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STRUCTURAL BEHAVIOR OF WALL PANELS FOR LOWER COST HOUSING

by

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The quest for lower cost housing has witnessed the use of countless construction techniques ranging from conventional on-site construction to completely prefabricated modules. While labor costs, labor shortages and quality control are largely responsible for the growing trend away from on-site construction, prefabricated modular construction has also been subject to limitations. Between these extremes, panelized construction utilizing prefabricated panels represents a logical and practical compromise for many building systems.

Panels vary widely according to size, construction and materials. While modular widths of two to four feet are the most common, some builders use full width panels. Some panels are constructed using conventional stud construction while other utilize sandwich or stressed-skin design made of a wide variety of core and facing materials.

This paper summarizes the structural performance of stressed skin and sandwich panels used or proposed for use in lower cost housing. Several of the panels were used in the Austin Oaks Low Cost Housing Development Project. (1) All of the panels had a nominal length of eight feet and a width of four feet or less.

TYPES OF PANELS

Three basic types of panels were tested in the program: asbestos-cement post and sheet panels, aluminum-skin paper-honeycomb panels, and plywood skin panels with wood perimeter members and polystyrene cores. A summary of the panel descriptions is given in Table 1.

Asbestos-Cement Panels

Asbestos-cement is a construction material that has been in use for many years. It has excellent durability, fire resistance, and compressive strength. Its compression and tensile strength, several times higher than concrete, are due to the asbestos fiber reinforcement. Asbestos-cement has been used extensively for housing in Europe, Puerto Rico, Latin America, and South America but has witnessed only limited use in the U.S. housing industry.

A section of panelized system utilizing asbestos-cement is shown in Figure 1. The system consists of hollow extruded asbestos-cement columns on 16 inch center connected by two 3/8 inch asbestos-cement panels. The system is not a true prefabricated panel since the panels are bonded to columns with adhesive after the columns have been attached to the slab with steel angles. A horizontal steel rod is used in the top of the panel to tie the wall together. Fiberglass batt insulation is placed in the cavity.

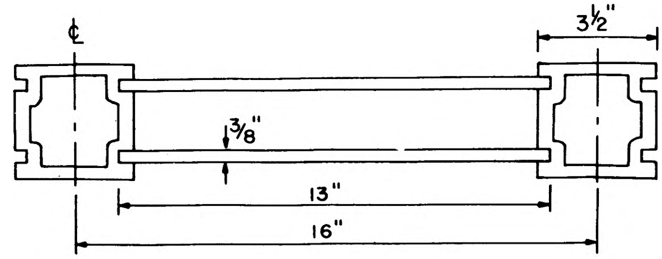

Fig. 1. Cross Section of Asbestos-Cement Panel

TABLE 1: SUMMARY OF FLEXURAL TESTS

Panel	Thickness, in.	Compression Face	Tension
T1	3-1/2	Asbestos-cement	Asbestos-cement
T2	3-1/2	Asbestos-cement	Asbestos-cement
T3	3	0.030 in. Aluminum	0.030 in. Aluminum
T4	3	0.030 in. Aluminum	0.030 in. Aluminum
T5	1-3/4	0.030 in. Aluminum	0.030 in. Aluminum
T6	1-3/4	0.030 in. Aluminum	0.030 in. Aluminum
T7	2-1/8	3/8 in. Douglas Fir Plywood	1/4 in. Mahogany Plywood
T8	2-1/8	3/8 in. Striated Cedar Plywood	1/4 in. Mahogany Plywood
T9	2-1/8	3/8 in. Striated Douglas Fir	1/4 in. Mahogany Plywood
T10	2-1/8	1/4 in. Mahogany Plywood	3/8 in. Asbestos Fiberboard
T11	2-1/8	3/8 in. Asbestos Fiberboard	1/4 in. Mahogany Plywood
T12	2-1/8	3/8 in. Tempered Hardboard	1/4 in. Mahogany Plywood
T13	2-1/8	1/4 in. Mahogany Plywood	3/8 in. Tempered Hardboard
T14	2-1/16	Aluminum-Clad 5/16 in. Douglas Fir Plywood	1/4 in. Mahogany Plywood
T15	2-1/16	1/4 in. Mahogany Plywood	Aluminum-Clad 5/16 in. Douglas Fir Plywood

Aluminum Sandwich Panel

Aluminum has been a primary aircraft construction material for years, but thus far has found limited use in housing. Its excellent corrosion resistance and high strength-to-weight ratio have encouraged several manufacturers to produce panels with structural aluminum skins with lightweight cores.

