8th Canadian Conference on Earthquake Engineering / 8ième Conférence canadienne sur le génie paraséismique
Vancouver – 1999

Behavior of Diaphragms Sheathed with FRP Panels

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ABSTRACT

This paper summarizes the results from the first phase of an ongoing research project to determine the suitability of using Fiber Reinforced Polymer (FRP) panels as sheathing material for roof diaphragms and to develop schemes using advanced composite materials to retrofit seismically damaged roof diaphragms. This was accomplished by constructing a typical plywood diaphragm and testing it under fully reversed, cyclic lateral loads. Following the diaphragm testing, damaged plywood panels were removed and replaced with FRP panels. The repaired diaphragm, sheathed with FRP panels and lightly damaged plywood panels, was then retested by again applying fully reversed, cyclic lateral loads. Observations and results obtained from the two sets of tests are briefly described in this paper.

BACKGROUND

Wood is one of the most common construction materials used in small to medium structures. Wood structures include horizontal diaphragms and vertical shear walls designed to resist earthquake forces in addition to carrying gravity loads. Medium size structures, in many cases, combine the benefits of a flexible plywood roof diaphragm with masonry or tilt-up reinforced concrete walls. Although such combinations make for an economical structure, these buildings are highly susceptible to seismic damage. Typically, the plywood panels are the limiting factor in the roof diaphragm strength, which in general, limits the overall lateral capacity of the structure.

Plywood Diaphragm Research and Observations

Extensive research has been conducted on full scale plywood diaphragms to observe their behavior when subjected to lateral loads. The American Plywood Association has been one of the leading organizations in performing this research. Tests conducted as early as 1954 indicated that one of the causes of failure in plywood diaphragms was nails tearing through the edges of the panels (Countryman et. al., 1954). By 1966, nail tear-through around the panel edges was concluded to be the main cause of plywood diaphragm failure (Tissell, 1966).

Prior to 1994, wood structures were commonly believed to be relatively immune to damage caused by earthquakes. However, over half the structural damage and nearly all of the fatalities associated with the 1994 Northridge earthquake were attributed to damage of wood structures (Hamburger et. al., 1997). One of the most common failures of wood buildings during this earthquake was nails tearing through the edges of plywood panels (Seismic Safety Commission, 1994). Thus, observations from this earthquake confirmed the findings of laboratory testing.

Plywood Diaphragm Retrofitting Practices

Retrofitting procedures for damaged plywood diaphragms are very seldom used. Generally, the preferred repair procedure for damaged wood buildings is to remove the damaged diaphragm element and replace it with a new one (Seismic Safety Commission, 1994). If this cannot be effectively done, the damaged structure is torn down and completely replaced (Holmes et. al., 1996). A retrofitting procedure using advanced composite materials could prove to be more economical than the replacement of damaged structures and could make the structure safer in future earthquakes by eliminating the problem of nail tear-through. Fiber Reinforced Polymers are one type of material that could be used in such a retrofitting procedure. FRP panels are already manufactured in sheets which are comparable in size to plywood panels. In addition, FRP panels are stiffer, exhibit greater capacity than plywood and are less likely to fail by nails tearing through the panel edges. These properties make FRP panels a good candidate for investigation in a plywood diaphragm retrofitting scheme.

