UW and LBS Full-Scale Building Research Initiative

By David R. Bohnhoff, Ph.D., P.E. • University of Wisconsin-Madison

In the most extensive post-frame building research project conducted to date, a series of tests were conducted on a heavily-instrumented 40- by 200-foot metal-clad post-frame building in an effort to better understand the distribution of horizontally applied building loads. Analysis of collected data and building modeling is ongoing.

The purpose of this article is to introduce readers to the intricacies of a full-scale building evaluation by overviewing the development, construction, instrumentation and testing of the 40- by 200-foot building. A sampling of test results is provided at the end of the article to whet the reader's appetite for more in-depth and detailed test results planned for future articles.

Project History

In early 1996, while employed by Lester Building Systems (LBS), I conducted a series of three-dimensional analyses on a post-frame building in an attempt to get a better handle on axial forces in girts and purlins (a.k.a. chord forces). Each section of metal cladding was modeled with a pair of diagonal spring elements which had different properties in compression and tension. Although modeling results were very dependent on spring properties and other assumptions, there was a strong indication that chord forces induced by loads applied normal to sidewalls, were largely influenced by the in-plane rigidity of the sidewalls.

The results of the LBS 3-D modeling underscored the need for a comprehensive series of full-scale building tests. Upon my return to the University of Wisconsin-Madison (UW), I began planning for a series of such tests with Paul Boor of LBS. I applied in 1997, and was awarded in 1998, a federal Hatch grant through UW-Madison as well as a USDA National Research Initiative Competitive Grant. Both of these large grants were spurred by a prior commitment by LBS to furnish materials and labor for actual building construction.

Detailed planning for the *UW & LBS Full-Scale Building Research Initiative* commenced in late 1998. Throughout 1999 and 2000, data acquisition (DA) and loading systems were designed, fabricated and laboratory tested at UW-Madison. LBS constructed the building at its headquarters in Lester Prairie, Minn., during 2001 at which time the DA and loading systems were installed and tested. After some minor adjustments, an extensive series of tests was conducted in 2002. This produced a tremendous amount of data that was condensed during 2002 and 2003. Modeling of the test building began in 2004 and continues along with analyses of the test data. The DA and load systems were removed from the building in 2005 and the building itself was taken down in 2006.

Building Design

The test building had an overall length of 200 feet, width of 40 feet, eave height of 9 feet and bay spacing of 10 feet. The length and width dimensions resulted from the desire to minimize total project cost while simultaneously obtaining a structure of reasonable size with a higher length-to-width ratio (i.e., something in the 5:1 to range). Nine-foot walls were selected over higher walls to obtain a higher wall racking stiffness, to lessen overall building costs, and to minimize climbing during building configuration change-over and equipment calibration. The 10-foot bay spacing was selected over narrower bay spacing simply to save cost, as each bay required its own loading system and its own set of load and displacement measuring devices.

Many unique features were incorpo-

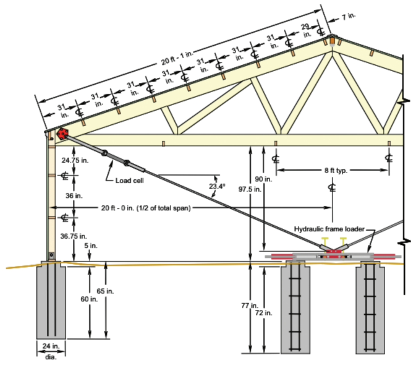


Figure 1. – Cross-section of interior post-frame with hydraulic frame loader.

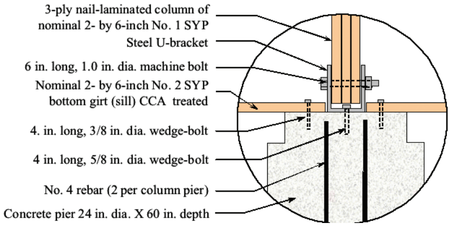


Figure 2. – Column-to-foundation and sill attachment details. A single 1-inch diameter bolt was used to pin-connect each nail-laminated column to the foundation system. Direct attachment of the bottom girts (sills) to piers enabled direct transfer of wall in-plane shear forces into the foundation.

