figure 6. This will help to correlate internal forces and deformations to that predicted in numerical whole building model.

4.1 Full-Scale Experiment

Various experimental sets of static loading were performed, Table 1. Each involved 12 tests that applied static load at various locations of the structure, Figure 5. Table 2 summarizes the magnitudes of static loading applied in various tests. All loads were applied at the top of the shear walls, where the structure would experience extreme peak load effects and overturning. Similarly, another set of uniform static load tests on the roof at 15 different locations, in a symmetrical fashion were performed. The uniform load was applied on the roof using 4.5kN of roof Asphalt shingle tiles. The testing was to determine the distribution of the reaction forces under elastic range.

<table>
<thead>
<tr>
<th>Table 1 Experiments sets</th>
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<tr>
<td><strong>Experimental set</strong></td>
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<tr>
<td>(Additions to test structure)</td>
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<tr>
<td>1. OSB only</td>
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<tr>
<td>2. Add rigid insulation panel</td>
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<tr>
<td>3. Add wood sidings</td>
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<tr>
<td>4. Add drywall (ceiling)</td>
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<td>5. Add drywall (wall)</td>
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<th>Table 2 Load application (elastic range)</th>
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<tr>
<td><strong>Racking test for each experimental set</strong></td>
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<tr>
<td>Test 1 &amp; 5</td>
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<tr>
<td>Test 2, 3, 4 &amp; 6</td>
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<td>Test 7 &amp; 9</td>
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<td>Test 8 &amp; 10</td>
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<td>Test 11 &amp; 12</td>
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The respective loads were applied at various locations of the structure (Figure 5), during different construction stages of the house. The addition of various non-structural elements to the house were correlated to the increase in stiffness of the structure, as noted from the load cell readings. The static load was applied to the structure using a mobile static load frame (Figure 6), which applied the load to the house using a load ram and load cell to record the load applied.

Initially, static load tests were performed on the house without the installation of any non-structural panels. Only the OSB sheathing panels were installed. A series of lateral point loads as shown in Table 2 were applied at different locations of the house. Uniform vertical load of 4.5kN was also applied on the roof and its elastic deformation behavior monitored. Associated deflection measurements were taken using LVDT's located at each corner of the structure. Load cells at roof and foundation level recorded the reactions and hence the flow of load along the structure as it elastically deformed by various lateral loads applied at various locations on the wall along with dead loads of the roof. The test was repeated for the second set of the static load and investigated the effects of sequential modification to the building as insulation, siding, and plasterboards were added. Partition walls and window opening are yet to be installed.

4.2 Results and discussion

Preliminary results indicated that stiffness of the building increased with addition of various panels as was observed in the recordings of the load cells. A linear increase of load resistance was noticed on each of the load cell recording as different stages of loading were applied at a given location. It was observed that the load did not always follow a path that was obvious. When static load was applied to the corners of the structure, the loaded wall did not carry significant load but the stiff corner transferred the load as a racking load to the shear wall lying in parallel to the load applied. Significant load distribution was observed as a result of roof and transverse walls rigidity. The results of the static loading were confirmed by equilibrium of the overall structure. The collected data needs to be further analyzed to quantify extend the load is shared among the walls and extend each non-structural element installation influenced the overall stiffness of the structure. Similar observations were also concluded by Doudak [7].
5. Final Comments

Static load testing confirmed the accuracy of the readings of the load cells at foundation level. The observed behavior of the structure and mechanism of load sharing between its structural and non-structural elements varied significantly from standard design calculations.

The collected data from the static load tests will be used to calibrate the finite element model created using commercial software SAP 2000, capable of performing static and dynamic analysis, to predict the performance of light frame structures under static loading. Modeling and calibrating decisions will be guided by test observations. Once established, the detailed model will be used to perform virtual physical tests to answer what if type questions and used as a base for defining less complex design level models.

The practical outcomes of the project are expected to be:

a) Contributions to understanding the overall behavior of load paths and specially the non-structural components on load paths.
b) Efficient performance based design.
c) The UNB test house will act; as a model test house to academic and industrial circles with collected data shared with such institutes and be used for further research and studies.
d) Support of wood design code revisions in Canada and elsewhere in relation wind design provisions and resistance to lateral loading.
e) Development of models suitable for everyday use of design engineers.
f) Engineer light-frame structures to better withstand wind loads.
g) Mitigate losses to these structures due to high wind events.

6. Conclusion

Controlled static loads, within elastic range were applied to a single storey, UNB full-scale test structure, instrumented with load cells to determine the load path within the structural system. Results indicated that internal forces are mainly concentrated near the corners of the building and the roof rigidity and transverse wall rigidity contributed significantly to load sharing. The research will address the extent to which modifications of buildings by addition of non-structural elements affects overall responses of those structural systems to external forces.

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7. Reference