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METHODS

Test Specimen

In order to determine the suitability of using FRP panels as sheathing material and to develop retrofitting schemes for seismically damaged diaphragms, two sets of diaphragm tests were conducted. A typical plywood diaphragm was constructed using standard wood building materials. The test diaphragm, shown schematically in Fig. 1, was 24-ft long by 12-ft wide. The 2 x 6 purlins were spaced at 8 ft. on center and the 2 x 4 sub-purlins at 2 ft. on center. The nominal sizes selected for the wood ledgers were 2 x 10 and 1 3/4 x 9 1/2 for the chords. Micro-lam were used because of the difficulty in finding 24-ft long wood members without warping. A structural grade plywood, 3/8 in. A–C Exterior, was used for sheathing material. The plywood panels were attached to the framing members with 8d nails at 4 in. on center along diaphragm boundaries and continuous panel edges parallel to the applied load, 8d nails at 6 in. on center along all other plywood edges, and 8d nails at 12 in. on center along intermediate framing members. The dimensions of the diaphragm, 24 ft. x 12 ft., were chosen in order to be big enough to provide a symmetric plywood layout pattern that might be seen in construction while still being small enough to be conveniently tested under controlled laboratory conditions. The materials used to construct the diaphragm were all common building materials that were obtained at local lumber yards. These materials are commonly used in wood construction practices.

Plywood Diaphragm Test Setup

The plywood diaphragm prior to testing is shown in Fig. 2. The diaphragm was subjected to a series of fully reversed, cyclic lateral loads. The loads were applied at the third points of the diaphragm by a system of tube steel forks attached to hydraulic rams. Each fork assembly distributed the lateral load from the hydraulic ram to the top and bottom of the diaphragm simultaneously at approximately one foot to both sides of the continuous plywood joints.

Two hydraulic rams applied the lateral loads. One was a master ram which was driven through direct displacement control. The second ram was a slave ram driven indirectly through load control. The master ram was run through several sets of fully reversed displacement cycles. The amplitude of displacement increased during each successive set of cycles. The diaphragm was subjected to diaphragm displacement amplitudes of 0.3, 0.6, 0.9, and 1.5 in. The slave ram was driven by reading the load signal from the master ram and then applying the same load level at the slave ram, regardless of the ram displacement amplitude required to accomplish this. The diaphragm was subjected to three cycles at each amplitude level. Testing was halted at the second cycle of a displacement amplitude of 1.5 in. because nails had torn through the plywood panel edges as expected.