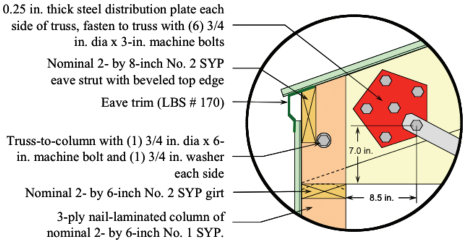


Figure 3. – Eave construction details. Attachment (and detachment) of wall panels from the eave strut and top girt enabled analysis of shear transfer between the roof diaphragm and sidewall. Pentagon-shaped steel distribution plates were used to transfer load into trusses. A single 3⁄4-inch diameter bolt was used to pin connect each post to the truss.

Table 1 Building Test Configurations

ID	Chord tensioning nuts tightened?	Wall paneling screwed to eave strut and top girt?		Ridge cap?	Screws in beveled ridge nailers?	Screws in ridge purlins?	Middle wall panels?	Eave trim?	Roof panels stitched together?
		North side	South side						
AL	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AT	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BT	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
BL	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
CL	No	No	No	Yes	Yes	Yes	Yes	No	Yes
DL	No	No	No	No	No	Yes	Yes	No	Yes
DT	Yes	No	No	No	No	Yes	Yes	No	Yes
ET	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes
EL	No	Yes	Yes	No	No	Yes	Yes	No	Yes
FL	No	No	Yes	No	No	Yes	Yes	No	Yes
GL	No	No	No	No	No	No	Yes	No	Yes
GT	Yes	No	No	No	No	No	Yes	No	Yes
HT	Yes	No	No	Yes	No	Yes	Yes	No	Yes
HL	No	No	No	Yes	No	Yes	Yes	No	Yes
IL	No	Yes	Yes	Yes	No	Yes	No	No	Yes
JL	No	Yes	Yes	Yes	No	Yes	Yes	No	No
KL	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes

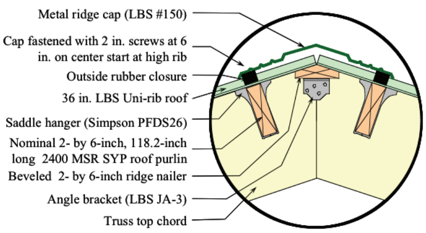


Figure 4. – Ridge construction details. Attachment (and detachment) of roof panels from beveled ridge nailers and ridge purlins enabled study of the effects of roof diaphragm continuity. Chord reinforcement hardware (figure 5) is not shown.

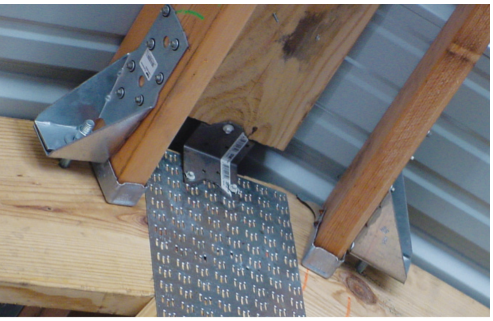


Figure 5. – Chord reinforcing hardware on two ridge purlins. Bracket between ridge purlins is supporting a beveled ridge nailer.

rated into the building to better assess diaphragm action including: 24-inch diameter, steel-reinforced concrete pier foundations; pin-type connections at the base and eave of each column; heavy-duty trusses; ridge nailers that could be quickly removed to simulate an open ridge; and chord reinforcing hardware that could be quickly activated and deactivated. Some of these details are shown in figures 1 through 4. Figure 5 shows chord reinforcing hardware on two ridge purlins. Bolts passing through trusses (or columns in the case of girts) tied brackets on chord ends together. When nuts on these bolts were tightened, the ability of purlins and girts to transmit tension forces to each other was significantly increased.

