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SOME INNOVATE HOUSING UNITS

by

Sidney Shore* and Jack R. Vinson**

INTRODUCTION

The need for innovations in housing throughout the world increases exponentially with time. The use of known, but relatively untried material systems, geometries of articulation, and methods of fabrication for an innovative housing unit called Unikraft[1] Model 400 are described in this paper. Section 1 describes the method of factory and in situ fabrication of the Unit. Section 2 includes the material properties and strength properties of the materials system utilized; Section 3 includes a brief summary of the structural integrity of the 400 Unit by analytical and experimental methods.

The versatility of the material and structural form of the Unikraft Model 400 makes it ideally suited for a wide spectrum of applications including temporary and/or emergency shelter, semi-permanent housing (5 to 10 year life) and permanent housing (greater than 10 years). See Figure 1. Hence depending on the options desired, the range of costs for the Unit varies from $4.00 to $12.00 per square foot.

Fig. 1

FABRICATION OF UNIKRAFT STRUCTURAL SYSTEM

The Unikraft system of construction consists of 10 foot long wall and roof channel members that form a one story trapezoidal prism. The basic building module is 8' 8-5/8" in height, 21' 4" in length, and 20" 0" in width at the base. The basic module can be extended in length in 16" increments or can be offset laterally; "T" and "L" shaped buildings can be achieved by combining basic modules. Wall and roof panels are nominally 5/16" thick, double wall corrugated virgin kraftboard. The kraftboard is die-cut to form a 16" channel shaped section that constitutes the basic Unikraft wall and roof structural unit. Fiberglass mats of varying thickness are applied to the kraftboard to produce a composite material of desired strength characteristics.

The factory supplied material is pre-cut and pre-scribed kraftboard channel members, pre-cut door and window wooden framing members, fiberglass mats, polyester resin, wooden clamping blocks, wooden gusset plates, standard door and windows and galvanized staples. An exploded isometric, Figure 2, shows the components for the basic 400 Unit.

The field erection consists of stapling the 16" channel members of the roof and walls then joining the channel members of the end walls to the roof and wall with blind staples. The bottom of the wall members are subsequently connected to a conventional wooden floor platform or reinforced concrete slab. The fiberglas mats are applied to the exterior surfaces and the polyester resin applied. Next the door and window openings are framed, and the door and windows installed. Interior partitions and doors, which are non-loadbearing, can be conventionally fabricated. The interior side of the exterior walls and the roof can be covered with conventional prefinished or unfinished board; the resulting roof and wall cavities can be insulated with conventional batt insulation and an appropriate vapor barrier. A completed house is shown in Figure 3.

MATERIALS AND THEIR PHYSICAL PROPERTIES

The composite material used in Unikraft construction is composed of three components: the paper sandwich, the fiberglass mat and the polyester. The paper sandwich is double walled corrugated fiberboard sheet of which the outer facings are 70 lbs/1000 ft^2 basic weight Kraft liner board having a maximum moisture vapor transmission rate of 12 grams/24 hours per square meter. The intermediate facing is a 62 lb. basic weight wet strength Kraft liner board. The fluting is of B/C configuration made from a special 33 lb. basic weight corrugated medium. All components are combined with a water resistant adhesive. The glass mat is of 3/4 oz. chopped strand fiberglass E grade mat with a silane binder. The polyester resin is characterized as follows: Type - rigid, promoted; Viscosity - low, slightly thixotropic; Reactivity - low to medium; Monomer - styrene.

In the following, "longitudinal" refers to the configuration in which the load applied is in the direction parallel to the flutes, while "transverse" refers to the configuration in which the load is applied in a direction normal to the flute direction. The repeated channel sections of the homes studied utilize the configuration shown below. (Figure 4)

All tests were conducted on an Instron Machine, Standard Model TTCML (metric). The temperature and humidity in the office in which the specimens were retained is generally around 70° F and 50% R.H. during the winter, and all specimens were retained sufficiently long to establish equilibrium with these conditions prior to testing.

In all Tables the barred quantities are the mean values of (usually) ten specimens, and the σ values are the standard deviations. Numbers in parentheses are the percentage of the mean value the standard deviation is. P refers to paper sandwich, while G refers to the glass mat: thus, GPG refers to a construction in which one layer of glass mat is bonded on each side of the paper sandwich.