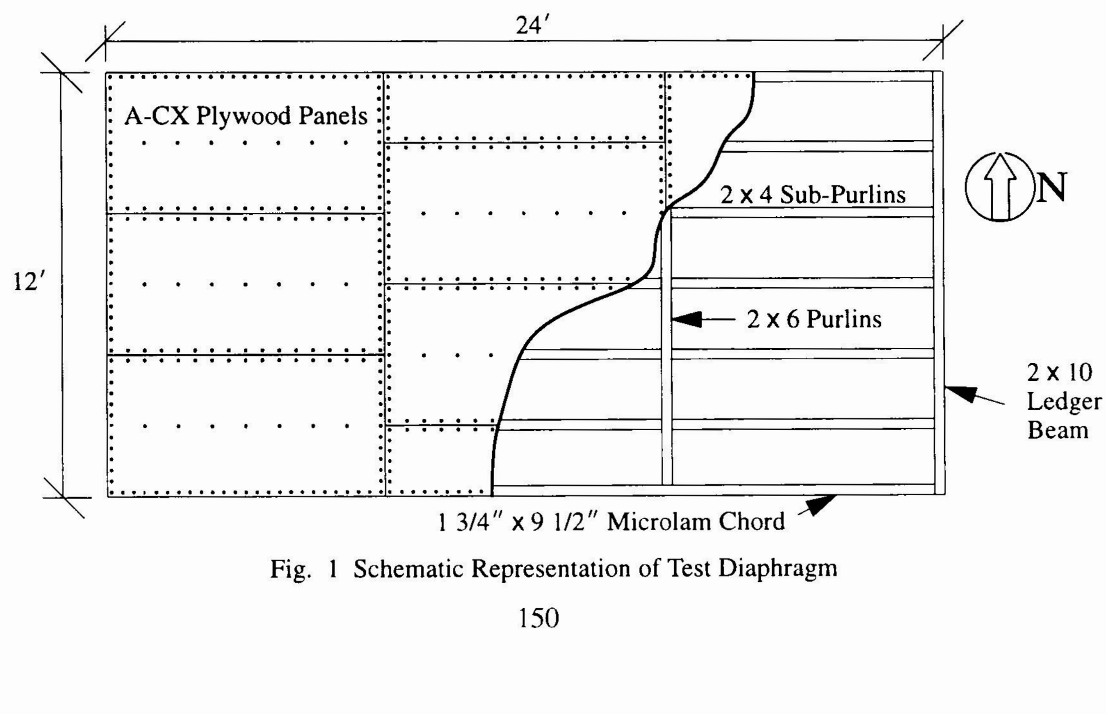

Fig. 1 Schematic Representation of Test Diaphragm

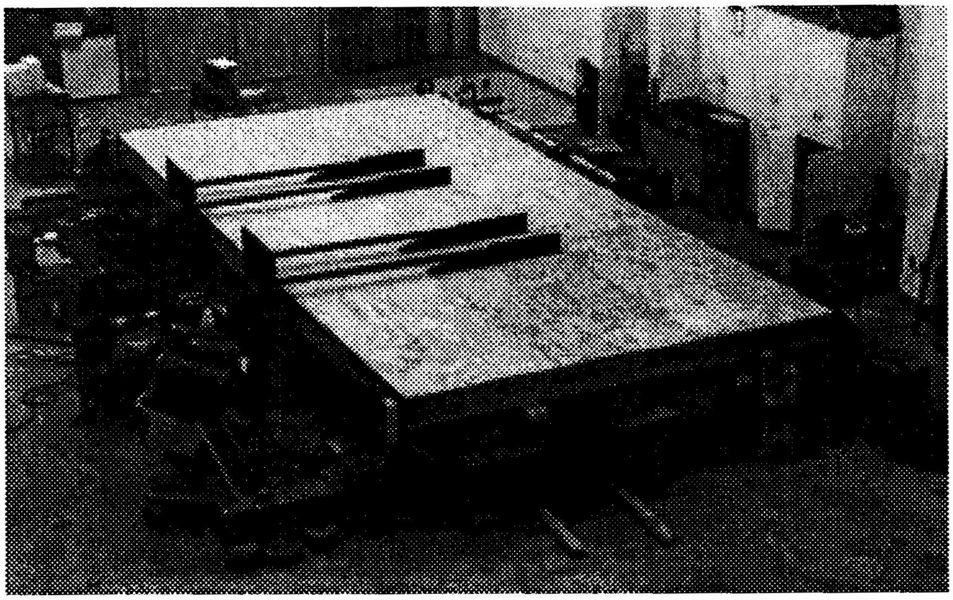

Fig. 2 Plywood Diaphragm

Repair Procedure

The majority of the damage to the diaphragm consisted of nail tear-through around the edges of the four corner panels. These four panels were removed and replaced with 1/4 in. FRP panels. Only one other repair was conducted on the diaphragm, which was the driving of additional nails into a plywood panel edge that had experienced nail tear-through. These new nails were offset from the original nail holes.

Composite Diaphragm Test Procedure

The diaphragm was tested with a similar series of fully reversed, lateral cyclic loads. As with the first set of tests, two hydraulic rams with attached fork assemblies were used to apply the lateral loads to the diaphragm. The same master ram/slave ram system that was used on the plywood diaphragm was used on the composite diaphragm. However, the master ram was subjected to displacement amplitude levels of 0.3, 0.6, 0.9, 1.2, and 1.5 in. The diaphragm was subjected to three cycles at each displacement level except at 1.5 in. displacement. The diaphragm was only subjected to one cycle at this displacement level. After one cycle of 1.5 in. displacement, testing was stopped due to the failure of the system attaching the actuators to the laboratory floor.

RESULTS

Plywood Diaphragm Test Results and Observations

The measured response of the plywood diaphragm is shown in Fig. 3. The maximum measured loads for the diaphragm were 6200 lbs per ram with the rams pushing on the diaphragm (north displacements) and 9400 lbs per ram with the rams pulling on the diaphragm (south displacements). The associated maximum measured displacements for these loads were approximately 0.85 in. with the hydraulic rams pushing on the diaphragm and about 1 in. with the rams pulling on the diaphragm. Figure 3 shows the points corresponding to maximum force at each displacement level. The points are shown connected to each other with straight line segments simply to make visualization easier.