The panels used in this test program consisted of nominal 0.030 inch pebble-texture prefinished aluminum skins with a resin-impregnated honeycomb paper core. A phenolic resin was applied separately to the core and the aluminum skins, and after the panel was assembled, heat was used to activate the adhesive. Exterior wall and roof panels were three inches thick while interior panels were 1-3/4 inches thick. All panels were 48 inches wide.

An aluminum channel attached to the floor is used to hold the panel; one-eighth inch pop rivets attach the panel to the channel. A vinyl lock-strip provides the connection between adjacent panels.

Plywood Stressed-Skin Panels

Plywood stressed-skin and plywood sandwich panels have been in use for many years in the aircraft and construction industries. The development of low density cellular plastic core materials and improved adhesives coupled with the trend toward prefabrication have witnessed the development of many types of plywood-faced panels.

Figure 2 illustrates the construction of the panels used in this test program. Using both wood stringers and polystyrene for the core, the panels are actually a combination of stressed skin and sandwich construction. Both plywood skins are bonded to the wood preimeter members and the polystyrene core to produce a panel four feet by eight feet by approximately 2-1/8 inches thick. The interior skin in all cases was prefinished Philippine mahogany plywood. The exterior skins used were: sanded Douglas fir plywood; Douglas fir plywood; V-grooved striated cedar plywood; asbestos fiberboard; and tempered hardboard. The thicknesses were 3/8 inch in all cases except the aluminum-bonded plywood which was 5/16 inches thick.

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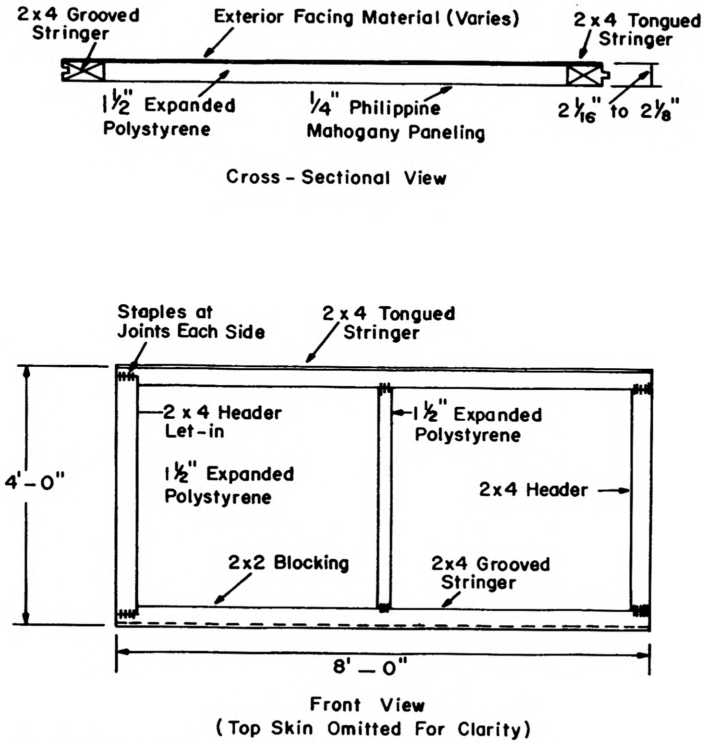

Fig. 2. Section and Elevation of Stressed-Skin Panel

The panels are connected together by the tongue-and-groove joint. An aluminum batten strip is used to weather-proof the joint.

FLEXURAL BEHAVIOR

The flexure tests were performed in accordance with ASTM E-72-61 except as otherwise noted. Panels T7 through T13 were tested with a span of seven feet; all other panels had a span of seven and one-half feet. At least two panels of each type or thickness were tested except in the case of three of the plywood panels (P7, P8, P9), in which case the exterior skins differed only slightly in strength. The behavior of each type panel will be discussed briefly. The results are tabulated in Table 2. The ultimate unit load has been reduced to correspond to an eight foot span for a typical wall. The factor of safety is given for a 20 psf superimposed lateral load. The deflection, Δ, and the deflection-to-span ratio, Δ/L, are also for an eight foot panel height and a 20 psf load.