The tensile tests were carried out largely in accord with TAPPI Standard T404 ts-66, using specimens 250 mm in length, with a gage length of 180 mm and widths varying between 24 and 26 mm. The desired quantities for subsequent structural analyses are: N_u, the ultimate tensile load per unit width, lb/in.; N_y, the tensile load per unit width corresponding to the yield load on the specimen, lb/in.; K, the extensional stiffness per unit width, lb/in.; and % Elong., the deflection corresponding to the ultimate load divided by the gage length (180 mm) x 100. The results are given in Tables 1 and 2.

The compression tests were carried out in accordance with the standards expressed in Forest Products Laboratory Report FPL-0109, entitled "Comparison of Two Specimen Shapes for Short Column Test of Corrugated Fiberboard," by J. W. Konig, Jr. The specimens were all rectangular with dimensions of 1.25" in height and 2.00" in width. The results are given in Table 3.

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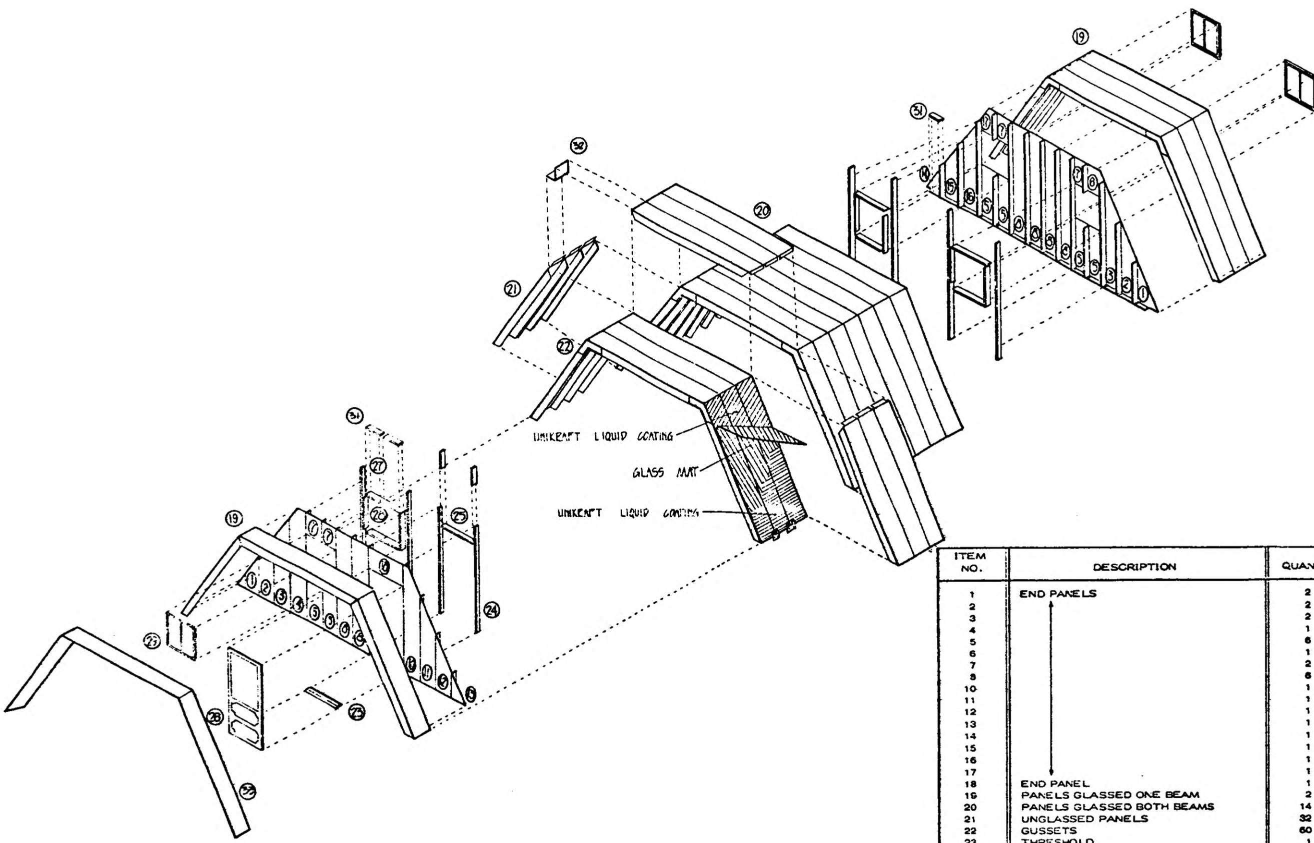