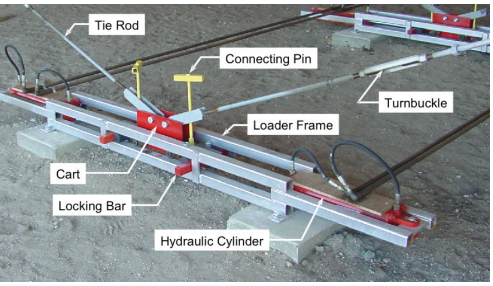


Figure 6. – Hydraulic frame loader in a locked mode.

See Bohnhoff and Boor (2002) for a comprehensive description of all building elements.

Frame Loading System

Hydraulic frame loaders or HFLs (fig. 6) enabled individual frames to be simultaneously operated in different modes. Operational modes included a float, lock, south load and north load. The HFLs automatically re-plumbed frames upon unloading. Eave displacements of 16 inches in either direction could be achieved and loading and unloading rates infinitely adjusted. The system also contained a series of adjustable relief values that were used to safeguard against accidental overload.

Incorporating the ability to lock, float, or load a frame in either direction enabled a tremendous variety of load configurations. This had several advantages. First, hysteresis effects associated with reverse loadings, permanent deformation, and creep could be explored. Second, the effects of reverse loading on an asymmetric building (e.g. a building with one open and one closed sidewall) could be investigated. Third, variability in chord forces due to construction and strain gage accuracy could be isolated (this was done by comparing forces on opposites sides of the building under opposing loads). Fourth, long buildings could be loaded so that they behaved as a series of short buildings as illustrated in figure 7.

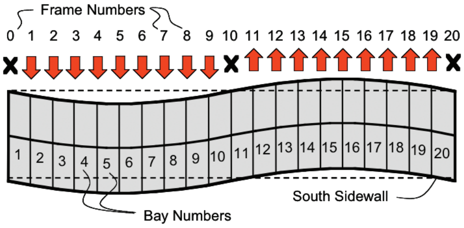


Figure 7. – Top view of 20-bay test building with three frames locked (X-marked) and the remaining frames loaded to cause 200-foot building to behave as two 100-foot buildings (load case 100).

Data Acquisition System

A laptop computer was used to control a Campbell Scientific CR5000 data-logger which provided excitation to, and processed input analog signals from, 225 transducers located throughout the test building. Twenty-one of these transducers were 10-turn wirewound precision potentiometers used to measure eave displacements at each frame (fig. 8). Forty-two transducers were load cells (a.k.a. tension links) used to monitor forces applied (or resisted) by hydraulic frame loaders and building endwalls (fig. 8). These load cells were specially designed and fabricated for this study. The remaining 162 transducers were located on the 54 frame force monitoring links (FFML) used to measure major axis bending, minor axis bending, and axial forces in purlins and girts (fig. 9). FFML's were only located in building bays 1, 4 and 10. Like the load cells, these links were developed specifically for this study with the goal of obtaining the most precise and accurate information possible.

Figure 8. Eave displacement being measured with a washer-tensioned track attached to a rotary potentiometer, while force in a tie rod is measured with a specially constructed load cell.

Figure 9. – Frame force monitoring links (FFML) mounted in an eave strut and top girt.

Fabrication details for the loading and data acquisition systems can be found in Bohnhoff et. al. (2002).

Building Configurations

One of the primary research objectives was to determine how changes in component connections affected load distribution between components and hence diaphragm action. With this objective in mind, 17 different building configurations were tested. These configurations are listed in Table 1 in the order in which they were tested. Each configuration is identified with a two-character designation. The first character identifies test order (i.e., AL and AT were tested first, then BT and BL, etc.). The second character is either an “L” or a “T” and indicates whether the nuts on the chord reinforcement hardware were loose or tight, respectively.