The majority of the damage in this test was sustained on the four corner panels of the diaphragm. Most of the nails around the edges of the diaphragm corners had torn through the panel edges. The four corner panels were subjected to the most rotation as the diaphragm deflected, causing higher localized stresses around the nails on these panels. The diaphragm's lateral capacity was significantly reduced because the plywood panels were no longer firmly attached to the framing members. As the corner plywood panels were removed during the repair procedure, the nails

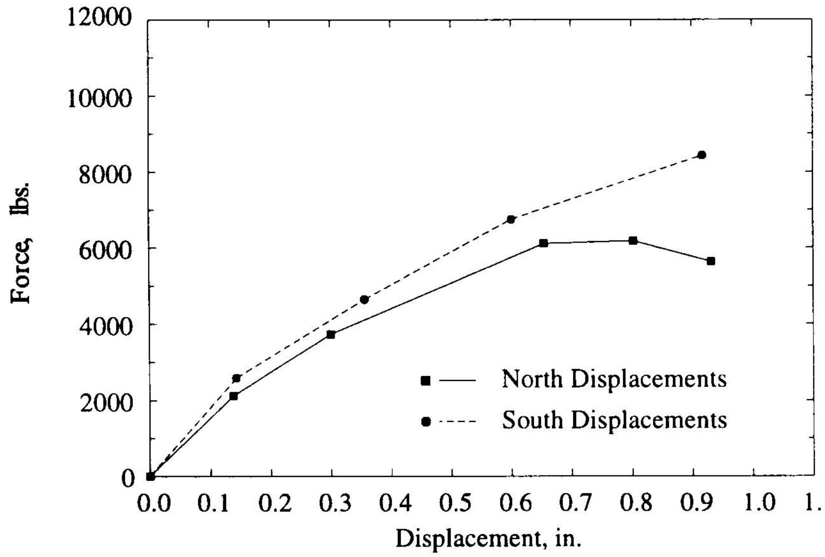

Fig. 3 Measured Response of Plywood Diaphragm

were observed to be relatively straight, suggesting that the nails had been subjected to little or no inelastic deformation and were still capable of withstanding higher lateral loads. However, the plywood around the nails had completely failed, indicating that the plywood was the weakest element in the diaphragm and had led to the diaphragm failure.

Composite Diaphragm Test Results and Observations

The measured response of the composite diaphragm is shown in Figure 4. In the composite diaphragm test, the maximum measured loads for the diaphragm were 8400 lbs. per hydraulic ram with the rams pushing on the diaphragm (north displacements) and 11200 lbs. per hydraulic ram with the rams pulling on the diaphragm (south displacements). The maximum measured deflections associated with these forces were approximately 0.85 in. with the rams pushing on the diaphragm and about 0.9 in. with the rams pulling on the diaphragm. Figure 4 shows the points corresponding to maximum force at each displacement level connected to each other with straight line segments simply to make visualization easier.