ITEM NO.	DESCRIPTION	QUANTITY
1	END PANELS	2
2	↑	2
3		2
4		1
5		6
6		1
7		2
8		6
10		1
11		1
12		1
13		1
14		1
15		1
16		1
17	↓	1
18	END PANEL	1
19	PANELS GLASSED ONE BEAM	2
20	PANELS GLASSED BOTH BEAMS	14
21	UNGLASSED PANELS	32
22	GUSSETS	60
23	THRESHOLD	1
24	DOOR FRAMES	2
25	DOOR HEADER	1
26	METAL DOOR WITH SCREEN	1
27	WINDOW SUPPORT	6
28	WINDOW BOX SECTIONS FOR 3 WINDOWS	12
29	METAL WINDOWS WITH SCREEN	3
30	METAL STARTING BRACKETS	36
31	BOTTOM NAILERS	40
32	BRIDGING	32
33	SHADOW BOX SECTIONS	3

Fig. 2

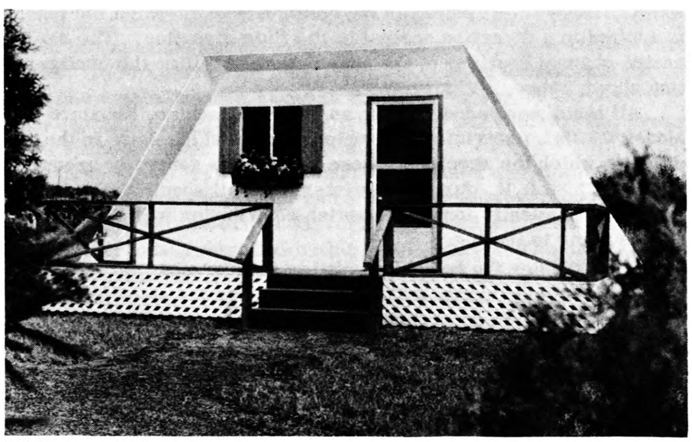

Fig. 3

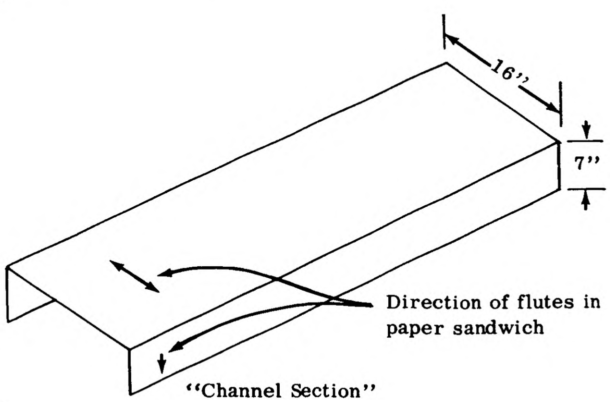

Fig. 4

TABLE 1: TENSILE MECHANICAL PROPERTIES - TRANSVERSE DIRECTION

Property	Paper Only	PG	GGP	GPG
$\bar{N}_u$ (lb/in)	396.6	626.9	825.5	926.2
σ_{N_u} (lb/in)	31.1 (7.88%)	49.7 (7.93%)	96.2 (11.62%)	81.44 (8.78%)
$\bar{N}_y$ (lb/in)	157.7	260.6	632.3	877.5
σ_{N_y} (lb/in)	50.9 (32.3%)	57.0 (21.9%)	95.3 (15.05%)	54.03 (6.16%)
$\bar{K}$ (lb/in)	36,544	74,480	75,709	91,509
σ_K (lb/in)	7300 (20%)	6530 (8.8%)	1339.7 (1.768%)	3014.1 (3.43%)
% Elong.	3.86	3.06	1.711	1.298%
$\sigma_{\%}$	0.379 (9.81%)	0.5697 (18.6%)	0.1369 (7.99%)	0.2702 (20.8%)