The first two series of tests (i.e., AL and AT) were not conducted until the building was completely assembled. This is somewhat the opposite of other major full-scale building tests where researchers have loaded their test buildings as they were being constructed. While testing during construction enables one to monitor increase in “overall system stiffness” as components are added, it also increases the likelihood of overloading one or more components.

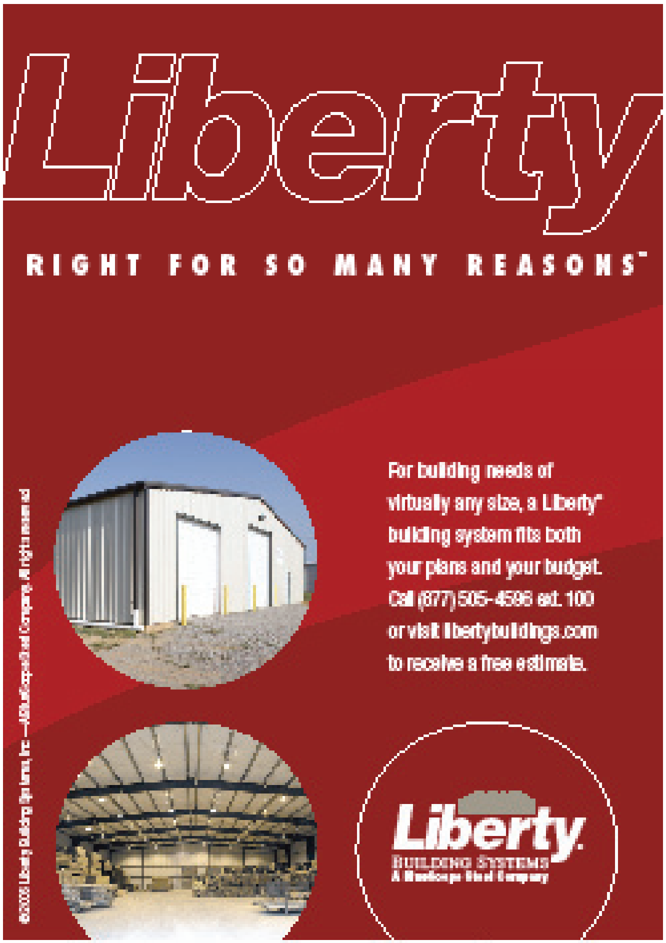
Major components were “reactivated” for the last test series (i.e., KL tests). This was done to check that individual component stiffness had not been diminished by repetition loading. A comparison of displacements from the KL tests with those from the first few test series indicated that repetitive loadings did not significantly alter individual component stiffness.

Load Cases

Each building configuration except for KL was subjected to 11 different loadings that were identified with the following numbers: 200, 100, 50, 20, 911, 713, 515, 317, 400, 210 and 420. For load cases 200, 100, 50 and 20, the number represents distance in feet between locked frames. Load case 100 is illustrated in figure 7. This figure also gives bay and frame numbers.

Load cases 911, 713, 515 and 317 each had only two loaded frames. The first numerical character in the designation is the first loaded frame, the next two characters are the number of the other loaded frame (e.g. frames 5 and 15 were the loaded frames in configuration 515).

Load case 210 had frame 10 (i.e., the middle frame) locked, both end frames were allowed to float, and all other frames were loaded. Load cases 400 and 420 had all frames loaded but only one of the two end frames was locked at a given time. With load case 400, frame 0 (zero) was locked and frame 20 was allowed to float. Load case 420 had frame 20 locked while frame 0 was allowed to float. Note that by locking one end frame and allowing the other to float while all interior frames were loaded resulted in diaphragm shear forces similar to what would be expe-



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rienced in a 400-foot building with both end frames locked. For safety reasons, at least one end frame or interior frame was kept locked at all times.

