Chapter 6: Conclusions and Recommendations

6.1 Summary

The fundamental objective of research on strength and stiffness of timber frame and SIP roof systems was to establish procedures for incorporating the significant in-plane strength and stiffness of SIPs within lateral load design of timber frame and SIP buildings in an effort to create more efficient and economical designs for contemporary timber frame buildings. Review of literature elucidated the lack of design procedures for incorporating diaphragm action within analyses of timber frame and SIP structures, and initial investigations verified that without including diaphragm action, timber frame buildings did not have the structural integrity to resist lateral loads for code compliant designs. Monotonic and cyclic testing conducted on 8 ft x 24 ft (2.44 m x 7.32 m) and 20 ft x 24 ft (6.10 m x 7.32 m) roof assemblies, and subsequent data analyses provided ample quantification of roof system behavior to allow designers to include diaphragm action as a means of reducing forces in timber frame members and providing code conforming designs for timber frame and SIP structures subject to wind and seismic loads.

Utilizing a typical residential timber frame and SIP building, example analyses were performed that demonstrated the powerful benefits of including diaphragm action within the lateral load resistance of the building. Assuming a rectangular two-story building with endwalls that are braced by steel strapping or framing, or by other sufficient methods to prevent lateral displacements, maximum roof shear for buildings with aspect ratios up to 3:1 can be conservatively estimated utilizing the following steps:

a) Construct structural analog of typical interior frame.
b) Apply design dead loads plus wind (or seismic), and other applicable loads.
c) Place a roller reaction at the leeward eave, as depicted in Figure 6.1.
d) Utilize a two-dimensional structural analysis program, such as PPSA4 to calculate the roller reaction force, R [lbs (N)].
e) Calculate maximum roof shear in lbs/ft (N/m) utilizing the following equation:

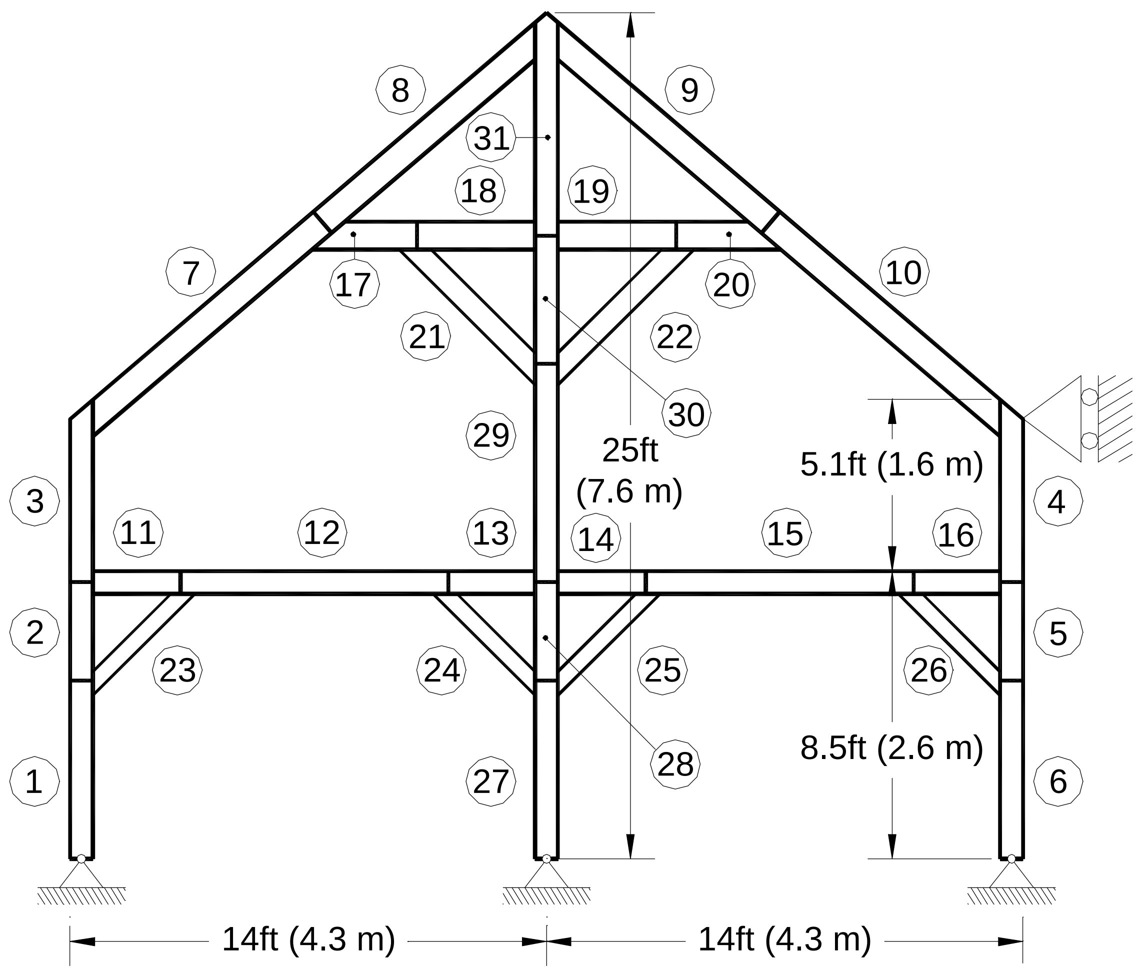

Figure 6.1. Typical interior timber frame with roller reaction at leeward eave, assuming wind blowing from the left. Dead plus wind loads not shown.

$$\text{Maximum roof shear} = (N + 1)(R/2)/W, \tag{6.1}$$

where:

N = number of frames, integer and

W = building width, ft (m).

In cases where building aspect ratios are greater than 3:1, repeated analyses on the example construction indicated that calculations of maximum roof shear assuming a rigid roof were too conservative, and the following steps are recommended:

a) Construct structural analog of typical interior frame.
b) Apply design dead loads plus wind (or seismic), and other applicable loads.
c) Place a roller reaction at the leeward eave, as depicted in Figure 6.1.
d) Utilize a two-dimensional structural analysis program, such as PPSA4 to calculate the roller reaction force, R [lbs (N)].
e) Calculate maximum roof shear in lbs/ft (N/m) utilizing ASAE EP484.2 (ASAE, 1999) diaphragm design procedures where R multiplied by shear force modifier, mS, and divided by building width in ft (m) provides maximum roof shear based on a three-dimensional frame-diaphragm interaction analysis.

Member forces in frames were reduced to allowable NDS-97 (AF&PA, 1997) design limits without increasing timber sizes, whereas without including diaphragm action members and joints were overstressed and thus not code compliant. Since timber frames are indeterminate, a two-dimensional frame analysis program should be utilized to determine forces within frame members. In calculating frame forces it is non-conservative to assume the roof diaphragm to be perfectly rigid, thus it is recommended that designers perform a complete frame-diaphragm interaction analysis for calculating frame forces. Diaphragm tests of two 8 ft (2.44 m) long roof assembly specimens may be required in order to determine diaphragm strength and roof stiffness for roof constructions significantly different from those tested for this dissertation. ASAE EP484.2 (ASAE, 1999) procedures to calculate frame member forces were presented in Chapter 5. For typical timber frame and SIP construction, this research demonstrated that there are no inherent features of these structures that would be a barrier to structural code conformance according to applicable building codes with respect to lateral load resistance.

Cyclic testing of a timber frame and SIP roof system provided data regarding ductility, strength and stiffness degradation, and energy dissipation of these assemblies. In addition to observed behavior of timber frame and SIP roof assemblies subject to cyclic loading, justification for estimating Response Modification Coefficient, R, for use with IBC 2000 (ICC, 2000) seismic design procedures, was based on research conducted on SIP shear walls, research currently underway regarding timber frame and SIP shear walls, and comparisons with several other building systems including nailed shear walls, shear walls with adhesive attached sheathing and plain masonry shear walls. An R-value of 1.5 was recommended for calculating seismic forces on timber frame and SIP buildings as part of IBC 2000 (ICC, 2000) seismic design procedures. This R-value is based on the assumption of a brittle, stiff vertical lateral load resisting system with relatively low energy dissipation and provides conservative values for determining seismic forces on timber frame and SIP buildings.