TABLE 2: TENSILE MECHANICAL PROPERTIES - LONGITUDINAL DIRECTION

Property	Paper Only	PG	GGP	GPG
$\bar{N}_u$ (lb/in)	227.6	446	691.5	677.0
σ_{N_u} (lb/in)	10.4 (4.58%)	24.5 (5.5%)	48.86 (7.07%)	41.5 (6.13%)
$\bar{N}_y$ (lb/in)	127.37	204.1	526.8	----
σ_{N_y} (lb/in)	13.22 (10.38%)	103.2 (50.5%)	52.25 (9.93%)	----
$\bar{K}$ (lb/in)	17,432	50,033	48,373	71,010
σ_K (lb/in)	1205 (6.91%)	8520 (17.0%)	1999 (4.14%)	3090.3 (4.35%)
% Elong.	4.71	2.598	2.115	1.1539
$\sigma_{\%}$	0.62 (13.15%)	0.947 (36.4%)	0.3344 (15.82%)	0.0874 (7.56%)

TABLE 3: ULTIMATE COMPRESSIVE LOADS FOR THE VARIOUS UNIKRAFT CONSTRUCTIONS (pounds per inch of width)

Type	Item	Transverse	Longitudinal
Paper	$\bar{N}_u$	61.70	116.25
	σ_{N_u}	7.74 (12.55%)	11.69 (10.05%)
PG	$\bar{N}_u$	192.77	340.3
	σ_{N_u}	35.35 (18.35%)	101.52 (29.9%)
GGP	$\bar{N}_u$	416.9	445.2
	σ_{N_u}	49.97 (11.95%)	101.92 (22.9%)
GPG	$\bar{N}_u$	254.2	408.6
	σ_{N_u}	36.8 (14.45%)	75.0 (18.3%)

Of the various standards set by TAPPI, ASTM and others for flexural tests, only one provides the actual flexural stiffness properties of the Unikraft type construction. The standard to use is ASTM C 393-62, "Standard Method of Flexure Test of Flat Sandwich Constructions." In ASTM C 393-62 one performs a central load flexure test and a flexure text with equal loads applied at the quarter span points on the same test specimen. Care, of course, must be taken not to permanently deform the specimen during the first of the two tests. The technique used herein is to run the four point flexural test first, followed by the three point load test, on the 8" long test pieces. The flexural stiffness per inch of width D (lb-in.^{2}/in.) and core shear modulus G(psi) are calculated for each specimen, using the equations from ASTM C 393-62. Using the values of the core shear modulus, a value of the core shear stiffnesses D_{qx} and D_{qy} are obtained by multiplying the shear modulus G by the core depth, which is the distance between the two outer face sheets. The results are shown in Table 4.

The repeating pattern of channel sections used in the present construction is shown below: (Figure 5)

Defining x as the dimension between the center line of the web section and the neutral axis, it is seen that the neutral axis is located at the following:

$$X = \frac{49\, K_L}{2(7K_L + 8K_W)} \qquad (1)$$

The extensional stiffness, $\overline{EA}$, and the flexural stiffness, $\overline{EI}$, are found to be

TABLE 4: FLEXURAL AND SHEAR PROPERTIES OF THE VARIOUS CONSTRUCTIONS

Transverse Direction				
Type	$\bar{D}$ (lb-in^2/in)	σ_D (lb-in^2/in)	$\bar{G}$ (psi)	$\bar{D}_{qx}$ (lb-in^2/in)
GP	1048	199 (19%)	867	204.6
GGP	1720	476 (27.7%)	677.5	185.0
GPG	1863	700.8(37.6%)	906	241.2
Longitudinal Direction				
Type	$\bar{D}$ (lb-in^2/in)	σ_D (lb-in^2/in)	$\bar{G}$ (psi)	$\bar{D}_{qy}$ (lb-in^2/in)
GP	811.6	141 (17.4%)	11664	2753
GGP	1084	208 (19.2%)	2190	604.5
GPG	1858.6	180.7(9.73%)	3188	832.8