Each load case had a north and south loading which was identified by adding an N or S after the numeric designation (e.g., 200N and 200S). Each north and south load case was replicated, with loadings alternating between north and south load cases. A "1" or "2" was added to the load case to differentiate between the replicates (e.g., 200N1, 200S1, 200N2 and 200S2).

Loads were applied with the goal of obtaining a total test time of around 3 minutes for each load application. This was accomplished with a flow control valve that had to be adjusted for each different load case and building configuration.

Data Collection and Reduction

During load application, each of the 225 transducers was scanned once every 4.7 seconds. With a test time around 3 minutes, each loading usually generated at least 10,000 data points. This was obviously an unwieldy amount of data to analyze without significant data reduction. To reduce the amount of data, use was made of the fact that the relationship between applied load and transducer output was very near linear once loads exceeded approximately 35 percent of the maximum established for that test. This point is illustrated by the plot in figure 10 of horizontal frame force versus eave displacement for frame 17 for the four AT317 loadings (AT317 is the 317 load case for building configuration AT). Note that the diagonal line drawn through the origin in figure 10 shows the approximate slope of the linear, upper portion of all four loading curves. It is the upper portion of loading curves that is of interest to the design engineer, as it is the behavior of the structure near maximum load that controls design.

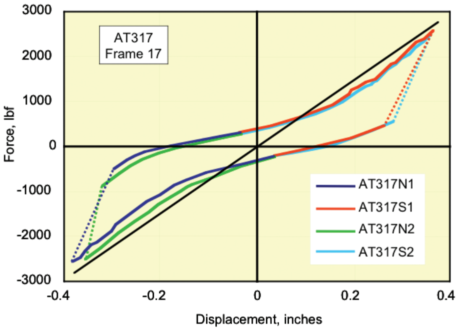


Figure 10. Relationship between horizontal frame force and eave displacement for frame 17 during the four AT317 loads. Dashed lines used where a low number of data points (due to rapid unloading) did not permit accurate curve development. Diagonal line through the origin shows approximate slope of upper portion of loading curves.

The curves in figure 10 show that there was a significant hysteresis effect. This was expected and was one of the main reasons that the loading system was designed to apply frame loads in both south and north directions. It is evident from figure 10 that frames had to be pulled back to their center position after being loaded.

The first step in data reduction for each loading was to calculate a horizontal frame force for each loaded frame (i.e., each interior frame that was not in a locked or float mode). This was accomplished by taking the difference in the load measured by the two load cells attached to the HFL and adjusting it for the slope of the load cells. These average frame load values were then examined to determine those scans associated with the loading (not unloading) portion of the curve between approximately 40 and 90 percent of maximum load. Only data points associated with these scans were used in future analyses.

The second step in data reduction was to linearly regress each horizontal frame force, each eave displacement, and each purlin and girt force on average horizontal frame load. After these regression analyses, the data file for each load case was reduced to 204 values: 21 horizontal frame force to average horizontal frame load ratios, 21 horizontal eave displacement to average horizontal frame load ratios, 54 chord axial force to average horizontal frame load ratios, 54 chord major axis bending moment to average horizontal frame load ratios, and 54 chord minor axis bending moment to average horizontal frame load ratios.

The third and last data reduction step was to average the ratios for the four load tests (i.e., N1, S1, N2, S2) for each building configuration-load case combination.

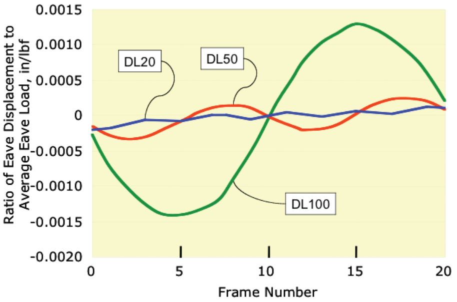


Figure 11. – Eave displacements for building configuration DL for load cases 20, 50 and 100.