6.2 Conclusions

Data obtained from diaphragm testing program of 6-1/2 in. (165 mm) SIPs attached to Southern Pine timbers, as specified in Table 3.1 and Section 3.2, provided sufficient information on the behavior of timber frame and SIP roof assemblies subject to lateral loads to reach the following conclusions about testing, analysis and design of these structures:

- A simple beam diaphragm test utilizing three rafters with load applied to the center rafter, and the outer rafters secured, is an appropriate method for assessing the strength, stiffness and cyclic responses of timber frame and SIP roof systems.
- Structural steel properties of the 9 in. (229 mm) screws used to attach the SIPs to the timber frame limited the ultimate shear capacity of the test assembly.

- Increasing screw diameter or decreasing the spacing of the screws would most likely increase the ultimate shear capacity of the test assembly.
- Timber frame and SIP roof assemblies tested cyclically within the elastic limit of the screws exhibited increases in cyclic stiffness and strain energy with decreases in screw spacing and installation of perimeter edge boards.
- A "chord force" failure did not occur in any diaphragm test simulating a roof with 11 ft (3.35 m) frame spacing and utilizing a splined joint with four 1 in. (25 mm) diameter oak pegs at the foot of the center rafter, however chord force transfer must be addressed by the building designer. A method for calculating chord forces for timber frame and SIP buildings is needed.
- Timber frame and SIP building designers should utilize a value of 1.5 for the Response Modification Coefficient, R, for use with IBC 2000 (ICC, 2000) seismic design procedures.
- A diaphragm-frame interaction analysis utilizing test data from a roof diaphragm assembly can be used to demonstrate the code conformance of timber frame members and joints when subjected to wind or seismic loads.
- A diaphragm-frame interaction design can not be executed without an estimate of the stiffness and strength of the building endwalls, thus the greatest research needs at this time are design models for stiffness and strength of SIP clad endwalls with doors and windows.

6.3 Recommendations

While current research effectively demonstrated procedures for incorporating diaphragm action within the lateral load resistance design of timber frame and SIP buildings, additional research remains to be conducted in order to advance understanding of these structures and how they behave under loading. The most critical information that is currently lacking in order to conduct a full diaphragm design is the strength and stiffness of timber frame and SIP endwalls under monotonic and cyclic loads. Research is underway at the University of Wyoming that may fill this void. Ideally, testing could be performed on a full-scale timber frame building, as was done for post-frame buildings, in order to observe, demonstrate, and document three-dimensional behavior as well as the interactions between the endwalls and roofs when subject to lateral loading. Studies should also be conducted in order to determine the effects of different SIP fasteners, fastener spacing, the use of washers with fasteners, and varying SIP thickness on roof assembly stiffness and strength.

In order to assess the nature of size effects as roof slope length and building length are increased, an additional recommendation is to take the data obtained from this dissertation and validate a finite element model, as previously discussed in Chapter 4. The model should represent the SIPs as a very stiff plate and the frame as a series of extremely stiff members free to rotate at their joints. It was observed that screws attaching the SIPs to the timbers were critical in dictating the strength and stiffness of the tested assemblies, therefore non-linear springs with failure criteria should be used to model the fasteners between the frame and SIPs. Although not completed at the time of this writing, connection tests utilizing SIPs, timbers and the 9 in. (229 mm) screws used to connect them were conducted by Vincent Spencer at Virginia Tech, which will provide additional data for modeling the screws. Test results could be utilized to conduct parameter studies and refine the model, with the objective being the creation of a robust structural model, representative of timber frame and SIP roof systems, and eventually entire timber frame and SIP buildings.