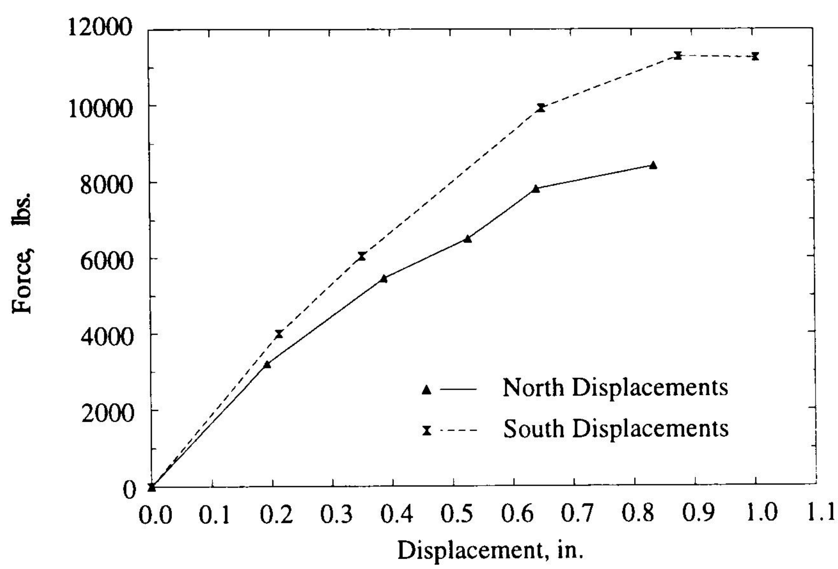

Fig. 4 Measured Response of Composite Diaphragm

Unlike the plywood diaphragm test, the composite diaphragm test resulted in very little observed damage at the four corners of the diaphragm where plywood panels had been replaced by FRP panels. Instead, most of the damage occurred on the remaining plywood panels, even though they underwent less rotation than the four corner panels. As in the plywood diaphragm test, the majority of the damage to the composite diaphragm was nails pulling out of the edges of the plywood panels. In addition to nail pull-through, some of the plywood began to buckle at the higher load levels attained in the test. No nails, however, tore through an FRP panel edge. As the panels were removed from the diaphragm, bent nails were observed in both plywood and FRP panels. Some of the nails sheared at the point of interface between the FRP panels and the framing members. This indicated that the nails had been subjected to more inelastic deformation than in the plywood diaphragm test and may have contributed to the overall capacity of the diaphragm.

Comparison of Test Results

The load-displacement curves for the plywood and the composite diaphragms are shown in Fig. 5 for north displacements and in Fig. 6 for south displacements. Straight line segments connect the points corresponding to maximum force at each displacement level simply to make the comparison easier. The data show that the composite diaphragm is capable of carrying higher lateral loads than the plywood diaphragm. The maximum measured load on the composite diaphragm was about 35 percent higher than that for the plywood diaphragm.

In the original plywood diaphragm, almost all of the observed damage was nail tear-through around the edges of the four corner plywood panels. In the composite diaphragm, the four corner FRP panels sustained no damage and the majority of the damage was transferred to the remaining plywood panels as well as to the individual nails. Plywood panels which remained on the diaphragm because they sustained little or no damage during the initial test failed in the retest by nails tearing through the plywood edges or by local buckling. In addition, most of the nails in the composite diaphragm underwent some degree of inelastic deformation. Some nails pulled out of the framing members and some of the nails sheared at the interface between the plywood and the framing members. This indicated that in the composite diaphragm, the plywood panels were still the limiting factor to diaphragm strength. However, the nails became more of a limiting factor to the diaphragm capacity.

CONCLUSIONS

In the plywood diaphragm tested, damage was primarily caused by the local failure of plywood panels around the nails. This was particularly true along the edges of the four corner panels. These panels were subjected to the most rotation as the diaphragm deflected and thus the local stresses around the nails on corner panels were higher than