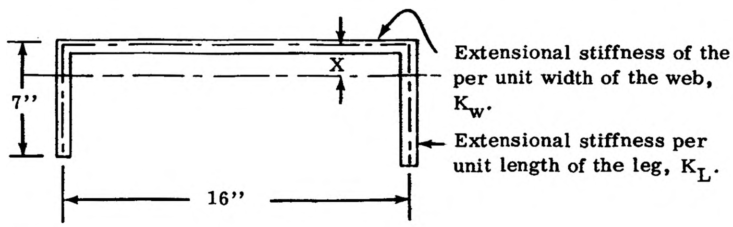

Fig. 5

$$\overline{EA} = 14K_L + 16K_W \qquad (2)$$

$$\overline{EI} = K_L \frac{2}{3}(7-x)^3 + \frac{2}{3}x^3 + 16\,x^2 \frac{K_W}{K_L} \qquad (3)$$

Note that in equations (1), (2), and (3), transverse extensional stiffness of all constructions must be used, which is obtained from data in Table 1. The properties of channels of various constructions are given in Table 5.

For the roof under a snow load the web of the channel is put into compressive inplane loading. The web may buckle, and it is therefore necessary to determine the buckling load for a plate 16" wide, clamped along the unloaded edges, very long in the direction of the load, account for orthotropy, with significant transverse shear deformation effects.

The best methods of analysis are in U.S. Forest Service Research Note FPL-070, "Buckling Coefficients For Simply Supported and Clamped Flat, Rectangular Sandwich Panels Under Edgewise Compression," by E. W. Kuenzi, C. B. Norris, and P.M. Jenkinson.

The calculations for the various constructions are summarized below in Table 6.

It is seen that buckling can occur only in the GGP construction. In both the PG and GPG construction buckling will not occur, only overstressing will cause failure. (Compare Table 3 with Table 6).

STRUCTURAL INTEGRITY

The structural integrity of the Unit was verified both analytically and by load tests.

A structural analysis was performed for a variety of loading conditions utilizing linear theory since the stress-strain relationship of the composite material described in Section 2 was essentially linear in the range of loading anticipated. Actual tests of assemblies and an entire Unit further confirmed the almost linear structural response assumed in the analysis in the range of realistic roof and wind loadings. To encompass the widest spectrum of structural behavior, the analysis considered the bottom of the walls under fully fixed and fully hinged conditions. The loadings and loading combinations were based on those recommended in a 1970 draft copy of the American National Standard Building Code Requirements, AHS A58 - Minimum Design Loads in Buildings. In particular the

TABLE 5: CHANNEL PROPERTIES FOR PAPER SANDWICH LEGS AND GPG WEB

	X (in.)	$\overline{EA}$ (lbs.)	$\overline{EI}$ (lb-in^2)
Mean	0.908	1.975×10^6	6.76×10^6
Mean - 1σ	0.785	1.825×10^6	5.56×10^6
Mean - 2σ	0.641	1.672×10^6	4.32×10^6
Mean - 3σ	0.471	1.525×10^6	3.01×10^6

CHANNEL PROPERTIES FOR PG LEGS AND GPG WEB

	X (in.)	$\overline{EA}$ (lbs.)	$\overline{EI}$ (lb-in^2)
Mean	1.455	2.503×10^6	11.7×10^6
Mean - 1σ	1.405	2.366×10^6	10.84×10^6
Mean - 2σ	1.350	2.225×10^6	9.99×10^6
Mean - 3σ	1.285	2.089×10^6	9.09×10^6

CHANNEL PROPERTIES FOR PAPER SANDWICH LEGS AND PG WEB

	X (in.)	$\overline{EA}$ (lbs.)	$\overline{EI}$ (Lb-in^2)
Mean	1.061	1.688×10^6	6.5×10^6
Mean - 1σ	0.957	1.498×10^6	5.32×10^6
Mean - 2σ	0.835	1.289×10^6	4.12×10^6
Mean - 3σ	0.663	1.083×10^6	2.87×10^6