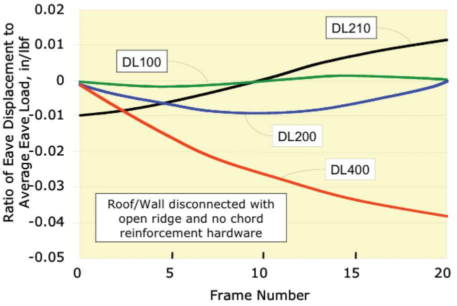


Figure 12. – Eave displacements for building configuration DL for load cases 100, 200, 210 and 400.

For more comprehensive overview of load configurations, load cases, data collection and data reduction see Bohnhoff et. al. (2003).

Some Results

Figures 11 through 14 provide a sampling of test results. Much of the data has yet to be studied in-depth. Look for detailed results and corresponding analyses in future articles.

Figures 11 and 12 contain eave displacements for building configuration DL under load cases 20, 50, 100, 200, 210, and 400. For this building configuration, sidewalls were disconnected from the roof, the ridge was opened up, and chord-reinforcing hardware was deactivated.

Plots like those in figures 11 and 12 help establish the relationship between diaphragm stiffness and building length. This is very important in the development of models for predicting diaphragm behavior. Although diaphragm behavior

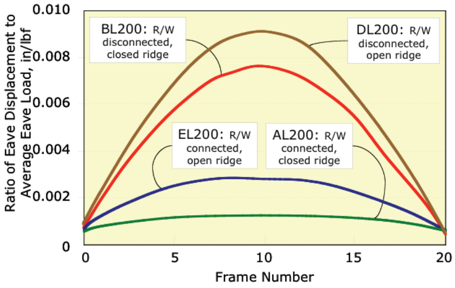


Figure 13. – Eave displacement under load case 200 as influenced by (1) roof-to-sidewall (R/W) connectivity, and (2) roof diaphragm continuity at the ridge.

is quite complex, engineers look to model them using relatively few modeling elements. For example, an engineer may try to model an entire roof diaphragm as a beam supported by a series of springs — each spring representing a single shearwall or interior frame. In such a case, plots like those in figures 11 and 12 can be used to determine effective shear and effective bending stiffness values for the beam elements used to model the diaphragm. This is because when beam displacements are controlled by shear stiffness (i.e., bending stiffness is relatively high), the displacements of a uniformly loaded beam will approximately quadruple when the unsupported beam length is doubled. Conversely, when beam displacements are controlled by bending stiffness (i.e., shear stiffness is relatively high), the displacements of a uniformly loaded beam will increase 16 times when unsupported beam length is doubled. Note that when rigid body rotation is accounted for, eave displacements associated with DL100 are about six times greater than those associated with DL50 (figure 11). Likewise, eave displacements for DL200 are approximately 7.5 times those for DL100 (figure 12).

The most significant find in this study is graphically illustrated in figure 13. This figure shows that connections between the roof diaphragm and walls normal to the applied load (i.e., the sidewalls) had a significant impact on eave displacements. This find confirms what pre-project modeling had indicated; that is, in-plane stiffness of walls normal to applied building loads enables them to effectively transfer some load from the roof diaphragm into the foundation.