TABLE 2: FLEXURAL TEST RESULTS[1]

Panel	Ultimate load psf	Factor of Safety	Δ, in.	Δ/L
T1	114	5.7	0.062	1/1550
T2	111	5.6	0.086	1/1110
T3	88	4.4	0.209	1/459
T4	112	5.6	0.216	1/444
T5	31	1.6	0.133	1/722
T6	28	1.4	0.184	1/522
T7	169	8.4	0.373	1/257
T8	144	7.2	0.373	1/257
T9	165	8.2	0.373	1/257
T10	96	4.8	0.328	1/293
T11	196	9.8	0.396	1/242
T12	152	7.6	0.381	1/252
T13	141	7.0	0.366	1/262
T14	112	5.6	0.394	1/244
T15	122	6.1	0.364	1/264

[1]All results have been adjusted to correspond to eight foot panels; factor of safety and deflections are based on 20 psf loading.

Asbestos-Cement Panels

The asbestos-cement panels were tested using one repetitive unit, 16 inches wide, consisting of a half-column section on each side of the two flat sheets instead of the 48 inch width specified by ASTM. The asbestos-cement panels exhibited a nearly linear load-deflection response to failure. In both panels, a sudden tension failure occurred on the bottom face between the quarter-point loads.

The moduli of elasticity were found by test to be 3,000,000 psi in compression and 3,400,000 psi in tension. The ultimate compressive stress was 13,600 psi; the ultimate tensile stress was 1,980 psi. It was determined that the calculated ultimate load could be very closely predicted using: (1) elastic theory; (2) a neutral axis location found by assuming the compression modulus for the entire session; and (3) an effective flange width from the face of the column equal to four times the panel thicknesses. Good agreement was also obtained for deflection response using the same assumptions. The panel proved to be by far the stiffest of all the panels tested with an average Δ/L ratio of less than 1/1200. The factor of safety for a 20 psf load was in excess of 5 for an eight foot panel.

Aluminum Sandwich Panel

Two 3 inch panels and two 1-3/4 inch panels were tested to failure. After panel T3 had failed in buckling due to stress between the reaction and the quarter-point load, the other three panels (T4, T5, and T6) were tested with four uniformly spaced live loads instead of the usual two as specified by ASTM. This was done to spread the applied load as much as possible to lower the stress concentrations in the thin aluminum skin at interior load points. The other 3 inch panel, T4, also failed by shear buckling. The 1-3/4 inch panels both failed by flexural buckling of the compression skin near the midspan.

All four panels exhibited essentially an elastic load-deflection response to failure. The deflection of the panels, with the exception of T4, was predicted within 20 percent using previously proposed theory considering both shear and flexural deflections. (2) From tests, the elastic modulus of the aluminum was found to be 10,350,000 psi, and the shear modulus of the core was determined to be 1,710 psi for the 3 inch panel and 327 psi for the 1-3/4 inch panel. The deflections for a 20 psf superimposed load were quite low, and the factor of safety against failure was in excess of four for the 3 inch panel; for the partition panels, the factor of safety averaged 1.5.

Plywood Panels

The plywood panels exhibited considerably greater deflection than the other two types of panels, but still less than 1/240th of the span for the 20 psf service load. With the exception of the aluminum-clad plywood, the panels exhibited a nearly linear load-deflection response, with a slight reduction in stiffness in the load range. The aluminum-clad plywood panels exhibited greater nonlinearity near the maximum load. In fact, the load-deflection curve for T14 became practically horizontal before failure finally occurred. All panels except T10, with the relatively brittle asbestos-cement fiberboard on the tension side, deflected at least 2-1/2 inches before failure occurred; panel T10 deflected 1.6 inches.

The plywood properties used for calculating deflections were those recommended by the American Plywood Association (3) since these are the values used by the design engineer. For the non-plywood skins, properties were found from tests. For the asbestos fiberboard the properties were: compressive and tensile moduli, 450,000 psi and 613,000 psi respectively; ultimate compressive and tensile strength, 3000 psi and 1130 psi. The tempered hardboard possessed compressive and tensile moduli of 455,000 psi and 618,000 psi; ultimate compressive and tensile strengths were 5000 psi and 2600 psi respectively.

The mode of failure varied. Shear failure in the perimeter framing members occurred in T7, T9, T12, T13, and T15. The bond failed between the top skin and framing member in T8 and T14, although T14 continued to deflect at constant load. Panel

T8 also developed cracks in both faces. Tension failures occurred in the skins of T10 and T11.