CHANNEL PROPERTIES FOR PAPER SANDWICH LEGS AND GGP WEB

	X (in.)	$\overline{EA}$ (lbs.)	$\overline{EI}$ (lb-in^2)
Mean	1.040	1.722×10^6	6.5×10^6
Mean - 1σ	0.897	1.600×10^6	5.41×10^6
Mean - 2σ	0.727	1.477×10^6	4.24×10^6
Mean - 3σ	0.531	1.351×10^6	2.97×10^6

TABLE 6: DETERMINATION OF BUCKLING LOAD PER UNIT WIDTH, N_{cr} FOR VARIOUS WEB CONSTRUCTIONS

	D_x	D_y	'	D_{qy}			N_{cr}
Type	lb-in^2/in	lb-in^2/in	α	lb/in	V	K	lb/in
PG	1048	811.6	1.29	2752.9	0.01467	6.48	261.5
GGP	1720	1084.4	1.585	604.5	0.11	4.6	305.0
GPG	1862.9	1858.6	1.003	832.8	0.0862	5.75	413.0

individual loadings were: -1- Dead load = 0.75 p.s.f.; -2- Roof (or snow) load = 30 p.s.f.; -3- Wind loading due to a basic wind speed of 100 mph (including gust effects) with a mean recurrence interval of 50 years for locations such as suburban areas, towns, city outskirts, wooded areas and rolling terrain; -4- Seismic loading consisting of a static horizontal force applied at the roof level and equal to 10% of the dead load of the structure. The load combinations examined were: -1- Dead load and snow; -2- Dead load and wind; -3- Dead load and seismic; -4- Dead load and 2/3 snow and wind.

The allowable stresses used in the calculations were based on the following formula:

$$N_a = \frac{\overline{N_u} - 1.645\sigma}{F} \qquad (4)$$

where N_a = allowable load per unit width of composite
$\overline{N_u}$ = ultimate load per unit width of composite as determined by strength tests (see Section 2)
σ = standard deviation of tests to determine the strength of the composite (see Section 2)
F = factor of safety.

Thus, using a mean value less 1.645 standard deviations ensured that 95% of all test results will have a value of that magnitude or greater. A factor of safety of 2 was chosen. In a similar manner all the average flexural, shear and channel properties of the various constructions given in Tables 4 and 5 were reduced by 1.645 standard deviations.

The results of the structural analysis indicated that the 400 Unit could sustain the loading combinations listed above without exceeding the allowable stresses based on equation (4).

To further verify the structural integrity of the structure two full scale loading tests were conducted. The first test was to determine the strength and stiffness of the wall and/or roof construction without any interior finish, that is, the bare structural frame. These tests were conducted in accordance with the Technical Circular No. 12 (dated October 5, 1949), "A Standard for Testing Sheathing Materials for Resistance to Racking" of the United States Department of Housing and Urban Development, Federal Housing Administration. The test specimens were 8' 0" x 8' 0" panels, positioned vertically, supported along the bottom edge, and loaded by a horizontal force applied to the top edge. Both dry and wet series of tests were conducted, and the panels satisfied the criteria specified in the Technical Circular.

The second test was an ultimate roof loading test of the Unikraft structural system without any interior panels or finish. A simulated snow load was achieved by building a wooden frame lined with a plastic sheet on the roof and filling this container with water by hoses. The 400 Unit supported a design roof loading of 30 p.s.f., but without any distress and a maximum roof deflection to span ratio of 1/200. The structure exhibited a small amount of creep at 30 p.s.f., but also the ability to recover when the load was removed. The maximum average ultimate roof loading sustained was 77.3 p.s.f., but locally the maximum loading at failure was 79.2 p.s.f.

CONCLUSION

On the basis of the material contained in this paper and other information, the United States Federal Housing Administration has approved (1) the Unikraft structural system so that any modules built become eligible for mortgage insurance. Further, the Committee on Compliance of the Southern Building Code Congress has approved (2) Unikraft structures.

ACKNOWLEDGMENT

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REFERENCES

1. Department of Housing and Urban Development, Federal Housing Administration Structural Engineering Bulletin No. 715, dated July 6, 1971.
2. Southern Building Code Conference, Committee on Compliance Approval Report dated January 5, 1972.