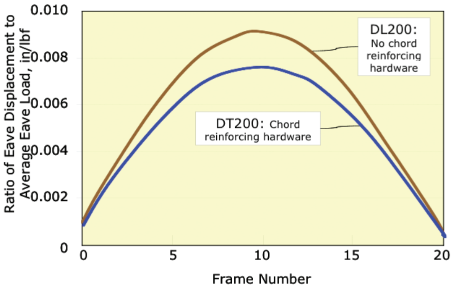
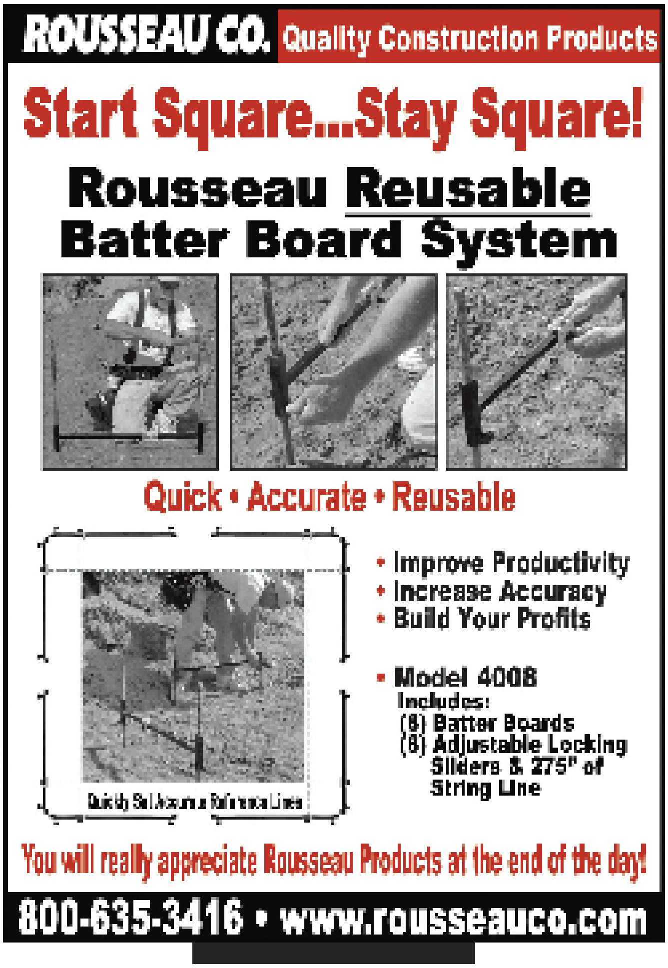


Figure 14. – Influence of chord force reinforcement on eave displacement of building configuration D under load case 200.

Figure 13 also shows the impact of disconnecting both roof halves at the ridge. The change in eave displacements resulting from this “opening of



the ridge" was similar in magnitude to that for "deactivation of the chord reinforcing hardware" which is shown in figure 14. Note that "opening of the ridge" and "deactivation of the chord reinforcing hardware" did not have near the impact on eave displacement as did disconnection of the roof diaphragm from the sidewalls.

Modeling

The vast majority of data analysis conducted to date has centered around the development of a building model that produces eave displacements and chord forces similar to that found in the test building. This is being accomplished by (1) selecting various structural analogs, (2) generating several different combinations of element properties for each analog, and then (3) identifying the analog and combination of element properties that best predicts actual building eave displacements and chord forces. It is important to understand that a model developed in this manner is not validated until building element properties determined using this three-step process can be accurately predicted from laboratory testing of metal-clad, wood-frame wall and roof panel assemblies. Such laboratory tests are planned for the near future.

Summary

A variety of loads were applied to a 40- by 200-foot metal-clad post-frame building as part of the largest and most expensive post-frame building research project ever conducted. Several different configurations of the building were loaded using a unique loading system that enabled each building frame to be independently controlled. Instrumentation allowed for the measuring of all applied frame loads and eave displacements, as well as bending moments and axial forces in several girts and purlins. While analysis of the test is ongoing, work completed to date has shown that walls positioned normal to applied building loads can have a significant impact on diaphragm action if the walls are well connected to the diaphragm. ■

Bohnhoff, D. R. and P. A. Boor. 2002. UW & LBS full-scale metal-clad wood-frame diaphragm study. Report 1: Project introduction and building design details. ASAE Paper No. 024007. St. Joseph, Mich.: ASAE

Bohnhoff, D. R., P. A. Boor, F.A. Charvat, M.H. Gadani, and G. Kovácsvölgyi. 2002. UW & LBS full-scale metal-clad wood-frame diaphragm study. Report 2: Frame loading and data acquisition systems. ASAE Paper No. 024008. St. Joseph, Mich.: ASAE

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