The predicted deflections were calculated using the theory for plywood stressed-skin panels (4) with the exception that no reduction in effective skin width was assumed since the core provided support as in sandwich panels. (5) For the panels T7, T9, T14, and T15, the calculated deflections for a 20psf superimposed load were approximately 20 percent less than the observed values; the deflections for panel T8 were in excellent agreement. However, the theoretical deflections were larger than the observed values for the panels with asbestos-cement fiberboard and hardboard facings. At the 20 psf service load, the deflection-to-span ratios were nearly the same for all panels ranging from 1/242 to 1/293. The factor of safety for service loads was in excess of four for all panels.

COMPRESSION TESTS

The compression test specimens each had a height of eight feet with the same width as the flexural panels. The panels were tested in accordance with ASTM E-72-61.

The asbestos-cement panel carried a total axial load of 28,900 pounds. The maximum deflection was 0.332 inches. Failure was due to a rupture in the tension face.

The aluminum sandwich panel developed a load of 3750 pounds before local buckling of the facing occurred at one end of the panel. The maximum deflection was observed to be negligible.

The three aluminum-clad plywood stressed-skin panels tested developed an average ultimate load of 20,200 pounds before elastic buckling occurred. The lowest ultimate load was 16,340 pounds. The maximum deflections ranged from 0.8 to 1.5 inches.

INPACT TESTS

Impact resistance was measured using a falling ball test very similar to ASTM D1037. The 2 inch steel ball was dropped from an increasing height on the specimen until a visible crack appeared on the upper surface or the maximum height of 80 inches had been reached. The maximum drop height, permanent set at last drop, and mode of failure are recorded in Table 3. The asbestos-cement panel was the most brittle and failed at a height of only 30 inches. The two plywood specimens did not rupture. The aluminum-clad plywood had a greater permanent set since the aluminum surface recovered less than the mahogany plywood.

The 3 inch aluminum panel failed whereas the 1-3/4 inch panel did not. Apparently the thinner panel had more compressive stiffness due to the shorter buckling length of the core material.

TABLE 3: RESULTS OF IMPACT TESTS

Panel	Maximum Drop Height, in.	Permanent Set, in.	Mode of Failure
Asbestos-cement	30	0.005	Punch Through
1/4 in. Mahogany Face of Stressed skin Panel	76	0.031	None
Aluminum-clad plywood face of stressed skin Panel	72	0.095	None
1-3/4 in. Aluminum Sandwich Panel	72	0.595	None
3 in. Aluminum Sandwich Panel	50	0.425	Split in skin

PANEL COSTS

The relative costs of the panels, including erection but no allowance for finishing of unfinished surfaces, are given in Table 4. The costs are given for sake of comparison only and may vary widely from one locale to another. It should be noted that maintenance costs and insurance rates will vary and can have a significant effect on costs.

POTENTIAL OF PANELS

All of the panels tested in flexure and compression indicated a satisfactory factor of safety and stiffness. Panels T5 and T6 had a factor of safety less than two in flexure, but should be adequate as interior partitions. In compression the panels are capable of carrying typical roof spans with an adequate factor of safety.

The asbestos-cement panels tested represent a structurally sound but inefficient system. Asbestos-cement is a material with enormous, but as yet untapped, potential for use in prefabricated building components. To be used economically, however, monolithic cellular panels are dictated to reduce labor and material (including adhesive) costs.

The aluminum sandwich panels proved to be structurally adequate. However, thermal and acoustic deficiencies seriously impair their suitability for use in housing. Polyurethane low-density foam is being applied to each face of the honeycomb core in an attempt to alleviate the thermal problem. The exterior skins are subject to damage by hail.

The plywood stressed-skin panels have been used for several years in the southwest primarily with the aluminum-clad plywood exterior skin. The panels have more than adequate strength, can be furnished in a variety of exterior finishes, and possess a warmth not found in other materials. The primary disadvantages are maintenance and lack of fire resistance for the all-wood panels.

TABLE 4: SUMMARY OF PANEL COSTS

Panel	Relative Cost, \$/sq. ft.
Asbestos-Cement	2.04
3 in. Aluminum Sandwich	1.36
3/8 in. Douglas Fir	1.30
3/8 in. Striated Douglas Fir	1.30
3/8 in. V-grooved striated cedar	1.38
3/8 in. Asbestos-Cement	1.59
3/8 in. Tempered Hardboard	1.38
5/16 in. Aluminum-Clad Douglas Fir	1.57

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