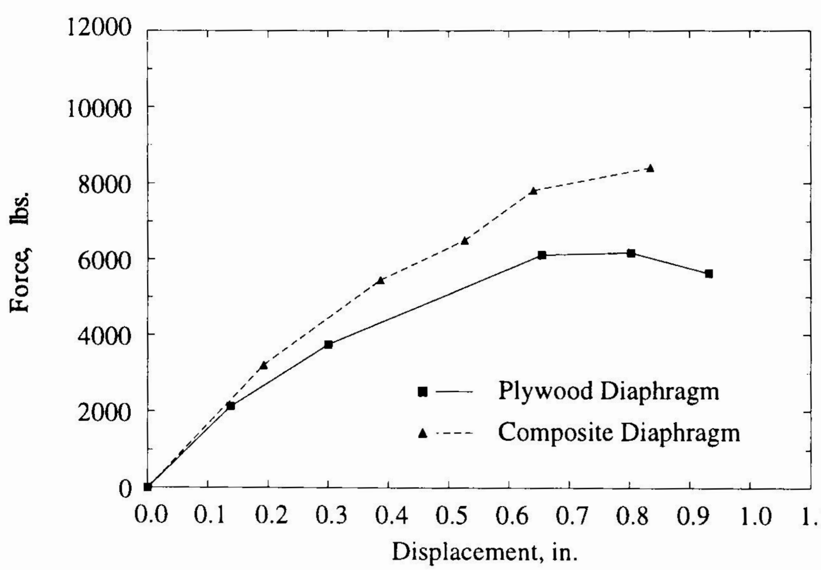

Fig. 5 North Displacements

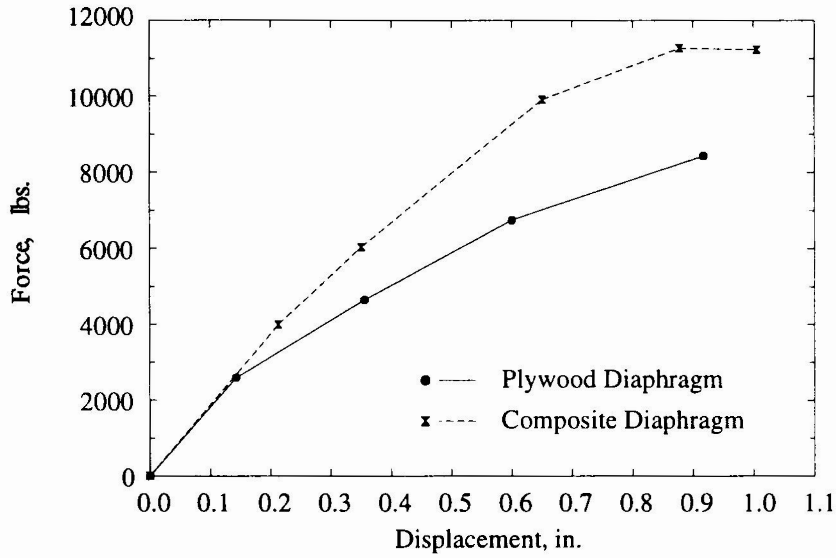

Fig. 6 South Displacements

in other areas of the diaphragm. In the composite diaphragm, damage was transferred from the four corner FRP panels to the remaining plywood panels and to the nails attaching both FRP and plywood panels to the framing members. Again, the corner panels of the diaphragm rotated the most as the diaphragm deflected. Thus, the nails attaching the FRP panels to the diaphragm were subjected to higher stresses than the nails attaching the plywood panels to the diaphragm. Despite this, the limiting factor for diaphragm strength was the plywood panels. The FRP panels were capable of withstanding higher stresses than the plywood panels, thus strengthening the diaphragm and allowing it to safely carry higher lateral loads.

From the observations and results obtained through these tests, FRP panels can be effectively used in retrofitting schemes for repairing seismically damaged plywood diaphragms. A diaphragm which has been damaged by an earthquake or by other types of lateral loads can be repaired by removing the damaged plywood panels and replacing them with FRP panels. A diaphragm repaired by this procedure will actually be stronger than the initial diaphragm. This becomes even more significant because within the repaired diaphragm, all of the diaphragm elements except for the new FRP panels have already been subjected to lateral loads and are probably weaker than they originally were. However, the diaphragm as a whole is still stronger than it was before by the addition of FRP panels.

Also, if FRP panels can be used to repair and increase the capacity of damaged plywood diaphragms, then new diaphragms initially built with FRP sheathing material may have significantly higher capacities. Thus, FRP panels may be used to strengthen and increase the safety of both damaged and new flexible diaphragms.

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